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# Proceedings of the 38<sup>th</sup> Annual Meeting of the Council on Forest Engineering

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## Engineering Solutions for Non-industrial Private Forest Operations



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Organized and hosted by the



Partners:



Division 3 - Forest Operations Engineering and Management



Department for Energy Development  
and Independence  
Division of Biofuels



## FOREWORD

The Council on Forest Engineering (COFE), founded in 1978, is an international professional organization interested in matters relating to the field of forest engineering. Its main objective is to foster the development of forest engineering in industry, government, and in university teaching, research, and extension programs in order to promote the best methods of managing and operating forests, both private and public.

For the first time, the COFE annual meeting is hosted by the Department of Forestry at the University of Kentucky. The theme of the 38<sup>th</sup> COFE annual meeting is “Engineering Solutions for Non-Industrial Private Forest Operations.” Technical presentations dealing with the following topics are addressed:

- Forest operations as a means to restore and improve forest health
- Biomass utilization for energy production
- Best management practices to reduce site disturbances and maintain stream water quality
- Transition to mechanized operations in hardwood forests
- Small-scale forest operations for non-industrial private landowners

Presentations related to other applied forest engineering and operations topics are also included. These proceedings include information from 44 presentations during plenary and concurrent sessions. There are 31 full papers and when not available, abstracts are provided. These full papers are not peer-reviewed and authors are responsible for their quality. Not COFE nor the University of Kentucky Department of Forestry shall be responsible for statements and opinions advanced in these publications.

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## PAPERS AND ABSTRACTS

### I. Plenary Session A

#### **Forest engineering/operations – a necessity for industry competitiveness**

Dale Greene<sup>1</sup>

<sup>1</sup>Dean, Warnell School of Forestry and Natural Resources, University of Georgia

Successful management of forests and forest products industries in today's competitive global environment requires a range of skills and abilities for which forest operations and forest engineering programs prepare graduates extremely well. Our decentralized industry structure, greater reliance on efficient logistical operations, and society's expectations for certification and high compliance with environmental regulations are just a few of the trends increasing the need for foresters with this type of training.

# Kentucky Logging Industry and Economic Report

Jeffrey Stringer<sup>1</sup>

<sup>1</sup>Professor of Hardwood Silviculture and Forest Operations, Department of Forestry, University of Kentucky

Kentucky's forest industry plays a significant economic role in the state's economy and is an important source of primary hardwood products for the nation. Historically Kentucky is one of the top producers of hardwood sawlogs and lumber, over the past 16 years one of the top two or three with annual outputs ranging 0.75 to 1.1 billion board feet. The total estimated economic output in 2014 was \$12.8 billion on par with tourism and greater than any other agricultural enterprise including well-known sectors like equine and tobacco. Over one-half of this economic input is directly fed by Kentucky loggers. The logging force ranges from approximately 1,000 to 1,500 firms with an average size of 3.1 workers including owners. Many Kentucky loggers purchase their own timber, and gate wood deliveries to mills are the norm. The majority of operations incorporate manual felling with mechanized operations more typical in western Kentucky that has relatively gentle terrain and a strong pulpwood market. Mechanized felling operations in the deeply dissected terrain of eastern Kentucky are less numerous. The logging sector is fiscally challenged with delivered mill prices for many important species and grades still similar to mid-2000 prices. Expansion of operations is difficult with the worker's compensation insurance running \$1.20 dollars per \$1 of payroll for manual felling operations and a shortage of workers. This fosters mechanization that maintains a worker's compensation rate of 0.20 to 0.25 dollars per dollar payroll and Kentucky has seen a slow progression to mechanization in recent years.

## II. Plenary Session B

### **From Butcher Holler to Monkey Broke Creek - Restoring Forests and Ecosystem Services on Surface Coal Mines**

Christopher Barton<sup>1</sup>

<sup>1</sup> Professor of Forest Hydrology and Watershed Management, Department of Forestry, University of Kentucky

Appalachia is a land of contrast—people have suffered from poverty for decades, but the region abounds with natural resources. Appalachian forests support some of the greatest biological diversity in the world’s temperate region, but extraction of the region’s abundant coal reserves has impacted the landscape. Since 1977, over 600,000 ha of Appalachian forest have been affected by surface mining, producing significant economic, environmental, and ecological challenges. Successful reestablishment of the hardwood forest ecosystem that once dominated these sites will provide a renewable, sustainable multi-use resource that will create economic opportunities while enhancing the local and global environment. The Appalachian Regional Reforestation Initiative (ARRI) and its partners have undertaken an extensive project to restore forests on surface-mined lands. Research and outreach with all stakeholders was instrumental in advancing knowledge and demonstrating techniques to restore productive forests and ecosystem services on surface-mined lands. Impacts resulting from the partnerships include: 1) water quality and flood mitigation improvements benefiting human and aquatic health; 2) improved wildlife habitat; 3) sequestration of carbon and air quality improvements; and 4) empowerment of the community to participate in beautification and enhancement of land that is neglected and often abandoned. Cooperation, consultation, and effective communication between parties have resulted in increased application of the Forestry Reclamation Approach (FRA). Since 2004, approximately 95 million trees have been planted on 140,000 acres of surface mined land in Appalachia. Efforts to test the global applicability of the FRA have begun with a project in the Hunter Valley region of Australia.



## Felling a Few Logs to Find Energy

Timothy Hughes<sup>1</sup>

<sup>1</sup> Director of Biofuels, Kentucky Department of Energy Development and Independence

Addressing LOGISTICS, current OPPORTUNITIES, future GROWTH, and SUSTAINABILITY of biomass is critical for the success of the bioenergy sector. It is imperative that the resources of the private sector, governmental agencies, academic institutions, and other interested parties work together effectively to clear many of the hurdles that have created stumbling blocks for success. Several research initiatives, industry investments, educational events, and networking sessions are taking place in Kentucky to tackle these areas. Improving the feasibility of these LOGISTICS from the farm or forest all the way to the final consumer is paramount to fostering bioenergy development. A lot of credence is paid to “finding the low hanging fruit” in many activities and that philosophy is sound in identifying the current OPPORTUNITIES for bioenergy. Fulfilling the future GROWTH potential of an international marketplace for energy will require new found creativity in crops, equipment, production practices, utilization technologies, policies, etc. Keeping interest in the long term possibilities and needs while the current economics discourage investment is challenging. As technology, methodology, and ecology are evaluated, the gatekeepers must continue to incorporate SUSTAINABILITY in their policies and not draft regulatory impediments based upon assumptions that fail to consider the accomplishments of today’s agriculture and the potential of tomorrow’s. The presentation will highlight activities going on in our state and efforts coordinated by our Statewide Wood Energy Team while raising a number of topics that must be addressed regionally, nationally, and internationally as we strive for increased energy access, affordability, and reliability.

## Point-of-Harvest and Logging Chain-Of-Custody Certification

Christopher Reeves<sup>1</sup> and Dr. Jeffrey Stringer<sup>2</sup>

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Certification of forest industries including logging and forestland remains an area of interest in the region. This involves chain of custody certification for industries (including logging) and point-of-harvest certification for logging operations. However, growing certification is difficult given the large percentage of small non-industrial forest owners in the region, which makes certification fiscally inefficient, and the minimal price premiums and industry sectors interested in certification. To make certification work, benefits must be distributed to all entities in the supply chain, certified supply chains must be streamlined and administrative costs of certification minimized. To assist in improving the competitiveness of Kentucky and surround states to benefit from certification a number of industries, consulting foresters, non-profits, and the University of Kentucky Forestry Extension program have partnered to establish an initiative to provide solutions focusing on overcoming the impediments to certification. In 2005 the University of Kentucky in partnership with MeadWestvaco initiated what is now the Certified Master Logger Program one of the first third party audited point-of-harvest certification programs in the U.S. and in 2007 obtained SmartLogging certification through Rainforest Alliance. In 2012 the Center for Forest and Wood Certification was formed providing industry assistance in chain of custody certification and maintaining group certification for small industries including logging and forestlands. The Center has provided innovative certification solutions resulting in certification of over 100 forest industries in 7 states and over 60,000 acres of certified lands.

### III. Plenary Session C

#### **Fresh Lessons Learned from Logging Litigation**

Dr. John Garland, PE<sup>1</sup>

<sup>1</sup> Consulting Forest Engineer, Affiliate Professor, Dept. of Environmental and Occupational Health Sciences, U. Washington; Professor Emeritus, Forest Engineering, Resources and Management, Oregon State University

#### **Abstract**

In a seminal paper and presentation for the COFE 2004 meeting in Hot Springs, AR, the author provided forest engineers, loggers, machine manufacturers, and others in public and private sectors with helpful information and insights based on 30 years and more than 25 cases of litigation. Ten lessons were offered for consideration and now after 40 years and more than 64 cases, some recent lessons are worth sharing with COFE members. The majority of cases involve logging accidents but others involve wildland firefighting, lost profits, yard accidents, vehicle accidents and even a shooting. The original lessons are reinforced over the years but other useful lessons emerge from reviewing the total cases. New lessons are found in accidents involving logs falling off trucks during loading/unloading. Typical accident investigation is found to be lacking and deficient. The widespread occurrence of an unsafe practice does not make it “usual and customary” for the forest industry. Finally, there are lessons from large scale litigation that use a “team of experts” approach. The best approach is to avoid the accidents and conflicts that result in litigation.

**Keywords:** logging, litigation, lessons learned, accidents

#### **1. Introduction**

In a seminal paper and presentation for the COFE 2004 meeting in Hot Springs, AR, the author provided forest engineers, loggers, machine manufacturers, and others in public and private sectors with helpful information and insights based on 30 years and more than 25 cases of litigation (Garland, 2004). Ten lessons were offered for consideration and now after 40 years and more than 64 cases, some recent lessons are worth sharing with COFE members. Fresh

lessons involve large scale litigation where teams of experts depend on other experts competence to contribute to their own opinions and findings. Fire litigation has implicated the usual and customary forest operations practices needed to prevent wildfires or their early suppression. Some incidents border on criminality in violent and tragic deaths. Finally, forest operations professionals put their credibility and licenses on the line in these tragic matters.

Besides the fresh lessons, additional litigation experience reinforces lessons from the earlier publication listing, including several of the earlier findings. It is amazing that litigation reveals that the “Bizarre does happen in logging.” More cases of litigation show repeatedly that “Time is of the Essence” for logging litigation. It is disconcerting that when the “Hazards may be known” accidents are continually occurring and obvious preventive measures are not made universal. Forest engineers are in the best position to document incidents by acknowledging “Location is Everything” in finding the truth for accident causation. Let’s look at the identified lessons first.

## **2. Past Lessons Reinforced**

### **Bizarre does happen**

Concepts of probability are challenged by actual events that cause astonishment. What are the chances that a vehicle traveling on a woods road will connect with a tree falling across the same road where the top of the tree strikes the cab of the vehicle? The two moving objects precisely intersect. The result was a fatality where microseconds of vehicle speed or tree movement could have averted the tragedy. What are the odds that on New Year’s Day a vehicle returning from the coast with two passengers would be struck by a wind blown tree killing the passenger? Except, a recent harvest left the trees in the highway right-of-way exposed to wind and said trees were infected with a root rot limiting their stability. The guardrails along that section of highway show many previous incidents of trees falling across them into the highway. Other incidents show the conflict where society’s preference for visual aesthetics of trees adjacent to the highway come face to face with the reality of trees or parts of trees falling on vehicles and killing occupants. Rare events perhaps but precautions can reduce the risks.

### **Time is of the essence**

Accidents disrupt human activities and once the event has been investigated by officials, there is sometimes considerable time for legal actions to materialize. The delay can be 2,3,5 or even 7 years before competent expertise is sought to assess the event and the investigations. A forest changes during the delay and important evidence and information may have changed, been destroyed, or machines sold or dismantled. The timely assessment by competent experts is crucial to finding the truth. Practical concerns also support timely assessments. Insurers and defendants need to know their potential liabilities so timely settlements don't include excessive litigation costs leading to and including trial costs.

### **Hazards are known**

It is inexplicable that similar accidents occur over and over again when the hazards are known and the preventive measures are also well known. This is especially true for loading logs and unloading logs on trucks. During loading, no one should be in a position where a log/tree can escape control of the loader and strike someone. During unloading and wrapper removal, the logs on the load should be secured so a log cannot fall and strike the driver. Rules and policies govern these activities but dozens of times they are not followed and someone is hurt or killed. Some defense approaches call the unsafe procedures the "usual and customary" practices of the industry. Lawsuits then follow. Individuals make the errors but organizations fail to insure safe procedures are followed and supervisors are culpable. Owners then pay. There are no savings in the shortcuts that produce the injuries!

### **Location is everything**

Coupled with the delays in getting competent assessments of accidents, the measurements taken at the time of the accident are critical. However, many accident investigators called to the immediate scene are not competent to document critical locations and essential details of the accident site. Some investigators wildly shoot videos or take photos from undocumented locations or fail to describe in a photo log of what is shown. Some others take measurements but do not relate them to known locations. The simplest measures of arcs taken from the endpoints of a documented baseline would be sufficient to re-establish critical locations, but few immediate investigators make the effort or know how to do it. Law enforcement agencies are taught how to measure for vehicle accidents but not for logging accidents. Detailed measures from total stations or laser imaging are accurate but need to measure the significant details and tie them to benchmarks for later use. GPS measures can be

useful if accurate and tied to physical objects, but if misused, they mislead experts. In one case, errors with GPS caused the opposing experts to assess an accident scene two hundred feet from where it actually occurred.

### **3. Fresh Lessons from Litigation**

You can't depend on others....

In large scale litigation, say involving a billion dollars in damages, forest engineering experts may be part of a large team of experts. Attorneys themselves are part of a team with each attorney managing a group of experts or some aspect of the complaint or defense. A lead attorney may have the full picture while experts and other attorneys may not know what others are doing in the matter. Experts are asked to rely on the work of other experts as precursors to their own findings and opinions. There is danger for experts to rely on work previously done by others and provided to them without validating the data, findings, or information themselves.

In a large California fire, several cases for damages were brought by the federal and state government against landowners, sale purchasers, and timber operators. I was asked to assess the actions of the logging crew with respect to their efforts in preventing, suppressing and even possibly causing the fire. The fire investigator for the "origin and cause" of the fire reported that a spark from the machine operation in rocky terrain caused the fire. Evidence was found and fire behavior from the origin seemed to support the findings. In my own experience, I have observed tracks producing sparks while moving over rock roads at night on a fire. The depositions found the logging employees did not provide the diligence needed for their fire watch and subsequent actions. It was later learned the fire investigator fraudulently manufactured evidence for his origin and cause determination. The conspiracy involved state employees, attorneys, and resulted in a miscarriage of justice against the landowners, sale purchasers, and timber operators. Lawsuits are still underway to set aside earlier verdicts and settlements (Wall Street Journal, 2015).

The findings on inadequate fire watch of the loggers holds, but are only relevant if the cause of the fire was machine operation not some other cause as defendants maintain like an arsonist or firewood cutter. I acknowledged this in my deposition but believed the other experts who testified. You cannot trust precursor work by others without your own verification. It should be a condition of employment. My own reputation was damaged by association with California state and federal prosecutors.

## **Vigilance in fire prevention**

Work involving wildland fires reveals a need for forest operations professionals to be more diligent in fire prevention and suppression from operational fires. Professionals who contract for forest operations (logging, vegetation management, site preparation, etc.) have contractual oversight for the provisions calling for fire watch after operations, maintaining fire suppression tools and equipment, and other prevention measures. However, operational fires are still occurring and both the contractors and those who use their services are being held accountable. It is impossible to show prevention efforts worked to avoid the fires that did not happen. However, there is documentation that early fire detection and quick suppression can avoid losses and lawsuits. Other findings change the way fire is treated in practice. For example:

- Fire watch and walks in operating areas now require a time and date to be painted on stumps in the area covered.
- Some hot saws are equipped with water tanks that allow dousing stumps after cutting during high hazard conditions.
- Fire suppression systems for harvesting machines help prevent machine caused fires, eg, hydraulic hose failure, etc.
- For cable harvesting, some firms have water sources that can be put on the cableway quickly to bring a small fire under control. Other firms pre-emptively lay fire hose in adjacent cableways for quick access to water.
- A number of fires have started on holidays/weekends when one or two people were operating during high hazard conditions. Suppression resources were inadequate to keep the fire from quickly spreading. Strict controls during high hazard days are now part of contracts.

It may be necessary for forestry professionals to physically fight a wildland fire to fully understand the devastating forces of a fire before they can appreciate fire prevention and early suppression efforts.

## **Violent deaths...**

In 2013 the Bureau of Labor Statistics reported nine percent of workplace deaths were from homicides but none were in the forestry sector (BLS, 2014). There have been reports of

threats against supervisors and other workers from workers carrying guns on forest operations. Others working in the forest face hazards from guns. An undocumented South American greenery harvester was mistakenly shot as a bear when the landowner allowed harvesting and hunting in the same area. The greenery harvesters preferred the black rain gear as it was inexpensive and effective. The hunter was criminally charged but was acquitted. The civil suit against landowner and greenery contractor/purchaser revealed other firms provided their greenery harvesters with high visibility vests (<\$3 each) and prohibited hunting near greenery harvest areas.

Another violent death occurred when a log stacker driver in a sort yard ran over a scaler and crushed the small SUV. The scaler had previously contacted log yard management over what he saw as unsafe practices of the stacker driver. Once in motion toward the vehicle, the heavy stacker could not be stopped before it reached the vehicle. The driver had no explanation why he backed up in the direction of the vehicle. He claimed he did not see him....

A serious injury occurred when a faller in training fell a short snag in the direction of his trainer for no apparent reason. The two were related and testimony indicated some resentment may have been present. The snag fell short of the trainer but broke apart with a large section traveling downhill and pinning the trainer against a tree he was bucking. The injuries to the trainer resulted in medical complications over the next few years that eventually caused his death. Why???? Lessons learned from such tragic events start with the realization that violence can occur from weapons, machines, and trees. It is noteworthy that such events are rare in the forestry sector.

#### **4. CONCLUSIONS**

Most forest operations professionals will avoid involvement in litigation; however, with a long career and the unpredictability of forestry, some folks will be caught in the middle of lawsuits. Perhaps the lessons learned from a larger number of events will help professionals avoid the circumstances leading to litigation or provide insights on the nature of forestry litigation.

#### **5. REFERENCES**

Bureau of Labor Statistics. 2014. Table 2. Fatal occupational injuries by industry and selected event or exposure, 2013. <http://www.bls.gov/news.release/cfoi.t02.htm>. Accessed March 12, 2015.



Garland, J. 2004. Lessons learned from logging litigation. Council on Forest Engineering. Annual Meeting. Hot Springs, AR. COFE. Corvallis, OR 5p. available at [www.cofe.org](http://www.cofe.org)

Wall Street Journal. 2015. Prosecutors Burn Down the Law: How fire investigators distorted evidence to loot a company. January 2, 2015. <http://www.wsj.com/articles/prosecutors-burn-down-the-law-1420242330>. Accessed on April 17, 2015.

## **Bourbon Barrel Industry**

Bob Russell <sup>1</sup>

<sup>1</sup> Wood Procurement Manager, Brown-Forman

Bourbon whisky production has been historically centered in Kentucky and surrounding states and the production of stave logs has been a part of the forest product mix in the region since the 1800's. Recently there has been a significant increase in bourbon whisky consumption both domestically and internationally. Market projections indicate that international consumption will continue to increase and the distilling industry is increasing capacity and production to meet this projected demand. The increase in production requires, both operationally and legally, an increase in the production of oak casks, in the case of bourbon, white oak casks (barrels). Domestic barrel production currently is derived from stave and header boards from stave logs grown and procured from the "white oak belt" of the Midwest and South. The increased demand raises questions within the distilling industry about both short and long-term white oak availability including availability of timberlands and logging capacity.

## **IV. Concurrent Session 1A – Productivity of Logging Operations I**

### **Wood Comminution Technology and Techniques**

Rafaele Spinelli<sup>1</sup> and Natascia Magagnotti<sup>1</sup>

<sup>1</sup> Researcher, CNR IVALSA, Trees and Timber Institute, National Research Council of Italy

This presentation will summarize the results of 10 years of CNR research about comminution technology. During this period, the Authors have conducted a very large number of chipper tests, with the purpose of determining the impact of a number of work factors on productivity, fuel use and product quality. All studies were conducted under carefully controlled conditions, in order to obtain reliable information. Machines were rigged with appropriate sensors, in order to measure engine torque and power, as well as fuel consumption. All product output was taken to certified scales, and carefully sampled for laboratory quality testing. Moisture content was determined with the gravimetric method and particle size distribution through sieving, according to EN standards. In their studies, the Authors examined and quantified the effect of such variables, as: comminuter type (e.g. crusher vs. chipper, disc vs. drum, open drum vs. closed drum), cut length setting, screen size, piece-breaker devices, chip discharge system (blower vs. conveyor), knife wear and feedstock type (logs, tops, branches – fresh vs. dry – hardwood vs. softwood). The presentation will have a simple and concise form, but it will also be extremely dense in contents, so as to offer an exhaustive overview within the allotted time slot.

## Some Notes on Centralized Biomass Processing

Dana Mitchell <sup>1</sup>, John Klepac <sup>2</sup>, and Jason Thompson <sup>2</sup>

<sup>1</sup> Project Leader, USDA Forest Service, Southern Research Station

<sup>2</sup> Engineer, Forest Operations Research Unit, Southern Research Station, USDA Forest Service

For this article, centralized biomass processing refers to processing forest products at a location away from the landing. Centralized processing may be advantageous for a variety of reasons. Some thoughts behind centralized processing are that it may reduce in-woods costs or improve production rates. One way to examine the costs of a centralized processing facility is to first examine the costs of a typical southern harvesting operation that includes biomass removal with processing occurring in the woods. Landing operations generally include delimiting and topping stems, bucking logs, sorting various products, loading log trucks, and other activities. Comminution of residues and unmerchantable material is performed to densify the material for efficient transport. As trucks and mill quotas are available, sorted products and biomass are hauled. All of these activities require quite a bit of equipment and scheduling. Transporting and setting up equipment can be time consuming and may negatively impact production. In addition, roads may need upgrading for passage by chippers, chip vans, and other rigs. This paper explores some of the potential production rates and costs of a couple of representative southern harvesting systems. Then, machine rates are calculated for a representative system that does not process the stems at the landing, but hauls the wood in whole tree form to a centralized processing facility. This information will be explored to gain insight into how much could be invested at a centralized processing facility to make it a feasible alternative to in-woods processing.

# Modeling the Productivity of Feller-Bunchers in Small-Diameter Pine Plantations

Timothy McDonald<sup>1</sup> and John Klepac<sup>2</sup>

<sup>1</sup> Professor, Biosystems Engineering, Auburn University

<sup>2</sup> Engineer, Forest Operations Research Unit, Southern Research Station, USDA Forest Service

## Abstract

Developing a general model of felling productivity is difficult because of the numerous factors affecting a specific machine's performance. The influences of the two largest contributors to variability among systems (other than the stand), operator behavior and the machine itself, are difficult to characterize. Instead, specific regression models based on observation are typically developed, which is time-consuming and expensive, and ultimately only truly applicable across a small range of conditions. We have attempted with this study to broaden the scope of applicability of feller productivity models by generalizing some parameters that effectively characterize machine and operator impacts on performance. The model requires stand information to calculate an average stem DBH that is used to predict the maximum carrying capacity of the felling head. This constitutes the portion of the model that is machine-specific, or at least specific to the felling head. Accounting for operator input requires selection of an average percentage of capacity to which the head is filled on each cycle. Predictions based on the proposed model were found as accurate as those based on simple regression of cycle time on number of trees per cycle, but the new model was simpler to apply in a predictive situation. Number of trees per cycle is a useful predictor of felling productivity, but not easy to calculate ahead of time since it depends so much on machine and operator. The new model provides a simple, rational means of estimating those effects for any stand/machine/operator combination and provides reasonable productivity results.

**Keyword:** model, cycle time, felling

## 1. Introduction

Numerous studies have measured felling productivity and presented some type of explanatory model describing observed behavior (see Table 1 for some examples). The purpose in developing such a model was presumably to generalize the observations to allow their use in other applications. Often, however, there were so many confounding factors this extrapolation of results would not be possible in any new situation likely to arise.

As part of a larger study of biomass harvesting for energy, the USDA Forest Service Forest Operations Research Unit has collected a quantity of detailed production study data on at least three different fellers operating in the same, or similar, stands. As others have, it was felt developing a mathematical relationship to describe the observations was a useful exercise, since it would provide a basis of comparison for other researchers when evaluating similar scenarios. As is always the problem, however, the studies represented a specific set of machines in relatively unique situations and any model developed would be useful only in the same context. The work presented in this paper was undertaken to derive an expression for felling productivity based on these data that allowed the parameterization of at least some of the unaccounted for factors when performing production studies. In particular, it was our hope to create a felling production model that had some parameters incorporating machine- and operator-specific characteristics, and those factors would be easily derivable from the observed data.

## **2. Methods**

Data collection methods used to assess productivity of a Tigercat 845D tracked feller-buncher equipped with a shear head were presented in Klepac (2013) and followed standard protocols. The machine was videotaped operating in plots of fixed size having each tree marked with its diameter. All sites were plantation pine and had roughly 80% of inventory in the size range of 4-8 inch diameter at breast height (DBH), with stocking averaging around 500 trees per acre (TPA). Other machines tested varied by manufacturer but were all of the saw head, drive-to-tree variety. Table 2 lists specifications and average production rates for the machines tested.

The models presented in Table 1 were a survey of those found in the literature and were selected as a cross-section of those available, not for any shortcomings or perceived flaws. The models were developed to achieve the authors' own objectives, but we wished to highlight the diversity of the forms present. A common thread among the models was that cycle times in felling were most often related to average tree size and number of trees per accumulation, the exception being Bolding and others (2009) in which only the numbers of trees per cycle were used as predictors. It was our conclusion, however, that tree size and count should be related through the harvesting head – number of trees collected in an accumulation ought to be proportional to their average size, up to the capacity of the pocket.

As explanatory models, all of those listed in Table 1 were perfectly fine, but from a predictive standpoint they confounded many factors important in determining cycle time that

were difficult to separate individually and, therefore, hard to specify. When using DBH as the single predictor of cycle time, for example, all the inherent variability in the model was captured in its single coefficient – everything to do with operator, with stand conditions, with the machine itself, etc. Ideally, a good predictive model should be suitably abstract, at a level that allows tuning of major factors but is also relatively simple and avoids the need for detailed data collection to adapt it for a particular set of conditions.

It was our contention the notion of head ‘capacity’ introduced a method of incorporating machine-specific characteristics into a predictive model. Any given felling head ought to have a point beyond which another stem cannot be added for a given size tree, and this should be characteristic of that particular head. Once established, although it might vary due to tree form, the filled capacity point should not vary much for a given head design. Then, given information on stem size distributions in a stand, that information should be easily converted into a number of stems per accumulation, which would then be used in predicting cycle time.

Table 1. A survey of feller production equations for a variety of machines, stands, and silvicultural regimes. Lower-case letters in the equations are parameters, upper case refers to variables.

Variable definitions were as follows:  $T_c$ ,  $T_t$  refer to cycle times, per accumulation and per tree, respectively;  $P$  is cycle productivity;  $N$ ,  $N_M$ ,  $N_N$  are numbers of stems in an accumulation cycle, of merchantable ( $M$ ) or non-merchantable ( $N$ ) size;  $D$  is average, or individual, tree diameter, depending on the application;  $W_t$  is tree weight;  $H$  is tree height;  $S$  is a species indicator;  $L_t$  and  $L_d$  are distances between trees, and to accumulation drops, respectively; and  $A_b$  is basal area. Greek letters imply some random effect related to operator or stand, but the interpretation of the term varies by application.

Citation	Model	R <sup>2</sup>
Heisl and Benjamin (2013)	$T_c = a + bN + cD + \alpha + \varepsilon$	0.4
Spinelli and Magagnotti (2010)	$T_t = a + bD^{1.2}$	0.63
Spinelli and others (2007)	$P = a + b \ln(W_t)$	0.4-0.6
Bolding and others (2009)	$T_{t,M} = [a + bN_n + cN_M]^3$	0.2
Adebayo and others (2007)	$\ln(T_c) = a + bD + \alpha$	0.5
Wang and others (2004)	$T_c = \mu + D + H + S + L_t + L_d + DxH + DxS + HxS$	0.6
Lanford and Stokes (1996)	$T_t = a + bD + \left(\frac{v}{A_b}\right)$	0.2

As mentioned above, maximum capacity should be a parameter related to the felling machine and be independent of the operator. The notion of ‘average utilization of capacity’ was felt to be a predictor variable that added the missing operator effect. Given a stand and site, an operator would perhaps choose to fill the head, on average, to some fraction of the total capacity. That fraction could be related to the operator’s personality, as in they may, or may not, be too impatient to fill the head to capacity when operating in small trees. Or conditions might be such that they would choose to fill the head to a lower average capacity, because of slope, or traction issues. Although this concept is not a rigorously defined effect, it does define a parameter that could be tuned to account for differences in operator behavior.

Based on the above, we proposed the following model for felling cycle time:

$$T_c = a + b \frac{U}{D^2} \quad 1]$$

where  $T_c$  was cycle felling time,  $U$  was fraction of head capacity utilized,  $D$  was cycle average stem diameter, and the two lower-case letters referred to regression parameters. In this model, cycle time referred to one entire accumulation of multiple stems and would include elements such as moving to the first tree, severing each individual stem, then emptying the head.

The term  $U/D^2$  in Equation [1] represented a ratio of a volume (expressed in unit-less form) to a basal area. It was our contention this term could be interpreted as a ‘number of stems’ variable, or, a ratio of scaled total head volume to an average tree volume. Although from an explanatory standpoint this equation was not much different from those listed in Table 1 and should, therefore, not do any better job of accounting for variability in cycle time than a simple regression on the number of stems per accumulation, when used as a predictive tool the result should be more applicable to different sets of circumstances because of the adaptability of the head utilization term.

### 3. Results

Felling cycle times and number of trees per cycle were linearly related for all machines tested. Figure 1 was a plot, by machine, of the relationship and Table 2 a summary of regression results for each feller. All models were statistically significant ( $Pr(>F) \ll 0.0001$ ). The regression parameters were roughly the same and, in fact, analysis of covariance indicated a significant machine and number of trees effect, but no interaction ( $P$ -value = 0.13), suggesting different intercepts but the same slope.



Table 2. Summary of model regression results fitting the function  $T_c = b + m N$  to the data collected on three different machines working in similar stands. F was the overall F statistic of the model and all parameter values were significant ( $P < 0.0001$ ). Cycle times were in seconds.

Machine	N	F	Adj $R^2$	$m$	$b$
Tigercat	320	479	0.60	6.15 (0.28)	19.7 (2.1)
TimberKing	216	221	0.50	5.78 (0.39)	20.9 (1.8)
HydroAx	71	91	0.56	4.70 (0.49)	18.9 (2.4)

There was also a significant ( $P$ -value  $< 0.0001$ ) linear relationship between tree size (DBH) and cycle time, but the effect was small, less than 4 seconds decrease in total cycle time for a 1-inch increase in average DBH. The adjusted  $R^2$  was also low (0.11), as seen in Figure 2.

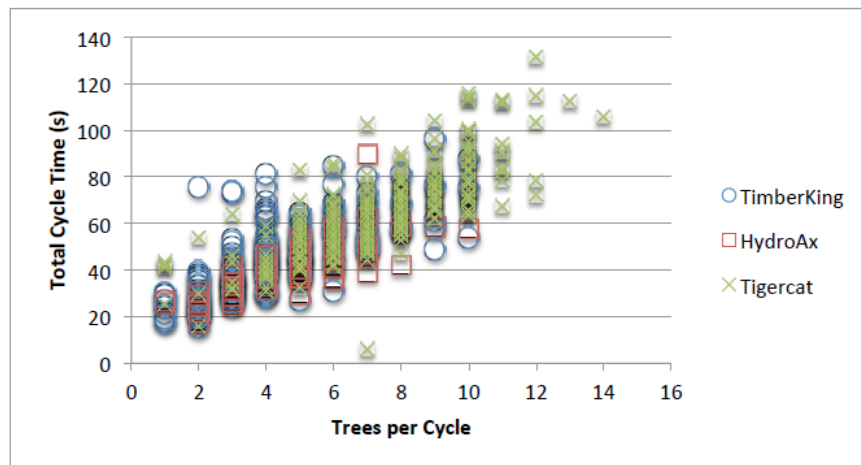


Figure 1. Feller accumulation cycle time as a function of number of trees per cycle.

The regression results suggested there was a slight difference in intercept in the cycle time predictions (based on number of trees per cycle), but no difference in slope. This further suggested the machines, operating in similar stands, would perform about equally with some small fixed difference in average cycle time that could have, but was not definitively proven to be, a result of operator or machine. That analysis, however, did not account for tree size as a covariate, and additionally would be difficult to apply when very little was known about a stand other than perhaps average DBH. It was decided, therefore, to more closely examine the relationship between tree size and number of stems per accumulation. Those data were shown in Figure 3, where trees per accumulation were plotted against the log of  $DBH^2$ . Figure 3a was for the Tigercat feller, and 3b the other two machines.

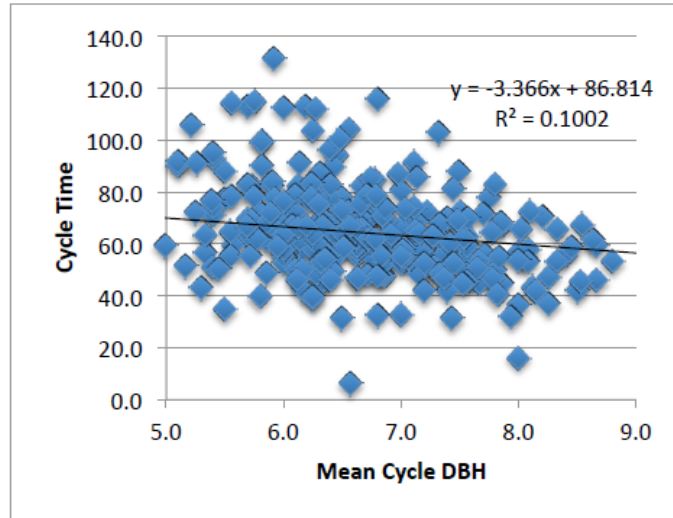


Figure 2. Mean felling cycle time as function of accumulation average DBH. Cycle times were in seconds, and DBH in inches.

There was in each case a visually distinctive frontier, or limit, in the number of stems that could be captured in the head for a given average DBH. This suggested a machine-dependent means of making the link between the stand and felling cycle times. The limiting number of stems for a given tree size we called ‘capacity’ and used regression to model it based on average cycle DBH. Table 3 presents results of fitting both linear and exponential regression models to the capacity data. The exponential model did not improve the capacity prediction for the two rubber-tired machines so the linear model was selected as best for those. In the case of the tracked Tigercat machine, however, the exponential model had both higher adjusted R2 and model F statistic, so it was chosen as best in that case.

Given a means to calculate a capacity value for each machine, it was possible to fit equation [1] to the cycle time data and results of that analysis are shown in Table 4. All models were significant ( $P \ll 0.0001$ ), as were all parameters ( $P \ll 0.0001$ ). Figure 4 shows plots of the measured and predicted cycle times for each machine.

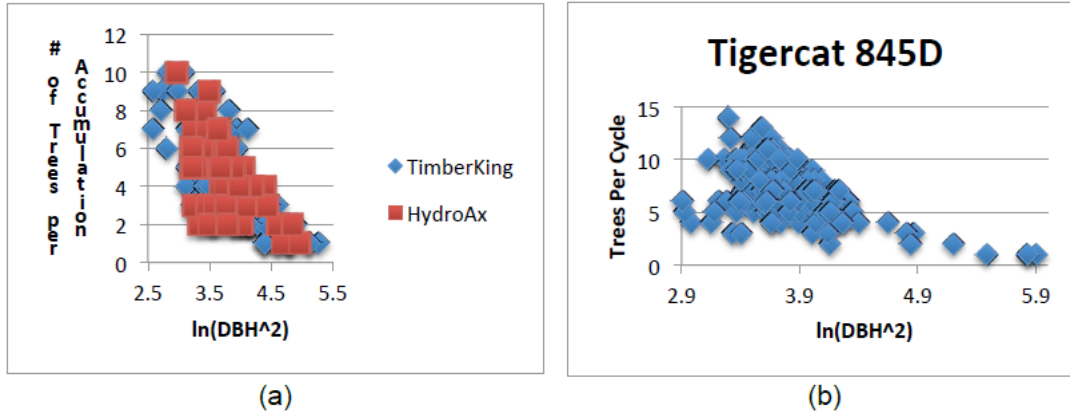


Figure 3. The figure shows number of trees per accumulation as a function of the average accumulation tree size, expressed as the natural log of average DBH squared.

Table 3. A summary of model fit and parameters for two variations on a prediction equation for the data shown in Figure 3. The F statistics were for the overall model and were all significant ( $P < 0.0001$ ).

Model	Machine	Parameters		Model F statistic	Adjusted $R^2$
		a	b		
Linear	HydroAx	23.8	-4.58	299	0.97
$C = a + b X$	Timberking	24.2	-4.50	80.9	0.90
	Tigercat	31.7	-5.67	110	0.89
Exponential	HydroAx	323	-1.07	71.9	0.89
$C = a e^{(b X)}$	Timberking	415	-1.09	78.3	0.90
	Tigercat	655	-1.10	823	0.98

Table 4. Results from fitting the felling data plotted in Figure 1 using the prediction model in eq.[1].

Machine	Parameters		Model F statistic	Adjusted $R^2$
	a	b		
HydroAx	23.8	959	60.1	0.45
Timberking	34.3	778	55.1	0.20
Tigercat	17.7	2925	481	0.60

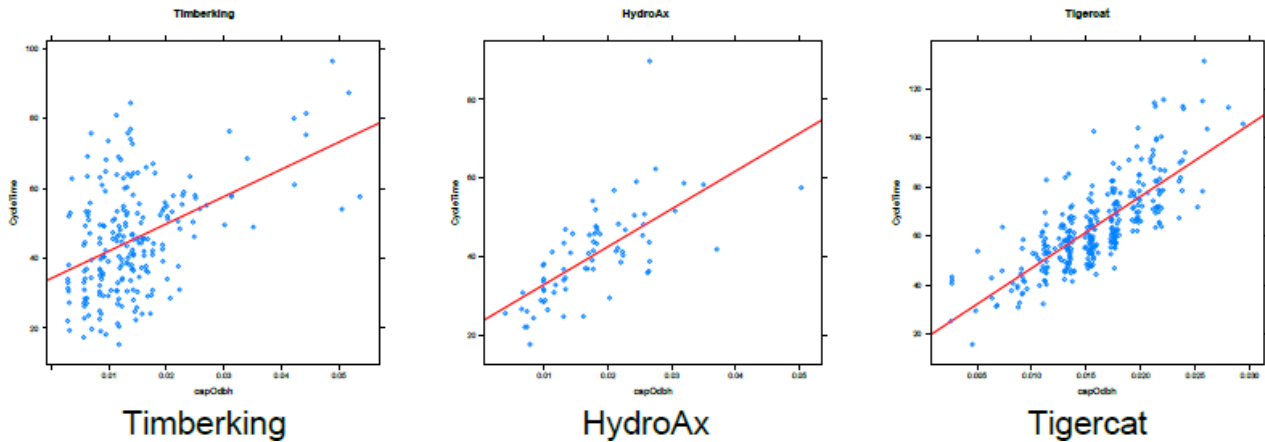


Figure 4. Plots of the fit of eq. [1] to the observed cycle accumulation times, by machine.

#### 4. Discussion

From the analysis presented above, the incorporation of the capacity term into the cycle time regression models did not improve the predictive results. For the Timberking machine, in fact, the opposite was true, predictions were worse. The three functions were plotted on the same graph in Figure 5, emphasizing the difference in slope among the machines for the cycle time equations based on the capacity variable. The tracked machine's (Tigercat) cycle time increased at a rate three times higher than the wheeled machines with increasing capacity term ( $U/\ln(\text{DBH}^2)$ ), which suggested some factor other than machine capacity was playing a significant role in determining performance.

The result implies the cycle time goes higher for all machines when the operator fills the head (capacity utilization is high) with small trees ( $\ln(\text{DBH}^2)$  is small). That is a perfectly plausible conclusion: cycle times should increase when operating in small timber. Cycle times for the wheeled machines, however, were less sensitive to the tree size/capacity interaction.

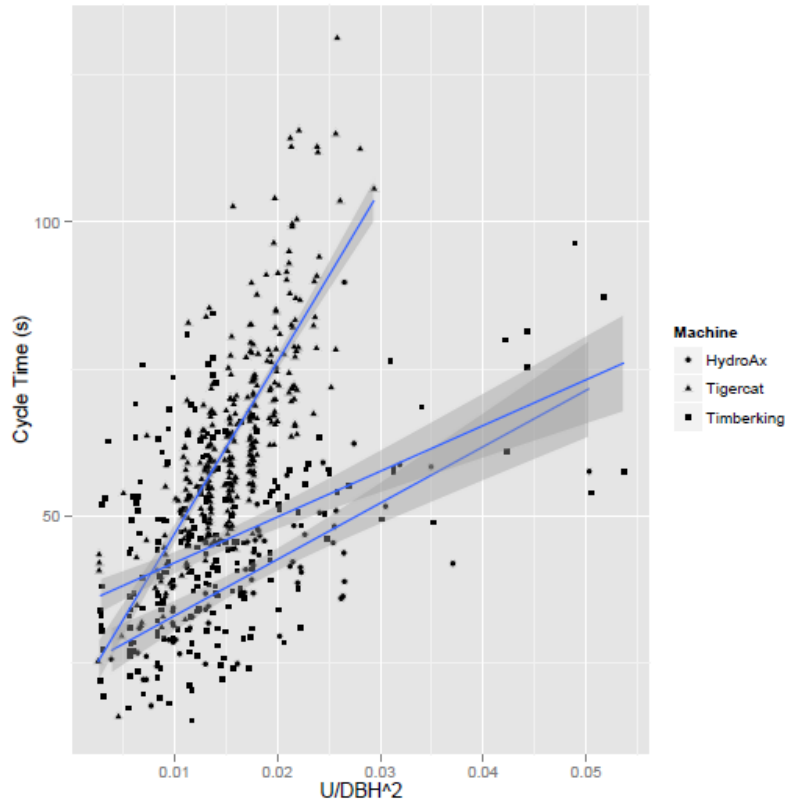


Figure 5. A plot of the felling cycle time as a function of the independent variable from eq. [1], capacity utilization divided by tree size, by machine.

That result could be at least partially explained by the higher capacity of the head on the tracked feller. Because the capacity number was unit-less, the actual capacity of the head was included in the regression parameter, or the slope. It was expected, therefore, the slope would be larger, but three times higher was still a bit more than anticipated. All of the increases in cycle time with capacity also appeared linear, which would imply there was no additional time penalty associated with filling the head with trees as the head became full.

Although the model was not as good at explaining variation in the observed data, the true utility of the capacity approach to describing cycle times was in its use as a predictive tool. When extrapolating these results to another machine, site, and operator, the use of a model employing number of trees per cycle for prediction was problematic, given the amount of information likely known about the conditions for which the model was being applied. If, for example, only an average DBH for the stand were known, how would one go about translating this value into a 'number of trees per accumulation'?

The model in eq [1], however, was useful in that situation because the tree size parameter was applied independently. One needed only arrive at an estimate of the average

capacity utilization for a given operator. This gave some degree of adaptability of the model to the operator and conditions. Data as in Figure 6 might be available for selecting a value based on past history for a specific operator. Or the operator could be expected to lower head capacity utilization on steep slopes, or in wet conditions.

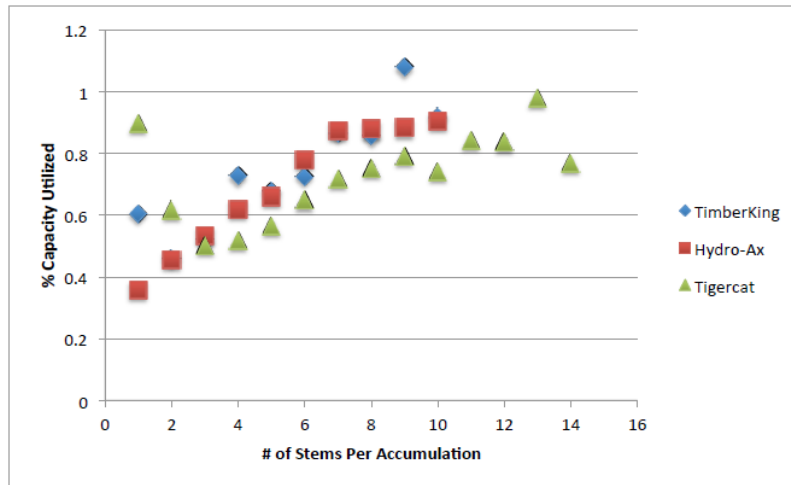


Figure 6. A plot of machine capacity utilization per cycle as a function of the number of trees per cycle.

## 5. Conclusions

A model was presented of felling cycle time as a function of operator utilization of head capacity and average tree size. Although the model did a poorer job in describing variability of some observed performance data, it had the advantage of being more robust in its application.

## 6. References

- Adebayo, A. B., H. Han-Sup, and L. Johnson. 2007. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. *Forest Products Journal* 57(6):59-69.
- Bolding, M. C., L. D. Kellogg, and C. T. Davis. 2009. Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon. *Forest Products Journal* 59(3):35-46.
- Hiesl, P., and J. G. Benjamin. 2013. A multi-stem feller-buncher cycle-time model for partial harvest of small-diameter wood stands. *International Journal of Forest Engineering* 24(2):101-108.

- Klepac, J. 2013. Performance of a tracked feller-buncher with a shear head operating in small-diameter pine. In: Proceedings of the 36<sup>th</sup> annual meeting of the Council on Forest Engineering. July 7-10, 2013. Missoula, Montana: University of Montana. 9p.
- Lanford, B. L., and B. J. Stokes. 1996. Comparison of two thinning systems. Part 2. Productivity and costs. *Forest Products Journal* 46(11/12):47-53.
- Spinelli, R., E. Cuchet, and P. Roux. 2007. A new feller-buncher for harvesting energy wood: results from a European test programme. *Biomass & Bioenergy* 31(4):205-210.
- Spinelli, R., and N. Magagnotti. 2010. Comparison of two harvesting systems for the production of forest biomass from the thinning of *Picea abies* plantations. *Scandinavian Journal of Forest Research* 25(1):69-77.
- Wang, J., C. Long, and J. McNeel. 2004. Production and cost analysis of a feller- buncher and grapple skidder in central Appalachian hardwood forests. *Forest Products Journal* 54(12):159-167.

# Loading Productivity of Untrimmed and Trimmed Pulpwood

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## Abstract

The increase in biomass usage for fuels and energy has required a re-examination of harvesting and transportation systems to efficiently deliver these products to market. Some biomass markets accept forest residues or whole trees (including stem wood, bark and needles) as a feedstock. Therefore, there is less need to remove limbs and tops or deconstruct the tree other than to make transport more efficient. Transporting untrimmed wood or whole trees directly to the mill would appear to be a viable option to achieve increased harvesting productivity and efficiency. In the spring of 2014 a pilot study was undertaken to examine the advantages and disadvantages of untrimmed wood in the wood supply chain. In the fall of 2014, a second study examined the productivity of loading untrimmed (whole) pulpwood trees compared to loading trimmed pulpwood trees.

**Keyword:** whole tree, pulpwood, biomass, loading

## 1. Introduction

Woody biomass is defined as “The trees and woody plants, including limbs, tops, needles, leaves, and other woody parts, grown in a forest, woodland, or rangeland environment that are the byproducts of forest management.” (Patton-Mallory, 2008). Woody biomass can come from mill residues or from the harvesting site itself as the by-product of the primary timber product. These byproducts may be bundled, baled, chipped or chunked and require different handling and transportation systems. The potential increased efficiency of transporting untrimmed or whole trees was examined by Thompson et al. (2014). The hypothesis was that by not deconstructing the tree in the woods, multiple products can be hauled on one truck to the mill resulting in increased harvesting and transportation productivity. Once at the mill, the biomass portion of the tree can be separated from the traditional forest products.

The initial pilot study in the spring of 2014 examined the loading and trimming times for a harvesting crew transporting untrimmed pulpwood in Perry, Florida. A second study gathered



additional data on the same harvesting crew loading untrimmed pulpwood and a second harvesting crew loading trimmed pulpwood.

Slash pine (*Pinus elliottii*) is the dominant plantation species planted in the Perry, Florida region. The Georgia Pacific Foley mill purchases untrimmed trees. Many local landowners plant dense stands (1000 trees/ac) and clearcut at 18 to 22 years old with no intermediate thinnings. The majority of the product removed from these stands is pulpwood with a small component of chip-n-saw logs.

## 2. Methods

A video camera was used to record the loading, trimming, and binding time for the two harvesting crews. Any loading activities that occurred out of view of the video camera were recorded with a stop watch. Load weights were recorded from load tickets. Elemental time analysis was performed using Timer Pro software (Timer Pro, 2013). The loading cycle was broken down into its individual elements and the trimming and binding time was recorded. Cycle elements are listed in the order of a typical sequence in Table 1. During the study period no recordable delays were observed.

Table 1: Pulpwood loading cycle elements for a knuckleboom loader.

<b>Element</b>	<b>Definition</b>
Sort	Element begins when grapple is lowered toward the banked wood. It includes all activities involving preparing stems to be loaded. These include sorting pulpwood and chip-n-saw logs, removing vines and small hardwoods. The element ends when a grapple of wood is heeled.
Swing to Trailer	Element begins after sorting is complete and a grapple of stems is heeled and is complete when stems are lowered and un-heeled at the foot of the trailer.
Arrange	Element includes all activities involving arranging the stems on the trailer to achieve a compact load.
Swing to Pile	Element begins after arranging stems on the trailer has ended and grapple has started back towards the pile of stems. Element ends when grapple is lowered to begin sorting.

The harvesting crews each consisted of a rubber-tired feller-buncher equipped with a shear head, a rubber-tired grapple skidder and a knuckleboom loader. The knuckleboom loader separated the pulpwood from the chip-n-saw logs, processed the chip-n-saw logs and removed any vines and scrub hardwoods. The receiving mill allows for the tops of the chip-n-saw logs to be mixed into the pulpwood loads if they are longer than 16-ft in length. The untrimmed pulpwood loads utilized the knuckleboom loader to break off excessive limbs and tops to make the loads road legal. The truck would pull up to allow the loader to use the grapple to break off a portion of the overhanging limbs and tops. The driver would then use a chainsaw to complete the trimming of the load, bind the load and add flags and a light. The trimmed pulpwood crew did not utilize the loader to help trim the load. All trimming was performed by the driver with a chainsaw. Three trucks were assigned to the untrimmed crew and four trucks were assigned to the trimmed crew.

### 3. Results

Over a three day period in September 2014, twelve loading cycles of untrimmed pulpwood and fifteen loading cycles of trimmed pulpwood were observed. Table 2 below summarizes the load data for each crew.

Table 2: Load data for two harvesting crews loading untrimmed and trimmed pulpwood.

<b>Untrimmed Crew</b>	<b>Obs</b>	<b>Min</b>	<b>Max</b>	<b>Avg</b>
Loading (min)	12	7.04	13.29	9.89
Driver Trim (min)	12	4.03	11.24	6.91
Loader Trim (min)	12	1.01	2.05	1.54
Total Trim (min)	12	5.75	12.56	8.45
Total Load Time (min)	12	13.49	24.34	18.34
Total Stems ( # )	12	85	123	98
Net Load ( lbs)	12	48200	57360	52140
<b>Trimmed Crew</b>	<b>Obs</b>	<b>Min</b>	<b>Max</b>	<b>Avg</b>

Loading (min)	15	7.37	17.66	11.6
Driver Trim (min)	15	3.43	9.63	6.96
Loader Trim (min)	15	.	.	.
Total Trim (min)	15	3.43	9.63	6.96
Total Load Time (min)	15	14.29	24.53	18.56
Total Stems ( # )	15	97	165	131.6
Net Load ( lbs)	15	47040	59680	53161

Driver trim times were almost identical for each crew. The loader trim time for the untrimmed crew added 1.54 minutes to each load on average. Loading time for the untrimmed crew was 9.89 minutes compared to 11.60 minutes for the trimmed crew. This can be attributed to the 131.6 average stems per load compared to 98.3 stems per load for the untrimmed crew. Of the 15 loads observed for the trimmed crew, 9 loads included chip-n-saw tops. Only 3 of the 12 untrimmed loads contained chip-n-saw tops. Total average loading cycles for each crew were almost the same at 18.34 and 18.56 minutes for the untrimmed crew and trimmed crew, respectively. Average net load for each crew differed by 1021 lbs.

Figure 1 shows the average time for the four elements of the loading cycle and the average count of Swing to Trailer elements per load. Swing to Trailer, Swing to Pile, and Arrange were similar for each crew. The trimmed crew averaged 20 Swing to Trailer elements per load compared to 15 per load for the untrimmed crew. This reflects the increased number of stems per load as noted in Table 2. Sorting time for the untrimmed crew averaged 15.7 seconds per observation for the untrimmed crew compared to 9.4 seconds for the trimmed crew. The increased time to sort reflects more vines and scrub hardwoods in the material and the added effort required to get the untrimmed trees untangled from each other while loading.

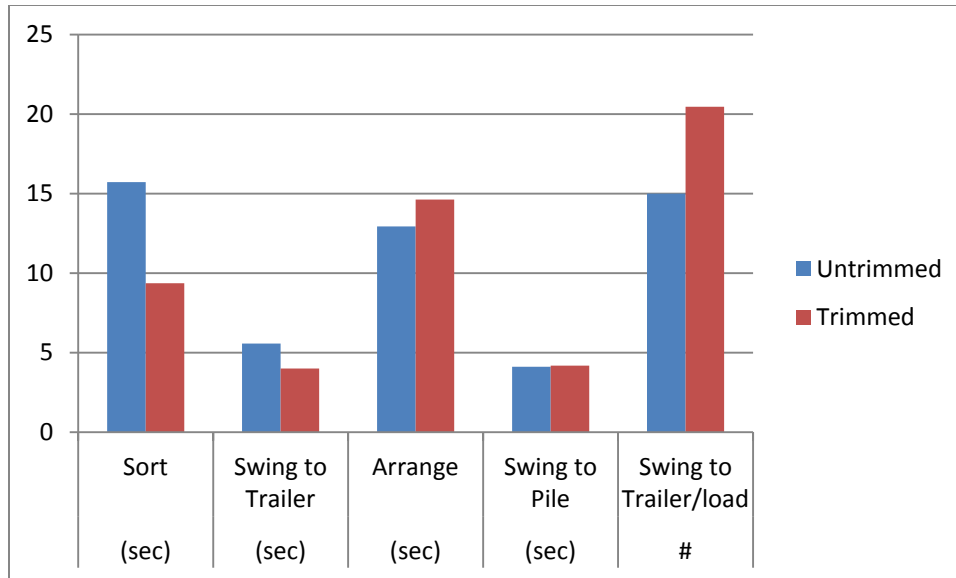


Figure 1: Cycle elements for two harvesting crews loading untrimmed and trimmed pulpwood.

#### 4. Discussion

Achieving efficient transport of woody biomass is an essential component in making it a viable product. This study is part of a larger effort in identifying alternative ways to harvest and transport woody biomass. The initial results indicate that loading and transporting untrimmed trees was just as productive as hauling trimmed trees. Net load was within approximately 1000 pounds for both crews, averaging 26 tons per load. Time to load was also almost identical at just over 18 minutes per load. This equates to approximately 84 tons/hr for both crews.

The knuckleboom loader of the trimmed crew was not observed actually limbing and topping any of the pulpwood loads, either during the loading process or between loads while the loader was sorting and processing chip-n-saw logs. The crew foreman indicated that the tops and limbs of the slash pine (*Pinus elliottii*) could easily be broken off by driving over them. The feller buncher operator and the skidder operator purposely drove over the tops of bundles of trees in the field and at the landing in an effort to break off the tops and limbs. The data suggests that these efforts did increase the productivity of the knuckleboom loader by removing the need to limb and top the trees.

The untrimmed crew averaged 34 fewer stems per load compared to the trimmed crew. This difference can either be attributed to a larger overall tree size or the increased volume associated with hauling untrimmed trees. Stand data was not obtained during the study;

therefore we cannot verify a difference in average tree size between the two sites. An analysis of the load data for the untrimmed crew showed that the 3 loads that contained tops averaged 111 stems per load compared to 94 stems per load for the 9 loads that did not contain tops. The average weight for the loads with tops was 50660 lbs. compared to 52598 lbs. for the loads with no tops. These results indicated that the addition of tops (with needles and small limbs) added volume to the loads while reducing payload. The trimmed crew averaged 143 stems per load for the 9 loads with tops and 53131 lbs. per load. The 6 loads without tops averaged 114 stems and weighed 53206 lbs. The trimmed crew's average load weights differed by 75 lbs. indicating that the tops included in the loads had been stripped of their needles and branches.

## **5. Conclusions**

Loading untrimmed pulpwood achieved similar productivity as hauling trimmed pulpwood. This would indicate that hauling untrimmed trees to utilize woody biomass without requiring a separate harvesting operation is a viable alternative.

The next phase of the research will focus on the complete harvesting and stand management system. Questions that need to be answered include: How much material is being trimmed from the loads to make them road legal? How much extra woody biomass is being removed overall from the stand?

## **6. References**

- Patton-Mallory, M. (Ed.). 2008. Woody biomass utilization strategy. USDA For. Serv. FS-899. 18p.
- Thompson, J. D., D. Mitchell, and J. Klepac. 2014. Advantages and disadvantages of untrimmed wood in the supply chain. 8 p. in Proc. of conf. on 37th Council on Forest Engineering Annual Meeting. Moline, IL.
- Timer Pro Professional. 2000-2013. Applied Computer Services, Inc.

## V. Concurrent Session 1B – Regional Logging Industry Assessments

### Logging Capacity Utilization in Wisconsin

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#### Abstract

There have been concerns expressed about a shortage of logging capacity in Wisconsin after previous studies suggested that Wisconsin was on pace to lose one-third of its loggers between 2003 and 2016 and mills experienced wood shortages during 2014. We conducted a short-term study of logging capacity utilization in Wisconsin from September 28, 2014 through March 14, 2015. Thirty loggers provided weekly production reports detailing the number of loads delivered; the number of hours worked; and the number of loads lost because of weather, mill quotas, regulations, etc. This data was then analyzed using stochastic frontier analysis. For this analysis, the output variable was loads delivered per week, the input variables were man-hours worked and capital invested per week, and six environmental variables were included. Thirty participating logging crews reported 513 crew-weeks of data and delivered 6,411 loads of timber. Stochastic frontier analysis indicated that participating loggers operated at an average efficiency of 71.5%, which is slightly higher than past studies. Loggers operated at 73.3% of capacity, which is slightly lower than past studies. The primary causes of lost production were weather (10.7% reduction in delivered loads), equipment repairs/maintenance (5.6%), vacation (3.6%), and labor (2.9%). No logging crew lost production because of mill quotas during this period, which is not surprising given the low mill inventories during 2014. While loggers will never achieve 100% logging capacity utilization, these results suggest that opportunities exist to improve the efficiency of Wisconsin's wood supply chain.

**Keywords:** Timber Harvesting, Efficiency, Stochastic Frontier Analysis

#### 1. Introduction

There are developing concerns about the adequacy of logging capacity in Wisconsin. Recent studies in Wisconsin and elsewhere indicate that loggers tend to be older than the U.S. population as a whole and the industry is struggling to attract and retain new logging businesses (Baker and Greene 2008, G.C. and Potter-Witter 2011, Rickenbach et al. 2015). In addition, independent loggers are leaving the logging industry. Rickenbach et al. (2015) estimated that 20% of Wisconsin loggers left the industry between 2003 and 2010 and an additional 21% expected to depart by 2016. If this comes to fruition, the state will have lost more than one-third of its loggers in just over a decade.

Logging capacity can be defined as the amount of timber that loggers are capable of harvesting in a specified period of time. Logging capacity utilization refers to the percentage of logging capacity that is actually being used during a given period. Theoretically, 100% logging capacity utilization would minimize the cost of delivered wood; however, achieving this level of utilization is impossible because of weather, mill quotas, regulations, etc. Recent surveys suggest that loggers were producing at 60% and 82% of capacity in Minnesota (Blinn et al. 2015) and Michigan (G.C. and Potter-Witter 2011), respectively. However, this research simply asked loggers to estimate their capacity utilization; it did not actually measure it. The majority of logging capacity research was conducted in the U.S. South more than a decade ago. Loving (1991) found that the U.S. South was utilizing only 51-59% of logging capacity in 1988 and 1989. Likewise, logging capacity utilization in the early 1990s was just 70% (LeBel 1993). In the early 2000s, the U.S. South and Maine were utilizing only 65% of their logging capacity and this inefficiency cost the wood supply chain more than \$430 million annually (Greene et al. 2004).

Clearly, there was excess logging capacity in the U.S. South from the late 1980s through the early 2000's because of substantial increases in productivity resulting from mechanization (Loving 1991, LeBel 1993, Greene et al. 2004). Therefore, the loss of loggers during this time probably made the wood supply chain more efficient by having fewer loggers working closer to capacity. It is unclear whether Wisconsin's loss of logging capacity is having the same effect. If Wisconsin loggers are producing near their capacity today, then continued reductions in logging capacity could make it difficult for Wisconsin mills to procure the wood that they need.

The primary causes of unused logging capacity in previous studies were mill quotas, weather, and moving (LeBel 1993, Greene et al. 2004). In these studies, the impact of regulations had a relatively small impact on production; however, regulations have tightened since these studies were conducted, best management practices have been refined, and forest certification systems have come into vogue (Ice et al. 2010). It is not known whether these guidelines and regulations are significantly reducing logging productivity.

The state of Wisconsin has a number of unique regulations that have the potential to reduce logging capacity utilization. For example, during spring break-up many roads have reduced weight limits that impede movement of timber from logging sites to mills. The Wisconsin Department of Natural Resources (WDNR) currently recommends that stands with  $\geq 15 \text{ ft}^2 \text{ ac}^{-1}$  of oak basal area not be harvested between early to mid-April and mid-July if the stand is located in a county that contains oak wilt or is within six miles of a county with oak wilt (WDNR 2013). In addition, Wisconsin loggers correctly implement best management practices (BMPs) more than 90% of the time (WDNR 2010). While all of these regulations and guidelines may be necessary and useful, they all have the potential to reduce logging capacity utilization.

In summary, the state of Wisconsin faces two challenges regarding logging capacity. First, because loggers are leaving the industry, current and future logging capacity may be insufficient to meet the demand of forest industry mills. Second, seasonal weather patterns and state regulations may be reducing logging capacity utilization, which would tend to increase harvesting costs and reduce the availability of wood to the forest products industry. Therefore, the goals of this study were to estimate logging capacity utilization in Wisconsin and identify the reasons for lost production.

## **2. Methods**

Members of the Great Lakes Timber Professionals (GLTPA) and the Wisconsin Master Logger Program were recruited to participate in this study. Loggers were recruited in-person at the 2014 Great Lakes Logging and Heavy Equipment Expo. GLTPA members that did not agree to participate at the Expo received an invitation letter along with a profile form and return envelope in mid-September of 2014. A similar invitation with an enclosed profile form and return envelope were sent to Wisconsin Master Loggers in late September of 2014. Loggers were asked to return the profile form with contact information if they were willing to participate in the study. Seventy-nine logging businesses representing approximately 120 logging crews returned the logger profile form. These loggers were contacted by phone to confirm their willingness to participate and to collect information on their timber harvesting equipment; number of employees; typical work schedule; and maximum, target, and break-even production levels. Forty-four logging businesses representing 68 logging crews agreed to participate after a telephone conversation. Thirty logging businesses representing 40 logging crews reported at least one week of data while twenty-five logging businesses representing 30 logging crews reported at least four weeks of data and were included in the analysis.



Participants were asked to complete a one page form each week detailing weekly production. Participating loggers reported the number of loads of timber delivered that week; hours spent logging; percent of loads hauled by company trucks; average haul distance to the mill; number of moves; type of harvest (thinning, clearcut, etc.); species of timber harvested; and number of loads that could have been delivered, but were not, along with the reasons the loads were not delivered. Logging efficiency was estimated using stochastic frontier analysis (SFA). SFA creates a production frontier based on observed production of all crews in the study and predicts potential production of an individual crew based on production inputs of that crew (Coelli et al. 1998). The output variable for the model was loads of timber delivered to the mill in a given week and inputs into the production process were labor and capital. Stochastic frontier analysis was conducted using the Frontier package (Coelli and Heningsen 2013) in R version 3.1.3 (R Core Team 2015).

The labor input represented man-hours worked during a given week as reported by participating loggers. The capital investment was estimated using the machine rate method and standard assumptions (Table 1). We calculated an average weekly cost for owning and operating each machine in the system, excluding labor costs. For each machine, we assumed a salvage value of 20% of the purchase price, a fuel cost of \$3.00 per gallon, and a lubrication rate of 36.8% of the fuel cost. These assumptions were based on published guidelines (e.g. Brinker et al. 2002) and prevailing fuel costs at the time of the study.

Table 1: Machine rate assumptions for equipment used by logging crews in this study.

	Tracked feller-buncher	Rubber-tired feller-buncher	Loader/slasher	Chipper	Skidder	Harvester	Forwarder
Purchase price	\$430,000	\$295,000	\$315,000	\$260,000	\$250,000	\$550,000	\$370,000
Economic life (years)	5	5	5	5	5	6	6
Interest, insurance, & taxes <sup>1</sup>	9.5%	9.5%	7.5%	11.0%	11.0%	10.0%	10.0%
Fuel consumption (gal/pmh)	7.9	5.0	4.4	14.0	5.0	5.3	4.5
Maintenance and repair <sup>2</sup>	75%	100%	90%	100%	100%	30%	30%
Utilization	60%	65%	65%	75%	60%	80%	80%

<sup>1</sup>Percent of average annual investment

<sup>2</sup>Percent of depreciation

When loggers agreed to participate in the study, they reported the equipment that they used and the number of employees or subcontractors that worked on their crew(s). Typically, cut-to-length crews included two employees or subcontractors and operated a harvester and forwarder. Chainsaw crews commonly used one or two chainsaw fallers and a cable skidder. The feller-buncher crews were generally larger than the other crews. They included between two and five operators, one or more feller-bunchers, up to three skidders, a loader, slasher saw, and in the case of one logger, a chipper that was used to produce whole tree chips for use in a wood-burning power plant.

In addition to varying levels of labor and capital investment, there are other factors that may explain the efficiency of a given logging crew. Factors such as type of harvest performed, location within the state, and woods condition certainly influence efficiency, but are not considered inputs in the production process and may not be under the manager's control in the short term. These factors are commonly referred to as environmental variables (Coelli et al. 1998). We attempted to explain some of the inefficiency calculated by including the following environmental variables in the SFA model: harvest prescription, felling technique, species harvested, trucking strategy, moving, size of logging firm (single or multiple crew organization), stumpage acquisition strategy, haul distance, and logging conditions during the week. These variables were removed using a backward elimination process until all variables were statistically significant ( $\alpha = 0.10$ ).

We analyzed the production reports as a single cross-section. We used this approach because the technology used to harvest timber did not change significantly during the study and because previous studies used this approach (Chumbler 2002, Greene et al. 2004).

We estimated logging capacity utilization by comparing actual production to the production potential of each crew. Production potential was calculated as the sum of loads actually delivered plus those that loggers reported could have been delivered, but were not, because of weather, breakdowns, etc. In addition, we compared the weekly production level of each logger relative to their stated maximum production potential, their target weekly production level, and their break-even production level. If a logger did not provide this information, they were not included in this part of the analysis. The averages between systems were analyzed using analysis of variance (ANOVA) and the Tukey HSD test using SPSS (IBM Corp. 2012). Seasonal differences were analyzed using independent sample t-tests in SPSS. Parametric tests were chosen because sample sizes exceeded 30 production reports for each system. The Levene's test for equality of variance was used to test the assumption of equality of variance. If the variance was not equal between systems, the data were transformed

logarithmically prior to statistical analysis. If the variance was unequal after the transformation, the Welch's ANOVA and the Games-Howell test were used (Maxwell and Delaney 2004).

### **3. Results and Discussion**

#### **Logger Characteristics and Location**

Thirty participating loggers reported 513 crew-weeks of data and 6,411 loads of timber delivered to the mill. Of the 30 participating logging crews, 10 were from multi-crew organizations and the remaining were single-crew firms. Seventeen logging crews were headquartered in the Wisconsin Department of Natural Resources Northern region, six were located in the West Central region, six were located in the Northeastern region, and two crews were headquartered in the South Central region. Twenty logging crews utilized cut-to-length equipment, seven used chainsaw systems, and three crews used feller-buncher/skidder systems. The distribution of harvesting systems is consistent with the volume of timber harvested by each system in Wisconsin (Rickenbach et al. 2015). Because the sample sizes were small for feller-buncher and chainsaw systems, the results may not be representative of these systems.

The average production of logging crews in this study was 12.5 loads per week (Table 2). The feller-buncher crews were significantly more productive than the other two systems and the cut-to-length crews were more productive than the chainsaw crews ( $P < 0.01$ ). The production level achieved by participating cut-to-length and chainsaw crews is comparable to median production levels achieved by loggers using these harvesting systems in Wisconsin, while the feller-buncher crews were more productive than the statewide median for this system (Rickenbach et al. 2015). Of course, the three systems required different capital investments and were not necessarily targeting the same type of tracts of timber to harvest. Generally, the feller-buncher crews required the highest capital investment and chainsaw crews the lowest. The feller-buncher crews were also more likely to conduct final harvests than the other crew types. Past research has found that feller-buncher systems are more productive and produce wood at lower cost than cut-to-length systems (Lang and Mendell 2012); nonetheless, the cut-to-length system is the most commonly used system in Wisconsin (Rickenbach et al. 2015). Cut-to-length systems can remain profitable on small parcels (Conrad 2014), reduce residual stand damage (Benjamin et al. 2013), and efficiently produce the shortwood demanded by Wisconsin mills (i.e. 100" pulpwood sticks).

The average production level achieved by all crews during the fall (September 28-December 20) was nearly four loads less (10.6) than during the winter (December 21-March 14)

(14.3) ( $P < 0.01$ ). This was expected because frozen ground allows loggers to access sites that may be inaccessible during the rest of the year and mills often increase timber inventories during the winter in preparation for the spring break-up period during which production is curtailed because of significantly reduced weight limits on many public roads.

### Logging Capacity Utilization

During the study period, loggers reported delivering 73.3% of the loads that they were capable (Table 2). Cut-to-length crews lost more loads per week than chainsaw crews ( $P < 0.01$ ); however, this difference was due to the varying scales of the operations as the percentage of potential production that was delivered did not differ between systems ( $P > 0.05$ ). The primary reasons for lost production were weather and equipment breakdowns (Table 3). During the fall crews lost an average of 6.3 loads per week while crews lost an average of only 2.9 loads per week during the winter ( $P < 0.01$ ). Crews lost an average of 3.0 loads per week for weather-related reasons during the fall versus only 0.7 load per week during the winter ( $P < 0.01$ ). The difference in loads lost for mechanical reasons did not differ by season ( $P = 0.09$ ). Loggers lost production because of vacation taken during the nine-day gun deer season, which coincided with the Thanksgiving holiday, and the Christmas holiday. Many landowners forbid logging on their property during deer season, and so vacation time during this time may be unavoidable even during periods of high timber prices.

Table 2: Average weekly production, lost production, capacity utilization, loads delivered by system along with standard errors (in parentheses) for participating Wisconsin loggers between September 28, 2014 and March 14, 2015.

Harvesting System	Crew-Weeks Reported	Average production (loads wk <sup>-1</sup> )	Average lost production (loads wk <sup>-1</sup> )	Capacity utilization (%)	Total loads delivered
Feller-buncher	33	24.1 <sup>a</sup> (3.7)	4.3 <sup>ab</sup> (1.2)	84.9	5,179
Cut-to-length	379	13.7 <sup>b</sup> (0.5)	5.4 <sup>a</sup> (0.4)	71.6	796
Chainsaw	101	4.3 <sup>c</sup> (0.3)	1.3 <sup>b</sup> (0.19)	76.2	436
Overall	513	12.5 (0.5)	4.6 (0.3)	73.3	6,411

<sup>a,b,c</sup> Means not connected by the same letter are statistically different ( $\alpha = 0.05$ )

Table 3: Number of loads lost by reason as reported by participating loggers in Wisconsin between September 28, 2014 and March 14, 2015.

Loads Lost Week<sup>-1</sup> Crew<sup>-1</sup>

Reasons for missed loads	Average	Maximum	Total loads	Percent of total loads
Mill quota	0	0	0	0
Mill loading/unloading	0.01	2	4	0.05
Mill closed	0.06	9	31	0.35
Regulations-mandatory	0.01	2	5	0.06
Regulations-voluntary	0.01	1	4	0.05
Mechanical-scheduled	0.29	25	147	1.68
Mechanical-unscheduled	0.67	21	339	3.88
Labor-amount	0.32	25	167	1.90
Labor-quality	0.16	10	84	0.96
Weather-Forest roads	0.68	30	348	3.98
Weather-Woods condition	1.14	30	584	6.68
Seasonal restrictions	0.13	23	67	0.77
Stumpage unavailable	0.03	6	13	0.15
Harvest plan	0.07	4	34	0.39
Vacation	0.62	25	316	3.62
Other	0.36	15	186	2.13

The cut-to-length systems reported losing 11.5% of production to weather versus only 3.9% and 2.7% for the chainsaw and feller-buncher systems, respectively. Likewise, the cut-to-length systems reported losing 3.3% of production because of labor issues versus only 0.5% and 0% for the chainsaw and feller-buncher crews, respectively. It is worth noting, however, that cut-to-length loggers may have been operating on wetter tracts than the other two systems and, because the sample size was larger for cut-to-length systems, their production losses may be more representative of Wisconsin loggers as a whole than the other two systems.

No loads were lost because of mill quotas during the study period, which is not surprising given the low mill inventories in Wisconsin during 2014 and early 2015. However, despite this fact, Wisconsin loggers delivered only 73% of the loads that they were capable. A similar study in the U.S. South and Maine found that loggers delivered approximately 80% of the loads they were capable even though loggers in that study lost an average of 6% of production per week for mill-related reasons, primarily restrictive mill quotas (Greene et al. 2004). In that study, production was only reduced by 4% for weather-related reasons, whereas production was reduced by 10.7% by weather in this study (Table 3).

This study probably underestimated the impact of regulations, seasonal restrictions, and labor issues on Wisconsin loggers. Regulations may dictate which stands are harvested and when, but it is difficult to assign lost loads to this cause during any given week. Seasonal restrictions are most prevalent during the spring and summer months, which were not included

in this analysis. The production lost because of labor issues only included lost production from existing crews. Anecdotal reports suggest that many loggers would like to add a crew to their organization, but have been unable to do so because suitable equipment operators are not available. This was not addressed in this study.

On average, loggers operated approximately 27% above their break-even production level, 12% below their target, and 35% below their maximum production capacity during the study (Figure 1). There were no differences by system. The average production level was well above the break-even level; however break-even production was achieved in only 58% of the weekly reports received. Loggers achieved break-even production just 55% of the time during the fall versus 67% during the winter. Logging capacity utilization was comparable to loggers' estimates of utilization in 2011 in both Wisconsin and Minnesota (Blinn et al. 2015, Rickenbach et al. 2015), but lower than estimates provided by loggers in Michigan (G.C. and Potter-Witter 2011).

### Logging Efficiency

Between September 28, 2014 and March 14, 2015 loggers in this study operated at an average efficiency of 71.5% as measured by stochastic frontier analysis. Efficiency ranged from 12.7% to 93.4% with a median value of 76.7%. Previous studies in the U.S. South found mean efficiencies of 86% (LeBel 1996) and 63.8% (Chumbler 2002).

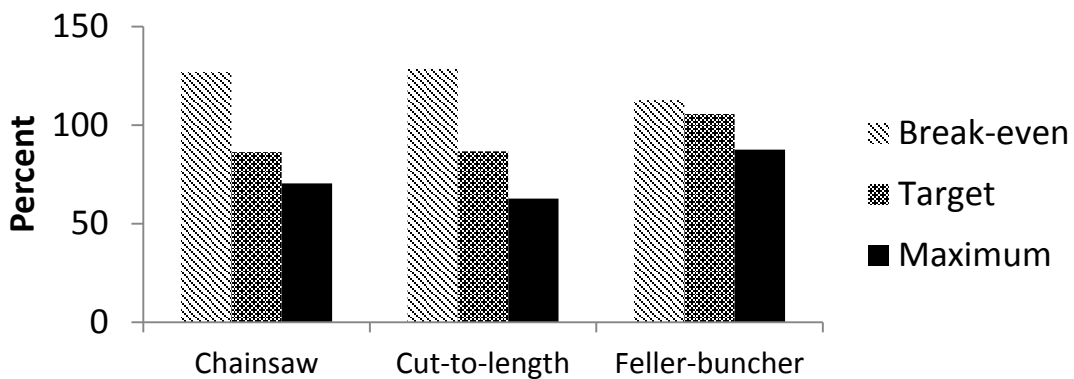


Figure 1: Percent of break-even, target, and maximum (stated capacity) weekly production achieved by participating Wisconsin loggers between September 28, 2014 and March 14, 2015.

Six environmental variables had p-values <0.10 and were included in the SFA model. Chainsaw felling and thinning were associated with reduced timber harvesting efficiency. This is intuitive because fully mechanized firms were significantly more productive than chainsaw

crews and were thus able to overcome their increased capital costs. Thinning requires loggers to maneuver around residual trees, and therefore reduces logging efficiency (Kluender et al. 1998).

Hardwood harvesting, trucking by logging firm, moving, and being part of a multi-crew organization were associated with increased logging efficiency. In 2008, nearly three times as much hardwood roundwood was harvested compared to softwood in Wisconsin (Haugen 2013) and so most logging firms employ systems that harvest hardwood efficiently. Owning at least one truck gives a logger flexibility in delivering the timber that he harvests and can facilitate efficient moves between sites. This result contradicts the finding of Chumbler (2002) who found that owning trucks was associated with reduced efficiency. Obviously, frequent moves do not cause increased efficiency. The reason that moving was associated with increased efficiency in this study is most likely because the most productive and efficient logging crews finished harvesting tracts rapidly and moved to the next tract, which increased the likelihood that they would report at least one move during a given week. Only nine instances of multiple moves during a week were observed out of the 513 crew-weeks reported, which indicates that loggers were avoiding unnecessary moves. In fact, 78% of the moves reported were conducted because the job was completed. Over the past twenty years there has been a consolidation in the logging industry with fewer logging firms producing more timber (Blinn et al. 2015, Rickenbach et al. 2015); it is therefore not surprising that being part of a multi-crew organization was associated with increased efficiency.

#### **4. Conclusion**

This study found that participating loggers produced 73.3% of the loads that they were capable and operated at 71.5% efficiency. Weather appears to be the primary culprit in reducing logging capacity utilization. LeBel (1993) posited that increasing environmental regulations increased the impact of rain on logging operations, and that may be the case in this study as well. Wisconsin loggers correctly apply BMPs over 90% of the time and soil disturbance is carefully minimized on timber sales in Wisconsin (WDNR 2010). However, staying out of the woods during periods of wet weather has costs for loggers as evidenced by the 10% reduction in loads delivered during the study period for weather-related reasons.

These results indicate that loggers produced below their potential during the time period covered by our study. During the analysis period, loggers were able to achieve enough weeks of strong production to operate above their break-even level on average. Nonetheless, it

appears from this data that logging capacity exists to produce significantly more wood than is currently being produced without adding new logging crews.

Future analysis should measure the impact of seasonal timber harvesting restrictions on logging capacity utilization. This analysis concluded in mid-March before spring break-up road weight restrictions went into effect. This restriction is likely to significantly reduce logging capacity utilization. In addition, seasonal timber harvesting restrictions to prevent oak wilt, protect species of interest, and prevent the spread of invasive species may also reduce utilization. While it is in everyone's interest to protect the forest resource, a healthy logging sector is needed to ensure sustainable management of Wisconsin's forests in the future.

## 5. References

- Benjamin, J.G., R.S. Seymour, E. Meacham, and J. Wilson. 2013. Impact of whole-tree and cut-to-length harvesting on postharvest condition and logging costs for early commercial thinning in Maine. *North. J. Appl. For.* 30(4):149-155.
- Baker, S.A., and W.D. Greene. 2008. Changes in Georgia's logging workforce, 1987-2007. *South. J. Appl. For.* 32(2):60-68.
- Blinn, C.R., T.J. O'Hara, D.T. Chura, and M.B. Russell. 2015. Minnesota's logging businesses: an assessment of the health and viability of the sector. *For. Sci.* 61(2):381-387.
- Brinker, R.W., J. Kinard, B. Rummer, and B. Lanford. 2002. Machine rates for selected forest harvesting machines. Circular 296 (revised). Alabama Agricultural Experiment Station, Auburn University, Auburn, AL. 32 p.
- Chumbler, J.M. 2002. Utilization of logging capacity in the southern United States and Maine. MS thesis. University of Georgia, Athens, GA. 63 p.
- Coelli, T. and A. Henningsen. 2013. Frontier: stochastic frontier analysis. R package version 1.0. Available online at [CRAN.R-Project.org/package=frontier](http://CRAN.R-Project.org/package=frontier); last accessed April 30, 2015.
- Coelli, T., D.S.P. Rao, and G.E. Battese. 1998. An introduction to efficiency and productivity analysis. Kluwer Academic Publishers, Boston, MA. 267 p.
- Conrad, J.L., IV. 2014. Adapting to a changing landscape: how Wisconsin loggers persist in an era of parcelization. *For. Prod. J.* 64(7/8):273-280.
- Greene, W.D., J.H. Mayo, C.F. deHoop, and A.F. Egan. 2004. Causes and costs of unused logging capacity in the southern United States and Maine. *For. Prod. J.* 54(5):29-37.
- G.C., S. and K. Potter-Witter. 2011. An examination of Michigan's logging sector in the emerging bioenergy market. *For. Prod. J.* 61(6):459-465.
- Haugen, D.E. 2013. Wisconsin timber industry—an assessment of timber product output and use, 2008. USDA Forest Service, Northern Research Station, Res. Bull. NRS-78, Newtown Square, PA. 110 p.
- IBM Corp. 2012. IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY.



- Ice, G.G., E. Schilling, and J. Vowell. 2010. Trends for forestry best management practices implementation. *J. For.* 108:267-273.
- Kluender, R.D. Lortz, W. McCoy, B. Stokes, and J. Klepac. 1998. Removal intensity and tree size effects on harvesting cost and profitability. *For. Prod. J.* 48(1):54-59.
- Lang, A.H. and B.C. Mendell. 2012. Sustainable wood procurement: what the literature tells us. *J. For.* 110(3):157-163.
- LeBel, L. 1993. Production capacity utilization in the southern logging industry. MS thesis. Virginia Polytechnic Institute and State University, Blacksburg, VA. 127 p.
- LeBel, L.G. 1996. Performance and efficiency evaluation of logging contractors using data envelopment analysis. PhD dissertation. Virginia Polytechnic Institute and State University. Blacksburg, VA. 201 p.
- Loving, R.E. 1991. Components of logging costs. MS thesis. Virginia Polytechnic Institute and State University, Blacksburg, VA. 205 p.
- Maxwell, S.E. and H.D. Delaney. 2004. Designing experiments and analyzing data. Lawrence Erlbaum Associates, Inc. Mahwah, New Jersey. 868 p.
- R Core Team. 2015. R: a language and environment for statistical computing. Vienna, Austria. Available online at [www.R-project.org/](http://www.R-project.org/); last accessed April 30, 2015.
- Rickenbach, M., M. Vokoun, and S. Saunders. 2015. Wisconsin logging sector: status and future direction. University of Wisconsin Extension G4073, Madison, WI. 26 p.
- Wisconsin Department of Natural Resources [WDNR]. 2010. Wisconsin's best management practices for water quality field manual for loggers, landowners, and land managers. FR-093. 162 p.
- Wisconsin Department of Natural Resources [WDNR]. 2013. Oak wilt: guidelines for reducing the risk of introduction and spread. Available online at [dnr.wi.gov/topic/foresthealth/oakwilt.html](http://dnr.wi.gov/topic/foresthealth/oakwilt.html); last accessed June 15, 2015.

# **An Assessment of the Logistics, Cost and Life Cycle of Supplying Wood Products in Tennessee**

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The presentation focuses on a study developed in Tennessee from 2011 – 2015, that focuses on developing an integrated analysis of forest harvesting machine operations, cost and life cycle assessment of supplying wood in Tennessee, from site to end use. Key production factors are identified that have not been looked into before in the state. The study also highlights work conditions and operational factors that need to be considered to improve the workforce operating conditions and promote a more sustainable and growing forest products industry. Factors analyzed in this study have not been investigated before in Tennessee. Results presented are being compiled into a final report to the funding agency and peer reviewed publications. The three sections of the study include: i) The logistics of forest operations in Tennessee. This section investigates the following questions: What are the work force characteristics and conditions? (location, owner or operator, annual number of employees on the crew, and production in acres and tons). What is the logging capacity? (equipment owned or subcontracted, type of equipment used, logging configuration and percentage and potential production capacity of the state), and What are the production rates per harvest conditions and prescriptions? (% of operations per cut types, skidding distances, operations per terrain types, shift hours, time of repairs and stand size), ii) The cost of the supply of timber in Tennessee. This section investigates the total cost of harvesting wood. It researched available stumpage prices, hauling, harvesting, and delivery variables. This section compares and contrasts operations in relation to their cost effectiveness, and iii) A life cycle assessment of the supply of wood in Tennessee. Life cycle assessment is used to quantify environmental impacts of the supply of lumber. System boundaries of the study start at the stand and end at points of delivery of variable distances. The study analyses, using SimaPro, Greenhouse Gas emissions and the Fossil Energy Demand per extracted tonne of green wood, harvesting and transportation. It also offers a sensitivity analysis to identify areas and supply chains of greatest environmental impact.

## **Logger Shortage Remediation Efforts in West Virginia**

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During the economic downturn of the late 2000's and early 2010's, approximately 50% of West Virginia's logging workforce left the industry for jobs in the emerging oil and gas and other industries. The current economic indicators for the forest products industry appear to be improving, today's low supply of logging contractors has been one of the key factors limiting production and supply delivery to the mills and other users of harvested wood. A group of industry, government, community development, finance, and academic professionals were gathered to assess the situation, identify barriers, and propose opportunities to redevelop the state's logging workforce. This paper will characterize the current situation, summarize the specific barriers and opportunities identified for West Virginian conditions, and provide initial results from an innovative new training and engagement effort that establishes "credit ready" applicants for established financing programs. Continuing efforts to recruit, train, and sustain a healthy and vibrant logging workforce is critical to the long term development and prosperity of the entire forest products industry.

## VI. Concurrent Session 2A – Productivity of Logging Operations II

### **Modeling Trucking Productivity Limits Due to in Woods Interactions**

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Increases in harvesting productivity have placed increasing demands on transportation that is characterized by low productivity per unit and cycle times influenced by events outside the operations control. While balancing logging and trucking production will maximize the system productivity maintaining the balance even on a daily basis is challenging. Dynamic modeling can help find opportunities to improve system efficiency and productivity. We developed a dynamic model for truck cycle time through STELLA 9.1.4 software to model the truck availability to an in-woods chipping operation determine the relationship between truck availability or capacity and system productivity and cost. Our objectives were to identify the trucking capacity levels that minimize cost or maximize productivity and determine the impact of changing load size (due to in-woods drying or larger vans) or product type (clean vs. dirty chips). While increasing truck capacity increases system productivity, landing interference limits the net benefit of increased trucking capacity as daily production nears maximum chipper utilization.

# Productivity and Cost of Processing and Sorting Forest Residues

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## Abstract

Biomass conversion technologies such as biochar, torrefaction, and briquetting have the potentials to increase the economic value of forest residues, however requires high quality feedstocks. The goal of this study was to evaluate the cost associated with processing and sorting forest residues in order to reduce feedstock contamination and facilitate comminution operations in an effort to control particle size. Three harvest units selected were further divided into three sub-units. One of three treatments, no sorting, moderate sorting and intensive sorting, were carried out for each sub-unit by the sawlog processor. For the sorted treatment units, the processed tree tops were sorted into conifer and hardwood piles. The remaining slash, consisting of chunks, branches, etc., generated during sawlog processing were piled separately. The sorting treatments varied the intensity in which residues were processed and sorted. Results showed that the total operational costs (stump to truck) were similar between sorting and not-sorting. A standardized comparison showed a cost range of \$97 to 106/MBF for sawlogs harvested. The productivity of the processor sorting the forest residue showed a gradual increment in cost of around \$ 2/MBF from non-sorting to the intensive sorting. Our results show that a majority of the cost was in forwarding for all treatment therefore additional processing cost to sort forest residues did not have an impact on total cost between treatments. Analysis done to predict the tops to slash ratio showed that 19-25 % of the total forest residues generated were tree-tops.

**Keyword:** biomass recovery operation, standardized comparison, tops to slash ratio

## 1. Introduction

Forest residues generated from timber harvesting operations have been traditionally regarded as economically low valued products. These by-products are currently being utilized as a feedstock for the energy production, as they are widespread, renewable, and can be used to offset the use of fossil fuels and reduce greenhouse gas emissions (Jones et al. 2010). A

study conducted in Montana estimated 1,096 bone dry tons (BDT) equivalent of forest residues generated for every million Scribner board feet of merchantable timber harvested (Morgan 2009).

In regions where there is a market for biomass or pulp, several treatments, including debarking of forest residues, removing foliage, field drying, etc. are carried out to enhance the quality of the feedstock. These treatments can accelerate drying, generate uniform particle size distribution, reduce contamination, and support comminution by chippers (Röser et al. 2011). The cost associated with these treatments, even though are documented often cannot be compared with operations in other regions, because the harvest operations are species, site, and practice dependent (Helmisaari et al. 2014).

Presently, the markets for biomass in northern California are mainly restricted to wood-based power plants. The range of feedstock collections are further limited by the transportation cost due to the low market values (Kizha. et al. In press). Therefore, forest residues generated from many timber harvest units are piled and burned on-site. Initial research on prescribed burning has showed that it can be detrimental to human health (Haikerwal et al. 2015). Further, slash burning can cost up to \$800/acre and can be carried out only in specific burn windows in a year (Alcorn 2014).

One of the greatest barriers for utilization associated with the traditional feedstock is its inherent low quality. This plays a major role in the economic feasibility of conversion into value added forest products such as torrefied wood chips, briquettes, and pallets. This will not only generate additional income, but also facilitate re-planting and reduce negative environmental impacts such as fire hazard and pest outbreak. In order to meet the specifications set by these emerging technologies, the forest residues have to be treated to minimize contamination, facilitate comminution, reduce moisture content, and improve handling / transportation efficiency (Han et al. 2015).

The objective of this study was to evaluate the operational cost associated with processing and sorting forest residues produced from timber harvesting. Attempts were also made to estimate the amount of tree tops and slash generated from the harvesting operation.

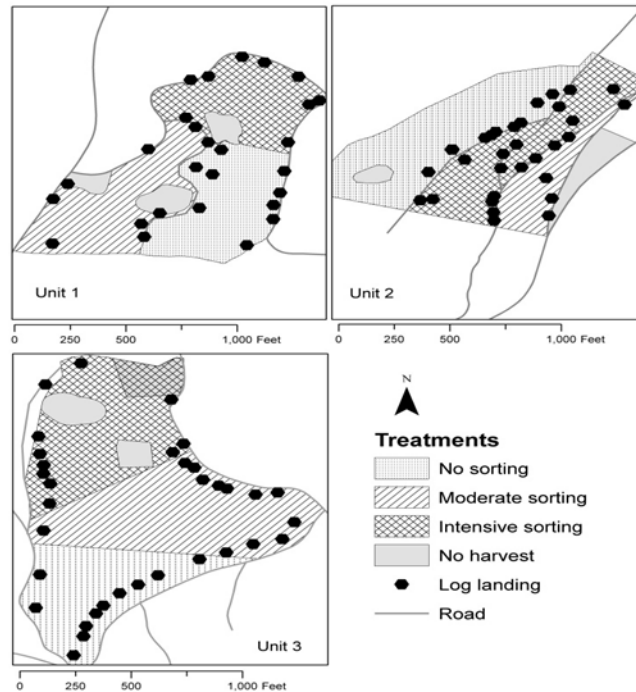


Figure 1. Study units for forest residues processing and sorting study in Humboldt County, California.

## 2. Methodology

### Stand and site description

The study site comprised of three even-aged management units on an industrial timberland property in Humboldt County, California (41° 02' 18" N, 123° 55' 35" W) (Figure 1). The sites primarily constituted even-aged (averaging 60 years) second- and third- growth coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and tanoak (*Notholithocarpus densiflorus*).

### Experimental designs and treatments

Three field based treatments were carried out to investigate how sorting and processing the forest residues at varying intensities influences productivity and cost of the operation. The timber harvest units were approximately one mile apart. Each unit was further divided equally into three distinct sub-units of which one of the three following treatments were carried out:

- No sorting: Typical residue management used by landowners. The focus of the processor in

this treatment was on the sawlogs and the forest residues were not given any consideration. All the forest residues generated from sawlog processing were usually piled near the log landing area. Piles consisted of tops, chunks, branches, broken logs, and small-diameter trees.

- Moderate sorting: The processed tree tops were sorted into conifer and hardwood piles by the processor. The remaining slash pile generated during processing consisted of chunks, foliage, branches and other broken material were piled separately. This pile was not appropriate to be comminuted by a chipper.



- Intensive sorting: Forest residues were processed and sorted into 5 classes(Figure 2):
  - Processed conifer tops: Tree tops processed (foliage removed along the entire length) to the top six inch length.
  - Unprocessed conifer tops: Tree tops were not processed and had branches with leaves and needles still attached on them.
  - Processed hardwood tops
  - Unprocessed hardwood tops
  - Slash pile

A stand inventory was done at 10 % sampling intensity (0.10 acre fixed circular plots) using a systematic sampling design. Species, height, and dbh for all standing trees over above three inches were recorded. The stand inventory quantified the stand conditions and evaluated volume (cubic feet per acre), basal area (square feet per acre), and species composition. All three units were clear-cut and both sawlog and biomass components were transported to the landing using a ground-based shovel logging system. The operation spanned over two months during the summer of 2014. All three treatments were operated by the same machine operator and harvesting machines, except for felling. After the harvest, biomass and sawlog piles were randomly scaled and positioned using GPS at the landing.



## Data analysis

To calculate delay-free cycle times, a detailed time study was conducted using standard work study techniques (Olsen et al. 1998). Elemental time-motion data were recorded by a centi-minute stop watch for each machine used in the treatments. Additionally, predictor variables hypothesized to affect cycle time were recorded for each cycle element (Table 1). The cost and productivity for harvesting sawlog and biomass components was analyzed separately. Sorting and loading was calculated only for sawlogs.

Table 1. Cycle elements and associated predictor variables for each machine.

Components	Cycle elements	Recorded predictor variable(s)
Felling	travel time to tree	trees cut per cycle
	cutting time	tree species
	bunching time	butt-end diameters (inches)
		distance between trees (feet)
	distance to bunch (feet)	
Shovelling	walking to the pile	walking distance (feet)
	swing empty	swinging distance (feet)
	grapple time	distance travelled during swing (feet)
	swing loaded	trees per cycle
		butt-end diameters (inches)
		angle rotation (45, 90, and 180)
	direction of shovel (uphill vs. downhill)	
Processing	swing empty	tree species
	grapple time	butt-end diameters (inches)
	processing sawlog	logs per cycle

	processing biomass	short length logs
	sorting sawlog	medium length logs
	sorting biomass	long length logs
		number of biomass pieces
		processed tops
		unprocessed tops
<hr/>		
Loading and sorting (sawlogs)	swing empty	logs per cycle
	grapple time	short length logs
	swing loaded	medium length logs
		long length logs
		total board feet
<hr/>		

### Machine rate calculation

Data obtained from scaling log decks and processor dataset were used to calculate the average volume per piece (board feet) required to calculate productivity for each sorting treatment operation. Localized allometric equations were used to calculate the volume of biomass trees. Purchase prices, salvage values, and all other necessary information for the standard machine rate calculation were obtained from the timberland company which owned and operated the equipment (Table 2). Diesel price was set at \$ 3.85/gallon, which reflected local market prices during the study. Hourly machine costs in dollars per scheduled machine hour (\$/SMH) were calculated using standard machine rate calculation methods (Miyata 1980). All machinery was assumed to have a 10 year economic life and worked 2200 scheduled machine hours (SMHs)/year with a utilization set at 80 percent.

Table 2: Machine rates and other costs of the equipment used in the treatment, not including support vehicles such as water truck for dust control, fuel truck, and personal vehicles. Assumptions used for machine rate calculations included 2200 SMH (schedule machine hours)/year and 80% utilization. The fuel and labor cost was estimated at \$ 3.85/gallon and \$47.20/hour respectively. \$/PMH (productive machine hours) rates were calculated using the assumptions of 59% fringe benefits, 10% interest, and 3% insurance.

	Felling and bunching	Primary transportation	Processing	Sorting and loading
Model	John Deere 959K	Caterpillar 568	John Deere 2454D	John Deere 2954D
Purchase price	\$ 625,000	\$ 500,000	\$ 610,000	\$ 425,000
Operating cost	\$ 57.95	\$ 45.77	\$ 56.49	\$ 41.76
Fuel use (gallon/PMH)	10	8	6	6
Machine rate (\$/PMH)	\$ 177.04	\$ 160.53	\$ 165.10	\$ 135.45

Joint products allocation was used to estimate the cost of primary transportation for the sawlog and biomass components as they were hauled together (Hudson et al. 1990). The unit cost of sawlog harvesting comprised from felling, shoveling, processing, sorting and loading; whereas biomass trees only included cost associated with felling to tree top processing and sorting.

Regression models were developed using IBM SPSS Statistical Software 21. Ordinary least squares estimators were used to predict delay-free cycle time based on predictor variables. Standardized variable comparison was utilized while conducting the analysis (Adebayo et al. 2007). The comparisons for each machine were expected to reflect the differences in cost and productivity due to the treatment irrespective of the variation in stand conditions. A dummy variable was used for representing the unit. The datasets were initially screened for outliers followed by which a scatterplot was developed for each variable to check if the relationships between transformed independent and dependent variables were linear. Several transformation models were developed and compared and the model with higher R2 and which satisfied all conditions was selected. Multi-collinearity was tested using a tolerance value greater than 0.1 and variance inflation factor (VIF) less than 10. ANOVA was performed to determine if there was any difference for species and dbh of trees between subunits within each unit.

## Estimating top to slash ratio

As a part of the study, attempts were made to estimate the amount of tops and slash generated (figure 3). Three potential methods that could be utilized to estimate them were:

- Allometric equation to predict the slash and tree tops weight.
- Scaling the tops and slash component to estimate the volume
- Scale tickets obtained from trucks

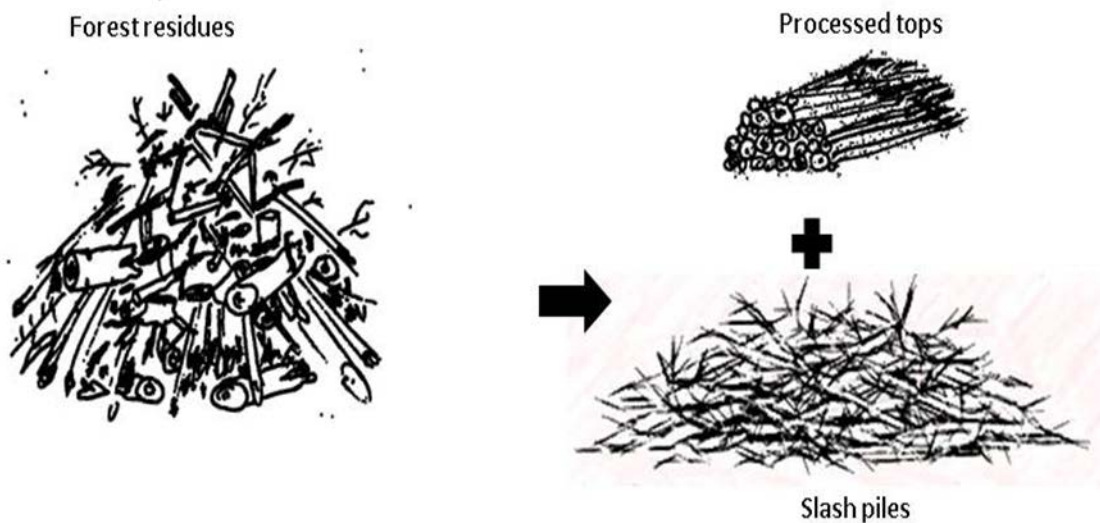


Figure 3. Demonstrating tops and slash generated from timber harvest units.

For this study, the amount of tops and slash were quantified in a series of steps. The average number of tree-tops generated during processing for tree species were collected from the processor data for each unit. The total number of standing trees was estimated from the stand inventory. These numbers were later used to estimate the potential ratio of tree tops to slash for the harvest units. The dimensions (length and diameter) of the forest residue (tops and slash) scaled from the biomass piles, were utilized to calculate weight of the tree tops. For estimating the weight of the slash generated, local allometric equations for the foliage were used.

## 3. Results and discussion

A total of 1113, 2052 and 1705 trees (both sawlogs and biomass) were measured from the timber cruise plots assigned for Unit 1, 2 and 3, respectively. Results from ANOVA showed

that there was no significant difference in the dbh between the trees from the different units (p-value= 0.90, 0.21 and 0.83). However, Unit 1 had less than 8% of hardwood trees, therefore this replicate unit was considered as conifer, while Unit 2 and 3 were regarded as mixed stands (Table 3). For determining the average sawlog piece size for the three units, 791 sawlogs were randomly scaled from the log decks.

Table 3. Summary of stand inventory for standing trees having a dbh of one inch onwards for the three units and subunits

Unit	Treatment	Area (acres)	Hardwood		Conifer		Total		% of Hardwood*
			Basal area	Ave. dbh (inch)	Basal area	Ave. dbh (inch)	Basal area	Ave. dbh (inch)	
1	No sorting	7.6	0.8	4	17.7	8	18.5	7	4
	Moderate	7.3	2.5	6	29.9	7	32.5	7	8
	Intensive	6.5	1.0	6	21.6	7	22.6	7	4
2	No sorting	8.1	19.2	6	16.4	7	38.8	7	50
	Moderate	4.1	22.6	6	19.0	10	41.7	7	54
	Intensive	6.8	22.4	6	21.2	8	43.6	7	51
3	No sorting	6.8	14.4	7	23.6	10	38.1	9	38
	Moderate	7.4	13.4	6	19.9	7	33.3	7	40
	Intensive	6.8	14.2	7	18.4	7	32.7	7	44

In general, the standardized comparison model predicted the cycle time for each machine more effectively for the sawlog component than the biomass. The R2 ranged from 0.10 to 0.63. The unit and species were found to be significant for most of the models predicted for the various machines, suggesting that species composition and stand condition within the units influenced the delay free cycle time.

Sawlog and biomass harvesting operations were decoupled, with each machine ahead of the consecutive machine by one week. Decoupling ensured maximum productivity for each machine and avoided a “bottle-neck” in productivity during the operation. The overall cost of

the three forest residue treatments showed that there was a gradual increase from the non-sorting (\$ 97/MBF) to intensive sorting (\$ 106/MBF). This trend was obvious in the processing phase for both biomass component and sawlogs (Table 4).

Table 4. Cost and productivity of the various phases in the integrated timber harvesting operation focused at processing and sorting forest residues. Sawlog components are conifer trees  $\geq 8$  inches diameter at breast height (dbh), utilized down to a small-end diameter of 6 inches, eventually sent to sawmills for producing sawlogs. Biomass components are trees between 3 and 8 inches dbh for conifers and all hardwood species from 3 inch upwards.

Sawlog	No sorting		Moderate		Intensive	
	Cost	Productivity	Cost	Productivity	Cost	Productivity
	\$/MBF	MBF/ PMH	\$/MBF	MBF/ PMH	\$/MBF	MBF/ PMH
Feller Buncher	\$ 13.28	13.3	\$ 12.46	14.4	\$ 15.43	11.3
Shovel*	\$ 45.68	2.3	\$ 47.43	2.2	\$ 46.30	2.2
Processor	\$ 18.98	8.7	\$ 21.97	7.5	\$ 26.04	6.3
Loader-loading	\$ 12.64	10.7	\$ 12.31	11.0	\$ 12.40	10.9
Loader-sorting	\$ 6.18	21.9	\$ 6.08	22.3	\$ 6.02	22.5
<b>Total</b>	\$ 96.76		\$ 100.24		\$ 106.19	

Biomass	No sorting		Moderate		Intensive	
	Cost	Productivity	Cost	Productivity	Cost	Productivity
	\$/BDT	BDT/ PMH	\$/BDT	BDT/ PMH	\$/BDT	BDT/ PMH
Feller Buncher	\$ 6.05	29.2	\$ 5.28	33.5	\$ 5.14	34.5
Shovel*	\$ 11.16	0.6	\$ 11.59	0.5	\$ 11.31	0.5
Processor	\$ 14.06	11.7	\$ 14.98	11.0	\$ 17.42	9.5
<b>Total</b>	\$ 31.27		\$ 31.85		\$ 33.87	

\*cost evaluated by joint product allocation

MBF- Thousand board foot, ODT- Oven dry ton, PMH- Productive machine hour.

The additional time to process and sort the tree tops generated while processing sawlogs increased cost by \$10/MBF (approximately 30%) from non- to intensive sorting treatments. For the same, the cost difference for the biomass component was around \$3/BDT. Although there was a difference in total cost attributed to processing, our analysis showed that 30- 59% of the total cost was actually from the shovel operation. This indicates that primary transport was still the greatest influence in the total cost, not processing. For the biomass component, the processing constituted about 45 to 51% of the total cost and was the most expensive component of the operation. During field data collection, the decrease in productivity from no sorting to intensive sorting was explicit.

## **Felling**

Unlike conventional felling operation conducted in the region, biomass and sawlog trees were bunched into different piles. There were two operators and machines during study. Unit 1 and 2 were felled by one operator while the third unit was felled using a different operator and machine. However, the feller-buncher machines used for all units were of similar model and make. A total of 2566 observations were taken from the three units. Travel time to the tree for felling constituted the longest time component within the feller buncher's delay free cycle and ranged between 36 to 52 %. The results from the productivity analysis showed that there was no trend among the three treatments (sub-treatment) and units for both sawlog and biomass components (Table 7).

## **Shovel**

The primary transportation was done using a shovel machine equipped with a log grapple. GPS technology was used to determine the positions for all 93 of the log decks and a total of 1009 delay free cycle times were captured from the three units. The average delay free cycle time for each swing was approximately 31 seconds. The swing loaded time had the largest share in the cycle (approximately 37%) and was highly influenced by the orientation of placement of the tree within the bundle. On an average 3.6 trees were hauled in a single swing and the average swing distance was around 59 ft for all the units. For Unit 1, 51% of the logs were downhill shoveled and the remaining up hill. Most of the subunits in Unit 3 were downhill shoveled (68%), and all but two decks in Unit 2 were downhill.

Joint product allocation was used to derive cost because often biomass and sawlogs trees were shoveled in the same bunch. Towards the landing, biomass and sawlogs were separated into different piles. The shoveling cost largely depended on the average yarding distance.

## Processing

The processor was integral to the study as it was responsible for processing and sorting the forest residues. A total of 1583 outlier free observations were taken from the three units and treatments combined. In general, it took more time to process hardwood (tanoak) species compared to conifers. This trend has been observed in other studies too (Kluender et al. 1997; Hiesl 2013). The average delay free cycle time averaged 34, 38 and 43 seconds for no, moderate and intensive sorting treatments, respectively.

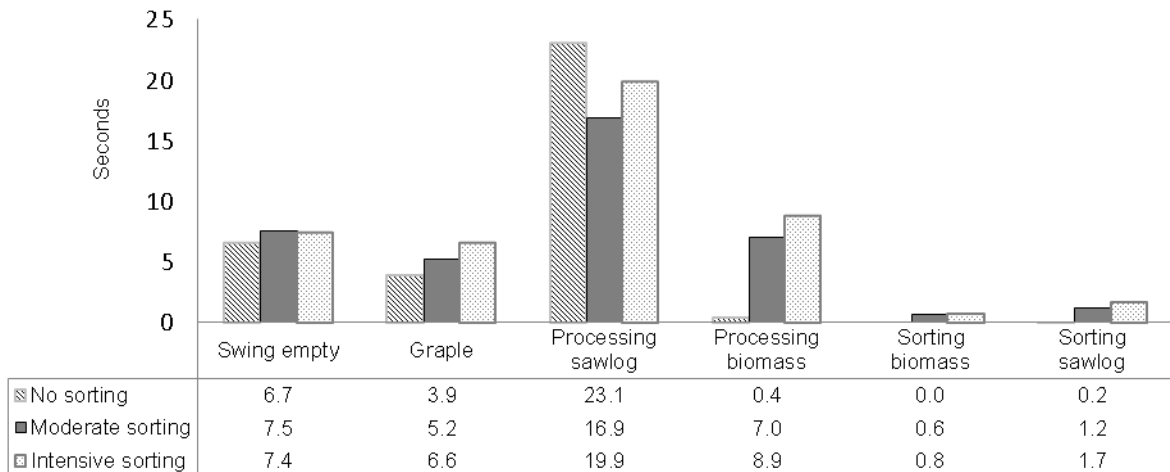


Figure 4. Average delay free cycle time component for the processor activities (both sawlog and biomass components) in forest residue processing and sorting study.

Total cost differences between the three treatments could be associated to the differences in processing productivity and cost, as other components of the operation did not show any such trend. The high cost of processing for the sorted treatment was primarily due to the extra time required to process and sort the biomass materials into different piles (figure 4). Whereas in the no sorting treatment, all the wood residues generated during sawlog processing were stacked into a single pile. However, the hardwood (biomass component) was processed for energy feedstock in the no sorting treatment subunits. The sorting treatment further



required extra space at the landing for decking the biomass materials in addition to the sorted logs. The cost difference between the treatments was much more for the mixed units (Unit 2 and 3) compared to the conifer unit (Unit 1), where more space was required to pile both conifer and hardwood forest residues separately. Additionally, processing cost differed between conifers and hardwood units for the no sorting treatment and averaged \$18.53 and 21.03/MBF, respectively.

### Assessment of slash and tops

One of the managerial advantages related with sorting of forest residues was the reduction in the amount of the slash pile by taking out the tree tops. Our results showed that the total amount of tops ranged from 19 to 25 % among the treatments (Table 5). The amount of tops and slash generated is directly related to:

- The minimum diameter of the sawlogs processed. For this calculation 6 inch small-end diameter was considered as the minimum diameter for sawlog.
- Acreage of the unit.
- Species processed (hardwood versus conifer). Certain trees have huge branches which increases the percentage of slash.
- Density of the trees in the stand.
- Biomass trees in the stand.

Table 5. Amount of slash and tops generated from the timber harvesting units.

	Percentage (%)	
	Tops	Slash
Unit 1	19.1	80.9
Unit 2	24.7	75.3
Unit 3	24.4	75.6

Mixed species units (Unit 2 and 3) showed same trends with the percentage of slash and tops generated for both sawlog and biomass components. This was because the hardwood species had a high top to slash ratio, suggesting that more tops was produced per tree compared to slash. However, tree forks in hardwood species and chunks generated during the sawlog processing were not considered for the study, which could potentially increase the percentage of tops.

## **Loading and sorting**

In general, there were no trends observed in the productivity between the various treatments and the delay free cycle averaged 30 seconds and 21 seconds for loading and sorting respectively. On average, it took 14 minutes for the loader to load a sawlog truck. For unit 2 and 3, which had two additional biomass piles from hardwood, more time was spent on sorting. Additionally, it was observed that the loading cycle times depended on the availability of landing space. During sorting and loading, the loader did not handle any biomass component; therefore this phase was limited to the sawlogs.

## **Implication on management and the timber harvesting operation**

Processing and sorting of biomass trees are common to regions where there are pulp markets. However in northern California there is limited demand and interest for woody biomass except as feedstock to power plants operating. Conventionally, biomass trees harvested are spread within the unit and are used as a slash mat by the harvesting machines to minimize soil compaction (Oneil and Lippke 2009). Even though these slash mats are recoverable the biomass can be contaminated. In this context, the sorting of forest residues facilitates chipping operations which generally generate higher quality comminuted feedstock of uniform size distribution which could be utilized for BCTs (Han et al. 2015). These products are of higher value and could create additional income for land owners. Therefore it is possible that the additional cost incurred by sorting and processing forest residues could be compensated by the income generated from these value added products. Processing and sorting of forest residues also reduces the cost of site preparation for replanting, as a major amount of the tops and broken sawlogs are taken out from the slash pile resulting in smaller slash piles. This also results in a reduction of biomass burned in the woods. From an operational point of view, forest residues are easier to handle when sorted than piled together.

## **4. Conclusions**

This study showed that the cost of processing and sorting biomass trees and tops generated from sawlog harvesting had little effect on the overall cost of the operation. Sawlog and biomass harvesting among the three sorting treatments were very comparable in productivities and costs. However, the processing cost increased 30% from the no sorting to intensive sorting. The overall cost of sorting and processing was less impacted by processing because a major share of the operational cost was incurred by primary transportation.

## 5. Acknowledgement

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## 6. References

- Adebayo, A. B., H.-S. Han, and L. R. Johnson. 2007. Productivity and cost of CTL and WT harvesting in a mixed conifer stand.pdf. *For. Prod. J.* 57(6):59–69.
- Alcorn, M. 2014. Personal Communication.
- Haikerwal, A., F. Reisen, M. R. Sim, M. J. Abramson, C. P. Meyer, F. H. Johnston, and M. Dennekamp. 2015. Impact of smoke from prescribed burning: Is it a public health concern? *J. Air Waste Manag. Assoc.* 65(5):592–598.
- Han, H.-S., J. Bisson, A. R. Kizha., and H. Woo. 2015. Quality feedstocks from forest residues generated from timber harvesting operations in northern California, United States of America (USA). in *Biomass resources*, Vienna, Austria.
- Helmisaari, H.-S., L. Kaarakka, and B. A. Olsson. 2014. Increased utilization of different tree parts for energy purposes in the Nordic countries. *Scand. J. For. Res.* 29(4):312–322.
- Hiesl, P. 2013. Productivity standards for Whole-tree and Cut-to-length. The University of Maine, Orono, Maine. 166 p. Available online at: [http://www.umaine.edu/cfru/All\\_coop/Publications/Hiesl\\_Master\\_Thesis\\_2013.pdf](http://www.umaine.edu/cfru/All_coop/Publications/Hiesl_Master_Thesis_2013.pdf); last accessed May 17, 2015.
- Hudson, J. B., C. P. Mitchell, and P. G. S. Storry. 1990. Costing integrated harvesting systems. P. 46–52 in *IEA/BA Task 6th Activity Integrated Harvesting Systems*, University of Aberdeen, Copenhagen, Denmark.
- Jones, G., D. Loeffler, D. Calkin, and W. Chung. 2010. Forest treatment residues for thermal energy compared with disposal by onsite burning: Emissions and energy return. *Biomass Bioenergy.* 34(5):737–746.
- Kizha., A. R., H.-S. Han, T. Montgomery, and A. Hohl. In press. Determining cost zones and hot spots for procuring feedstock for woody biomass-based power plants in northern California. *Calif. Agric. J.*
- Kluender, R., D. LORTZ, W. McCoy, B. J. Stokes, and J. Klepac. 1997. Productivity of Rubber-tired Skidders in Southern Pine Forests. *For. Prod. J.* 47(11/12):53–58.
- Miyata, E. S. 1980. Determining fixed and operating costs of logging. General Technical Report,

North Central Forest Experiment Station, Forest Service - US Department of Agriculture, St. Paul, Minnesota.

Morgan, T. A. 2009. An assessment of forest-based woody biomass supply and use in Montana.

Forestry Assistance Bureau, Forestry Division, Montana Department of Natural Resources and Conservation, Missoula, Montana.

Olsen, E. D., M. M. Hossain, M. E. Miller, and others. 1998. Statistical comparison of methods used in harvesting work studies. Corvallis, Or. College of Forestry, Forest Research Laboratory, Oregon State University. Available online at:

<http://ir.library.oregonstate.edu/jspui/handle/1957/7737>; last accessed May 17, 2015.

Oneil, E., and B. Lippke. 2009. Eastern Washington biomass accessibility. Washington State Legislature and Washington Department of Natural Resources, Seattle, WA. Available online at:

<http://pacificbiomass.org/documents/Report%20to%20the%20Washington%20State%20Legislature.pdf>; last accessed October 8, 2014.

Röser, D., B. Mola-Yudego, L. Sikanen, R. Prinz, D. Gritten, B. Emer, K. Väättäinen, and A. Erkkilä. 2011. Natural drying treatments during seasonal storage of wood for bioenergy in different European locations. *Biomass Bioenergy*. 35(10):4238–4247.

# A survey of Grinding Operations in the Sierra Nevada, California - Relationship Between the Slash Pile Size and The Productivity of a Grinder

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Slash pile burning, which involves gathering the slash and subsequently burning it in piles, is a very effective slash disposal method. Open burning (in piles or broadcast burning) within the harvested site is the usual and frequently the only economic method of disposal for a significant quantity of the excess woody waste biomass throughout much of the western United States. The utilization of biomass material for energy production is an appealing outlet for biomass disposal that can provide benefits in helping meet the objectives of density management, forest health, and fire hazard reduction. This study investigated processing the woody biomass waste piles for use as fuel instead of burning them. At each landing slash pile location, a 132 kW excavator with grapple was used to transfer the piles into a horizontal grinder (522 kW). Economies of scale can be expected when grinding a larger pile, while the efficiency of a loading operation may be diminished. Therefore, three piles, i.e., 'Small (Length: 20 m; Width: 15 m; Height: 4 m),' 'Medium (L: 30 m; W: 24 m; H: 4 m),' and 'Large (L: 35 m; W: 30 m; H: 4 m)' piles, were ground and the operations were time-studied. As a result, grinding the 'Medium' pile was found to be the most productive, 31 BDT/PMH0, thereby suggesting that there might be an optimum size of slash pile for a grinding operation

**Keyword:** California, fuel reduction, horizontal grinder, slash pile, time study

## 1. Introduction

### 1.1 Backgrounds

Increasing fierce wildfires is currently one of the severest problems in the western United States. To make matters worse, California is now in the fourth year of one of the state's worst droughts in the past century. Under natural fire conditions, a proper amount of thinning was effected and the remaining trees were thereby given a better chance to mature. Furthermore, it is said that forest thinning may increase water yield from the Sierra Nevada, California (Downing 2015). However, after a century of fire suppression, California forests are denser and have fewer large trees, that is, from the 1930s to the 2000s, the number of large

trees in the Sierra Nevada decreased by half while the density of small trees doubled. Severe fires are increasing in frequency and size throughout the Sierra Nevada, and regeneration is not a given for severely burned forests where seed trees have been killed across large areas (Kocher 2015). Despite the potential for long-term negative impacts, large-tree removal is still common throughout the United States. Removing all large trees without planning to replace them with either planted or naturally regenerated younger trees is widely thought to have negative consequences on a forest's productivity and species composition. York (2015) reported from a long-term study at the Blodgett Forest Research Station (BFRS), the Center for Forestry, the University of California, Berkeley that large-tree removal resulted in more species change, with white fir increasing in the canopy and ponderosa pine decreasing.

Fuel reduction operations (prescribed fire, mechanical treatment, mechanical plus fire) are effective to reduce the risk of high intensity wildfire and return forests to a more fire-resilient landscape (North et al. 2012). From this point of view, Hartsough et al. (2008) analyzed that gross costs of mechanical treatments were more expensive than those of prescribed fire, but net costs of mechanical treatments after deducting the values of harvested products were, on most sites, less than those of fire. The mechanical-plus-fire treatment was the most effective, followed by fire-only, at reducing the modeled severity of wildfire effects under extreme weather conditions. The effectiveness of mechanical-only treatments depended on how much surface fuel remained on site. A whole-tree harvesting system removed the tops and limbs along with the felled trees, thereby reducing potential fire severity more than methods which left slash and/or masticated material within the stands. Stephens et al. (2009) demonstrated that some of carbon (C) stored on site should be removed using active treatments, including prescribed fire, mechanical thinning from below, and mastication, thereby reducing total stored C in the short term but increasing fire resistance in the long term, which is the more prudent approach to storing C over the long term in the ecosystems of fire-prone dry coniferous forests of the western United States that burned frequently.

## **1.2 Blodgett Project entitled "Forest Biomass Diversion in the Sierra Nevada"**

Current business as usual activities for biomass disposal in much of the Sierra Nevada include pile and burn, mastication, and drop/scatter techniques. The utilization of biomass material for energy production is an appealing outlet for biomass disposal that can benefit objectives of density management, forest health, and fire hazard reduction. In the previous study, the Placer County Air Pollution Control District (PCAPCD) and the Sierra Nevada Conservancy demonstrated significant air emissions reduction through the diversion of forest

biomass that was scheduled for open pile burning (Springsteen 2011). In this project, as a next step, the PCAPCD sponsored a research that tracked the economic costs and air emissions generated from the collection, processing, and transport of forest harvest residuals generated at the BRFS in 2012, with the objective of quantifying the emissions reductions gained from utilizing the biomass for energy production compared to open pile burning (Figure 1).



Figure 1. Open pile burning



Figure 2. Grinding operation

The market value of forest biomass was not sufficient to cover 100% of the forecasted costs to collect, process, and transport material to the Buena Vista Biomass Power (BVBP) facility, the nearest biomass power generation facility located near Lone, California so the PCAPCD offset the cost differential between the forest biomass market value and actual costs of collection, processing, and transport. A forest biomass processing contractor, the Brushbusters Inc., was retained to process and transport six woody biomass waste piles for use as fuel in the BVBP facility. In order to monitor equipment operating costs and efficiencies as well as equipment air emissions, the authors of this paper investigated processing the woody biomass waste piles. At each landing slash pile location, an excavator with grapple was used to transfer the piles into a horizontal grinder (Figure 2).

Economies of scale can be expected when grinding a larger pile, while the efficiency of a loading operation may be diminished. With respect to the impact of slash pile size, Seymour and Tecle (2004 and 2005) studied the impact on soil physical properties and chemical characteristics by burning, while that on biomass moisture change has been also tested (e.g., Kim and Murphy 2013, Lin and Pan 2013). Relationship between the slash pile size and the productivity of a grinder, however, has been discussed little so that three piles, i.e., ‘Small,’ ‘Medium,’ and ‘Large’ piles, were ground and the operations were time-studied by using a

similar protocol used by the authors of this paper (e.g., Hartsough and Nakamura 1990, Yoshioka et al. 2002, 2006a, and 2006b).

## 2. Materials and methods

The BFRS, 1,198 ha (2,961 acres) of Sierra Nevada forest land locates east of Georgetown, California. Woody biomass waste piles at the BFRS included tree tops, limbs, and small trees. The piles were generated from thinning treatments in mixed conifer plantations during the summer of 2012. The treatment objectives were to reduce fire hazard, increase average tree vigor, and increase species diversity. Operations were typical of those in the Sierra Nevada, where young and dense forests have developed following wildfires or even-aged harvests. Plantations were thinned to an average of 272 trees per ha (110 trees per acre) from pre-treatment stocking levels of 549 trees per ha (222 trees per acre). Four plantations were thinned, covering a total of approximately 32 ha (80 acres). Because smaller trees were preferred for removal, average stem diameter (for residual trees) at breast height (DBH) increased from 30.2 to 33.3 cm (11.9 to 13.1 inches). Sawlogs greater than 15.2 cm (6 inches) diameter on the small end and at least 3.05 m (10 feet) long were transported to a sawmill for processing into lumber products. Unmerchantable trees (too small to process into sawlogs) plus the tops and limbs of merchantable trees were piled at landings adjacent to roadside for disposal by open burning. The overall size of the piles generated were typical of thinning operations in young and mature forests, with bulk volume averaging 1,784 m<sup>3</sup> (63,000 ft<sup>3</sup>) per pile.

At each BFRS slash pile, an excavator with grapple was used to transfer the waste material into a horizontal grinder. Wood chips from the grinder were conveyed directly into chip vans, and transported to the BVBP facility, typically a 105 km (65 mile) one-way trip. Due to road construction projects and detours, the actual one-way distance averaged about 127 km (79 miles) one-way. Equipment and engines used for the chipping and transport operations (Table 1) were sized for scale of operations that a medium or large landowner might consider. Landing piles for the project contained at least 100 green tons (GT) of biomass wastes (the equivalent of 4 chip vans each holding 25 GT). All biomass received at BVBP has been chipped prior to transport since BVBP does not have fuel processing equipment on site. Brushbusters' operations, grinder, excavator, and chip vans, were carefully observed and tracked including total operating hours, productive operating hours, diesel fuel use, biomass production, and miles traveled. The following equipment cost factors were used based on current contractor bid rates: grinder: \$450/hr; excavator: \$175/hr; chip van: \$90/hr.



Table 1. Equipment and engines for biomass processing

Equipment	Horizontal grinder	Excavator with grapple
Vendor, model	Bandit, Beast 3680	Link-Belt, 290 LX
Engine, horsepower	Caterpillar C18 Tier III, 522 kW	Isuzu CC-6BG1TC, 132 kW
Length	11,890 mm	10,410 mm
Width	2,845 mm	3,400 mm
Height	4,115 mm	3,270 mm
Weight	28,122 kg	29,211.4 kg
Capacity	890 mm	-
Infeed conveyor	6,110 mm x 1,520 mm	-
Maximum reach	-	10,540 mm

For analyzing the relationship between the slash pile size and the productivity of a grinder, three piles, i.e., 'Small (Length: 20 m; Width: 15 m; Height: 4 m; 51bone dry tons (BDT)), 'Medium (L: 30 m; W: 24 m; H: 4 m; 123 BDT),' and 'Large (L: 35 m; W: 30 m; H: 4 m; 174 BDT)' piles, were picked out from total 6 piles for process and transport, and grinding operations were time-studied. The element operations of the excavator monitored were as follows: loading (grabbing and pivoting); unloading (releasing and pivoting); shaking waste material off; waiting for the grinder's swallowing of material; pushing material into the grinder; reorienting or repositioning material from the pile; loading with moving; unloading with moving.

Table 2. Results of the time study

Element operation		Pile		
		Small	Medium	Large
Loading	Time (sec)	3484	5312	7614
	<i>n</i>	359	550	802
	Avg. (sec)	9.70	9.66	9.49
	Std. Dev. (sec)	5.55	4.29	4.56
Unloading	Time (sec)	3114	4776	6848
	<i>n</i>	383	594	863
	Avg. (sec)	8.13	8.04	7.94
	Std. Dev. (sec)	3.09	3.00	2.73
Shaking	Time (sec)	92	95	201
	<i>n</i>	14	15	29
	Avg. (sec)	6.57	6.33	6.93
	Std. Dev. (sec)	3.08	2.50	2.84
Waiting	Time (sec)	479	1314	1875
	<i>n</i>	29	71	88

	Avg. (sec)	16.52	18.51	21.31
	Std. Dev. (sec)	18.06	19.95	19.32
Pushing	Time (sec)	1013	1190	1316
	<i>n</i>	132	168	180
	Avg. (sec)	7.67	7.08	7.31
	Std. Dev. (sec)	5.02	4.83	7.06
Reorienting or repositioning	Time (sec)	52	1056	6826
	<i>n</i>	3	11	21
	Avg. (sec)	17.33	96.00	325.05
	Std. Dev. (sec)	2.31	126.17	732.85
Loading with moving	Time (sec)	100	201	284
	<i>n</i>	13	29	33
	Avg. (sec)	7.69	6.93	8.61
	Std. Dev. (sec)	3.82	2.25	3.19
Unloading with moving	Time (sec)	185	464	581
	<i>n</i>	18	47	56
	Avg. (sec)	10.28	9.87	10.38
	Std. Dev. (sec)	6.95	5.44	9.28
Total		8519	14408	25545

### 3. Results and Discussion

During the period of August 20, 2013 through September 4, 2013 on eight separate work days, 601 BDT (928 GT) of forest slash from BFRS were collected, processed, and transported by Brushbusters for energy use to BVBP. This comprised a total of 37 separate chip van loads, with each delivery averaging 16.3 BDT (25.1 GT).

#### 3.1 Relationship between the slash pile size and the productivity of a grinder

Results of the time study are shown in Table 2. The times of loading and shaking will be shortened by improving the piling method such as orienting the tops and limbs so that they can most readily be fed into the grinder. Modifying the infeed conveyor of the grinder, e.g., extending its length, will improve the times of waiting and pushing. With respect to the impact of slash pile size, the average times of loading and unloading were not influenced by the pile size. On the other hand, the frequency and the average time of reorienting or repositioning were increased and lengthened, respectively, as the size of pile bulked up. Percentages of the time of reorienting or repositioning to the total observed were also proportional to the pile size (Figure 3).

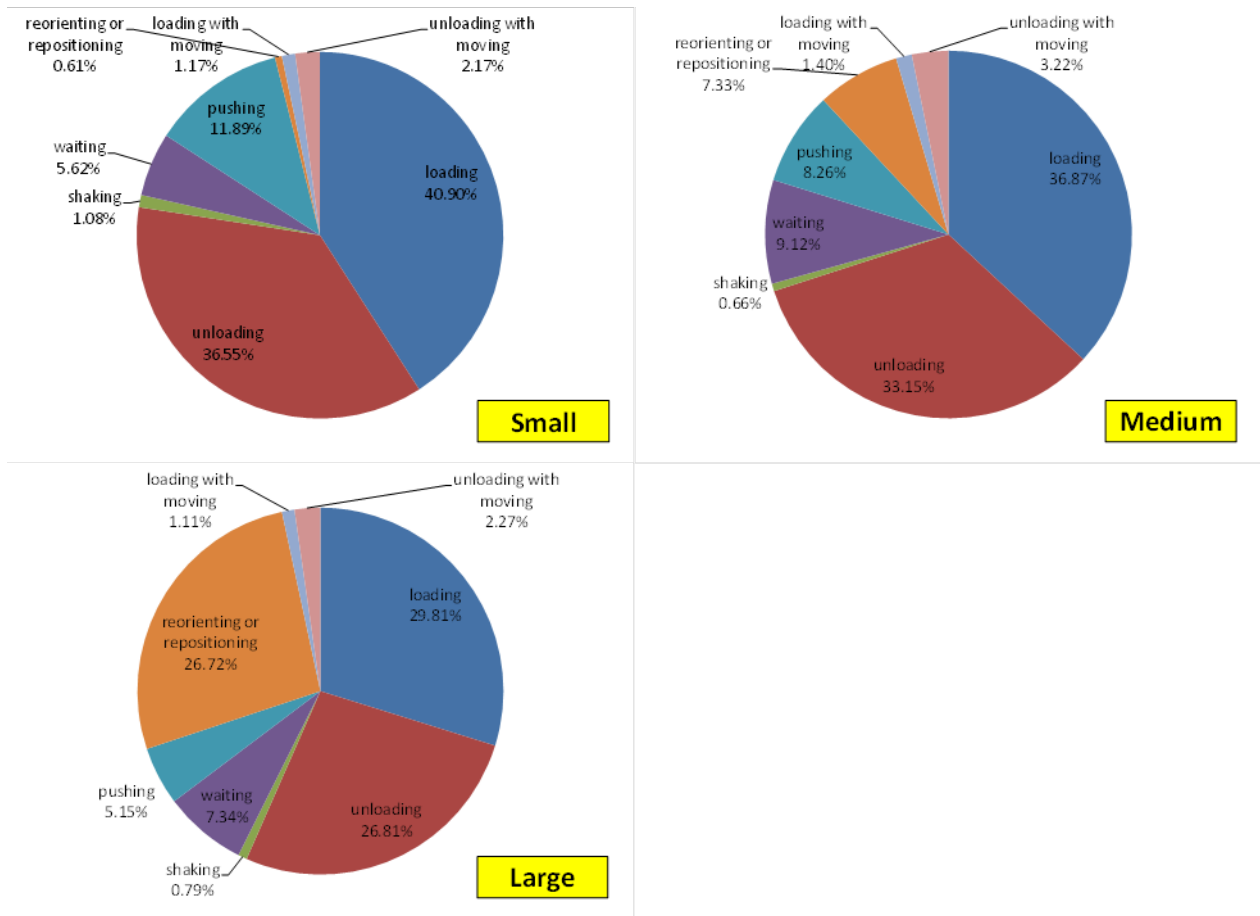


Figure 3. Percentage of each element operation time to the total observed

Results of the time study per BDT (Figure 4) show that grinding the ‘Medium’ pile was the most productive, 31 BDT/PMH0 (= 123 BDT / 14,408 sec x 3,600 sec/hr), thereby suggesting that there might be an optimum size of slash pile for a grinding operation. The Nordic guidelines stating the preferable size is 20-30 meters length of at maximum 4 meters height may assist this result (Nilsson 2009). The weights of slashes per loading were calculated to be 0.14 BDT/time (= 51BDT / 359 times), 0.22 BDT/time (= 123 BDT / 550 times), and 0.22 BDT/time (= 174 BDT / 802 times) when grinding ‘Small,’ ‘Medium,’ and ‘Large’ piles, respectively, which suggests that reorienting or repositioning material from the pile could make the amount of slashes per loading increase and the productivity of the grinder raise. However, reorienting or repositioning from too large pile may take too much time, resulting in the decline in the overall operational efficiency.

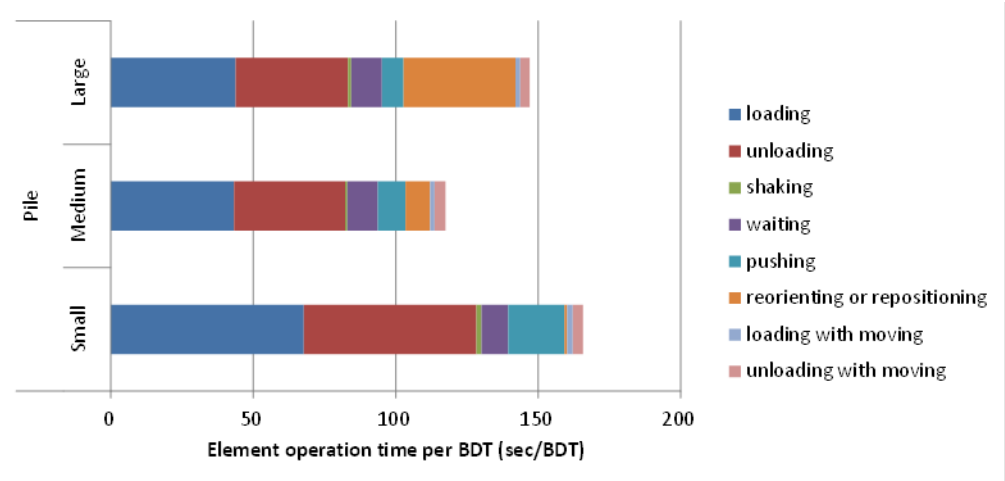


Figure 4. Element operation time per BDT

### 3.2 Economics of forest biomass waste processing and transport

The total delivered cost of \$70/BDT was almost equally split between collection and processing at \$34/BDT and transporting to the BVBP facility at \$36/BDT (Table 3).

Table 3. Economics of forest biomass waste processing and transport

Equipment	Unit operation cost (\$/operating hour)	Avg. operating time(hr/day)	Production rate (BDT/machine-day)	Total cost (\$/BDT)
Delivered				
Grinder	450	3.8	75.1	22.8
Excavator	175	4.8	75.1	11.2
Chip van	90	8.0	20.3	35.5
Total				69.4
Projected for 30-mile one-way haul distance				
Grinder	400	5.0	95.0	21.1
Excavator	160	5.0	95.0	8.4
Chip van	85	9.0	48.9	15.6
Total				45.1

Production rates were less than expected due to lack of full time availability of chip vans to the grinder landings. This was due to the following considerations:

- BVBP was not in commercial operation and curtailed the hours they were accepting fuel deliveries. In many cases, trucks had to be parked loaded overnight rather than complete a one day round trip;
- Public road construction activities caused transport delays and slowdowns, resulting in average chip van transport speeds of only 50 km/hr (31 mph);

- Need to clear trees and brush from BFRS spur roads and landings to allow van access.

Three to four separate chip vans were used each day for hauling. Each chip van averaged only 1.25 delivered loads per day rather than the potential 2 loads per day for the round trip distance of 254 km (158 miles).

The restrictions on hauling also affected the activities at the landing, as three to four trucks each day and an average of little more than a load per truck-day, the trucks were capable of transporting only 4.6 vanloads per day on average, and therefore the grinder was limited to this amount and operated only 3.8 hr/day. By remedying the unusual problems with transport and increasing loads per truck to two per day (and utilizing four trucks each day), grinder output can be increased to 8 loads per day. As shown in the table above, this would reduce the total cost for grinding and transport to about \$45/BDT, which was the competitive market value at the time of the project for biomass sourced from timber harvest residual in the central Sierra Nevada region. To achieve this, the breakeven transport distance would need to average approximately 48 km (30 miles) or less, one-way.

Other factors also limited grinding productivity. For example, the processing residues had been piled with intention of burning rather than grinding them, therefore no attention was paid to orienting the tops so that they could most readily be fed into the grinder. This is reflected in results of time-motion study mentioned above, which found the grinder to be actively processing material during only 2.5 hr/day, while the grinder engine actually operated for 3.8 hr/day, based on readings of the engine meter. In addition, the excavator operated for 4.8 hr/day. During much of the times beyond the 2.5 hours of active grinding, the grinder was idling while the excavator was reorienting or repositioning material from the pile so that it could be effectively fed to the grinder (some of the extra time for the excavator was spent moving the grinder and excavator from landing to landing and preparing the spurs at the residue piles).

#### **4. Conclusions**

An optimum size of slash pile from the point of view of a grinding operation will be discussed further by simulation since the demand of forest residuals for power generation are rapidly increasing in Japan with the purpose of selling the electricity in a higher price using a 'Feed-in Tariff' scheme.

Concerning the other results derived from the Blodgett Project, it was demonstrated that utilization of biomass from these large debris piles can result in energy and air quality benefits:

- Energy (diesel fuel) expended for processing and transport was 2.5% of the biomass fuel (energy equivalent);
- Based on measurements from a large pile burn, air emissions reductions of 98-99% for PM<sub>2.5</sub>, CO, NMOC, CH<sub>4</sub>, and BC, and 20% for NO<sub>x</sub> and CO<sub>2</sub>-equivalent greenhouse gases.

## 5. References

- Downing, J. 2015. Forest thinning may increase water yield from the Sierra Nevada. *Calif. Agr.* 69(1):10-11.
- Hartsough, B.R., and G. Nakamura. 1990. Harvesting eucalyptus for fuel chips. *Calif. Agr.* 44(1):7-8.
- Hartsough, B.R., S. Abrams, R.J. Barbour, E.S. Drews, J.D. McIver, J.J. Moghaddas, D.W. Schwilk, and S.L. Stephens. 2008. The economics of alternative fuel reduction treatments in western United States dry forests: Financial and policy implications from the National Fire and Fire Surrogate Study. *For. Policy Econ.* 10(6):344-354.
- Kim, D.-W., and G. Murphy. 2013. Forecasting air-drying rates of small Douglas-fir and hybrid poplar stacked logs in Oregon, USA. *Int. J. For. Eng.* 24(2):137-147.
- Kocher, S. 2015. Californians must learn from the past and work together to meet the forest and fire challenges of the next century. *Calif. Agr.* 69(1):5-9.
- Lin, Y., and F. Pan. 2013. Effect of in-woods storage of unprocessed logging residue on biomass feedstock quality. *For. Prod. J.* 63(3-4):119-124.
- Nilsson, B. 2009. Costs, CO<sub>2</sub>-emissions and energy balance for applying Nordic methods of forest biomass utilization in British Columbia. M.Sc. thesis, Dept. of For. Resour. Manage., Swedish Univ. of Agr. Sci., Umeå, Sweden. 43 p.
- North, M., B. Collins, and S. Stephens. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. *J. For.* 110(7):392-401.
- Seymour, G., and A. Teclé. 2004. Impact of slash pile size and burning on ponderosa pine forest soil physical properties. *J. Ariz. Nev. Acad. Sci.* 37(2):74-82.
- Seymour, G., and A. Teclé. 2005. Impact of slash pile size and burning on soil chemical characteristics in ponderosa pine forests. *J. Ariz. Nev. Acad. Sci.* 38(1):6-20.
- Springsteen, B., T. Christofk, S. Eubanks, T. Mason, C. Clavin, and B. Storey. 2011. Emission reductions from woody biomass waste for energy as an alternative to open burning. *J. Air Waste Manage. Assoc.* 61(1):63-68.
- Stephens, S.L., J.J. Moghaddas, B.R. Hartsough, E.E.Y. Moghaddas, and N.E. Clinton. 2009. Fuel treatment effects on stand-level carbon pools, treatment-related emissions, and fire risk in a Sierra Nevada mixed-conifer forest. *Can. J. For. Res.* 39(8):1538-1547.

- York, R.A. 2015. Large-tree removal in a mixed-conifer forest halves productivity and increases white fir. *Calif. Agr.* 69(1):27-35.
- Yoshioka, T., K. Aruga, H. Sakai, H. Kobayashi, and T. Nitami. 2002. Cost, energy and carbon dioxide (CO<sub>2</sub>) effectiveness of a harvesting and transporting system for residual forest biomass. *J. For. Res.* 7(3):157-163.
- Yoshioka, T., K. Aruga, T. Nitami, H. Sakai, and H. Kobayashi. 2006a. A case study on the costs and the fuel consumption of harvesting, transporting, and chipping chains for logging residues in Japan. *Biomass Bioenerg.* 30(4):342-348.
- Yoshioka, T., R. Sakurai, K. Aruga, T. Nitami, H. Sakai, and H. Kobayashi. 2006b. Comminution of logging residues with a tub grinder: Calculation of productivity and procurement cost of wood chips. *Croat. J. For. Eng.* 27(2):103-114.

# Assessing Productivity of Ground-based Logging Operation in Mediterranean City of Osmaniye in Turkey

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## Abstract

Logging operations are usually one of the most difficult, costly and time consuming activities among forest operations. Thus, logging operation should be well planned and factors that affect operation productivity should be evaluated prior to field applications. This issue becomes even more important in mountainous areas with steep slope such as Eastern Mediterranean region of Turkey. In this study, productivity of ground-based logging operation was investigated in a Mediterranean city of Osmaniye in Turkey. The time study was conducted during a thinning operation in a Brutian Pine stand. The average ground slope on the study area was measured as 35%. During logging operation, tree length logs were skidded from stump to road side landings by a rubber-tired farm tractor. It was found that the loaded travel time was the most time consuming work stage (36.22%) during skidding operation. The results indicated that the average productivity was 2.26 m<sup>3</sup>/hr for an average skidding distance of 110 m. The operation productivity was not very high since full tree method was implemented during a thinning operation and single tree was skidded in each trip. The average tree volume per turn was computed as 0.19 m<sup>3</sup>. Besides, heavy terrain conditions due to frequent rainfalls in the region negatively affected mobility and maneuverability of rubber-tired tractor during skidding operation.

**Keyword:** Logging operations, wood production, Mediterranean Region, Brutian Pine

## 1. Introduction

The timber extraction can be defined as transportation of wood based products from stump to landing area as in logs, tree length, or full tree. This operation can be performed by utilizing several methods based on terrain conditions, side slope, machine availability, product



size and types. According to previous studies, the cost of timber extraction is up to 50% of the total timber production costs. Besides, this amount can increase as skidding or forwarding distance increases (Büyüksakallı, 2010).

In Turkey, more than half of the forest lands are on steep terrain, which makes it difficult to utilize ground-based mechanized harvesting systems. The most common equipment used in mechanized harvesting is tractor which is employed to extract about 10% of the timber in Turkey. Modified and reinforced farm tractors are also commonly used for skidding, winching, loading and transportation operations (Öztürk and Akay, 2007).

Tractor logging is very common method for extraction of timber in many countries, especially in productive forests. The productivity of tractor logging highly depends on road network density in the forest. If road density is not adequate, logging managers should consider locating skidding roads in harvesting unit (Erdaş, 2008).

The tractors used for logging operation can be classified under two groups: farm tractors that are modified to be utilized in forest operations, and forest tractors (skidders) which are solely built for forest operations. The farm tractors can operate on 5-30% ground slope, while skidders can run up to 40% slope (Büyüksakallı, 2010). However, modified and reinforced farm tractors have been successfully employed in many forest operations such as skidding, forwarding, winching, cable yarding, and loading (Öztürk and Akay, 2007).

Logging operations are difficult, costly, and time consuming activities among forestry activities. Therefore, the main factors that affect productivity of logging operation should be carefully evaluated. Timber extraction planning is very important in mountainous areas with steep slope such as Eastern Mediterranean region of Turkey. In this study, productivity of ground-based logging operation was investigated in a Mediterranean city of Osmaniye in Turkey. The time study was conducted during a thinning operation in a Brutian Pine stand.

## **2. Material and Methods**

### **2.1. Study Area**

The study area is selected from Osmaniye Forest Enterprise Chief at Osmaniye Forest Enterprise Directorate located in Mediterranean city of Adana, Turkey (Figure 1). Total area of the Chief was 30111 ha in which the forested area was 8027.5 ha (productive forest: 7706 ha and coppice forest: 321.5 ha). The stand characteristics were listed in Table 1. The dominant species in the area was Brutian Pine. The timber extraction was performed in Forest

Compartment 109 by using a farm tractor. The specifications of the tractor are shown in Table 2.



Figure 1. Study area

Table 1. Stand characteristics

Forest Compartment	Tree Species	Silvicultural treatment	Elevation	Aspect	Ground Slope (%)
109	Brutian pine	Thinning	310	Northeast	35

Table 2. Technical specifications of the tractor

Specifications	
Model	Fiat 70-56
Engine Power	70 HP 3613 (cm <sup>3</sup> )

Weight	2880 kg
Transmission	8 Forward/2 Rear
Fuel capacity	61 lt
Drive system	Four-wheel

## 2.2. Time Study

Time data collected during skidding operation were recorded into data tables. In order to prevent any bias, data collection was done during regular work performance. The operation was followed from a location where operation could be seen and controlled easily. Repetition method was used in the time study in which chronometer was run for each work stage separately. The work stages evaluated during time study were listed below:

- Moving in empty: The time of moving from landing to stump
- Setting chokers: The time of setting chokers around logs
- Moving back loaded: The time of skidding logs from stump to landing
- Unloading logs: The time of unloading logs at landing

The full tree method was implemented during logging operation (Figure 2). The cycle time and work stages were recorded for 30 turns with average skidding distance of 110 meters. The tractor skidding was divided into four main work stages. The operation started with unloaded travel of the tractor to the harvesting site. At the stump, cut trees were hooked up to the tractor by setting chokers at the trees. Then, tractor maneuvered at the stump and moved back to landing. Finally, logs are released from the chokers at the landing area. The variables (wsi) were defined for work stages and time spent for each stage was recorded in minutes:

ws1 = moving in empty  
ws2 = setting chokers  
ws3 = moving back loaded  
ws4 = unloading logs  
ws5 = delay time

The time spent on resting, maintenance, and unexpected stoppages were also included into total cycle time (CT) as a delay time (ws5) component:

$$CT \text{ (minutes)} = ws_1 + ws_2 + ws_3 + ws_4 + ws_5 \quad (1)$$



Figure 2. The farm tractor used in logging operation

### 3. Results and Discussion

In this study, the productivity of ground-based logging operation was investigated in a Mediterranean city of Osmaniye in Turkey (Figure 3). The time study was conducted during a thinning operation in a Brutian Pine stand where the average ground slope was 35%. During logging operation, full trees were skidded from stump to landing area by a rubber-tired farm tractor.

The cycle time and work stages were recorded for 30 turns during timber extraction. Summary table with average values was indicated in Table 3. The results indicated that the skidding road slope in the study area varied from 3% to 27%. The average skidding distance was 109 m, with the range of 67-144 m. The average load per turn was computed as 0.19 m<sup>3</sup>.



Figure 3. Plan view of the tractor logging operation

Table 3. Summary table for tractor logging

Variables	Unit	Average	Minimum	Maximum
Skidding road slope	%	15	3	27
Skidding distance	m	109	67	144
Load volume	m <sup>3</sup>	0.19	0.05	0.37

It was found that the loaded travel was the most time consuming work stage (36.22%) during skidding operation, followed by moving in empty (33%) (Table 4). The similar results were reported by Öztürk (2001) where the most time consuming work stage during a tractor logging operation was loaded travel (26.99%) and followed by moving in empty (23.43%). The task of releasing chokers from the logs was the least time consuming work stage (8.05%). The results indicated that the average productivity was 2.26 m<sup>3</sup>/hr for an average skidding distance of 110 m. Figure 4 indicates the graphical representation of work stages in percentages.

Table 4. Time study data for each work stage

Work stages	Average (min)	Minimum (min)	Maximum (min)
Moving in empty	1.64	1.10	2.56

Setting chokers	0.51	0.25	0.83
Moving back loaded	1.80	1.10	3.20
Unloading logs	0.40	0.11	0.65
Delay time	0.62	0.30	1.45
Total cycle time	4.97	3.30	6.98

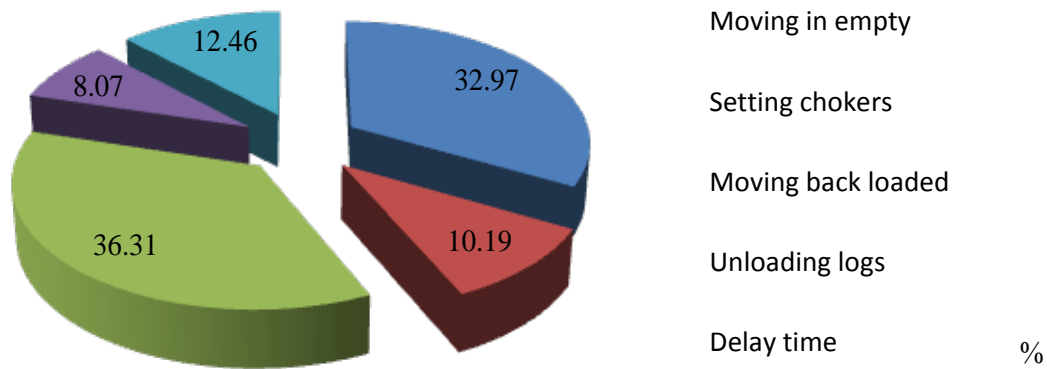


Figure 4. The graphical distribution of work stages in skidding operation

The results indicated that productivity of a farm tractor was low comparing with skidding by skidders which have higher load capacity and pulling power. Öztürk (2009) reported that productivity of a skidder (MB Trac 900) was about 8.7 m<sup>3</sup>/hr for an average skidding distance of 105 m. The other reason of low productivity rate was that full tree method was implemented during a thinning operation and single tree was skidded in each trip.

According to previous studies, the productivity may also decrease as skidding distance increases (Büyüksakallı, 2010). In fact skidding distance can be the most important variable since it may affect cycle time more than any other variables. Thus, if the skidding distance increases, travel time will increase accordingly (Akay et al., 2004). Besides, if ground slope on the skid trail is steep, the tractors have to travel with lower speed, which leads to higher cycle time.

#### 4. Conclusions

In mountainous regions, timber extraction activities can be the most costly and time consuming forest operation. The logging managers should develop an optimum logging plan by considering all the important factors that affect operation productivity. In this study, a time study was conducted to investigate the productivity of ground-based logging operation with farm tractor in a Mediterranean city of Osmaniye in Turkey.

The results indicated that the average productivity of skidding operation was 2.26 m<sup>3</sup>/hr for an average skidding distance of 110 m. The operation productivity was not very high since full tree method was implemented during a thinning operation where relatively small-size single tree was skidded in each trip. The results indicated that two stages including loaded travel and moving in empty are the most time consuming activities during tractor logging operation. Skidding distance and ground slope are the main factors that affect logging productivity.

In Turkey, the tractor logging systems have been increasingly used especially in the regions with intensively managed forests. Therefore, determination of the main factors affecting productivity is very important for logging managers to develop cost effective mechanized harvesting systems. It is expected that assessment of operation productivity presented in this study may assist logging managers to predict productivity for the tractor logging systems. Other important factors that are not aimed to include in this study such as operation cost, road costs, worker safety, and environmental costs should be also considered in future studies to determine optimum logging systems.

#### 5. References

- Akay, A.E., Erdas, O., Sessions, J. 2004. Determining productivity of mechanized harvesting machines. *Journal of Applied Sciences*. 4 (1): 100-105.
- Büyüksakallı, H. 2010. Winter production (early production) possibilities, applications, and improvements in eastern Mediterranean Region. Phd thesis, Kahramanmaraş Sütçü İmam University, Faculty of Forestry, Kahramanmaraş, Turkey. 182 p.
- Erdaş, O. 2008. Transportation techniques, Kahramanmaraş Sütçü İmam University, Publication No: 110, 544 p. Kahramanmaraş.
- Öztürk T. 2001. A study on forest tractors used in logging operations. *Journal of the Faculty of Forestry Istanbul University (JFFIU), Series B*, 51(2):101-110.
- Öztürk, T., Akay, A.E. 2007. Modifying farm tractors for forest harvesting operations. The 150th Anniversary of Forestry Education in Turkey International Symposium: Bottlenecks,

Solutions and Priorities in the Context of Functions of Forest Resources. 17-19 October 2007, Istanbul, pp. 1111-1120.

Öztürk, T. 2009. Productivity analysis of MB-Trac 900 skidder at hauling of beech timber. Journal of the Faculty of Forestry Istanbul University (JFFIU), Series A, 59(2):45-58.



## VII. Concurrent Session 2B – Biomass Feedstock Transportation

### **A Computer-aided Model to Operations System to Optimize Woody Biomass Feedstock Storage and Transportation**

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Due to the greater demand in bioenergy and bio-based products, feedstock supply chain optimization is critical to decrease the logistics costs. As a primary phase in the biomass feedstock supply logistics, the storage of harvested biomass can directly affect transportation cost, biomass quality and its combustion efficiency. A model structured with linear programming was developed to determine an optimized biomass pre-processing, storage, and transportation strategy. The optimization model was applied in a simulated case study for an energy plant in Michigan. The results indicated that lower supply chain logistics costs and higher feedstock quality could be achieved by applying an optimized supply chain strategy while simultaneously meeting the feedstock user's demand. The sensitivity analysis indicated that transportation distance had no impact on the supply chain logistics strategy. The additional profit brought by higher quality biomass can offset the increased transportation cost for up to 151 miles. Through biomass MC increases, logging residue pile is always the preferred storage method. The impact of biomass moisture content (MC) is concluded to be more significant when it is higher. Through the increase of biomass MC, more biomass is required to satisfy the same energy demand. In average, every 1% increase in biomass MC can result in \$760.68 increase in total cost and 52.1 more green tons biomass to satisfy the four-month energy demands.

#### 1. Introduction

As a carbon neutral and renewable fuel, forest-based biomass has gained popularity in recent years and has been commonly used by independent power plants to generate energy in U.S (Biomass Energy Resource Center, 2011). 541 Exajoules (EJ) energy was consumed in the world during 2010, and about 9% of the energy consumption was generated from woody

biomass (IEA, 2013; Lauri et al., 2014). Due to the ever-increasing demand of bioenergy, the number of biomass power plants will be steadily increasing (Berndes et al., 2003; Jager-Waldau and Ossenbrink, 2004). The increasing number of power plants will bring more restrictions and higher complexity for the management of the woody biomass supply chain (Rönqvist, 2003). In addition, the relatively scattered locations of the power plants will largely increase the transportation distances and costs for forest biomass (Rauch and Gronalt, 2010; Tahvanainen and Perttu, 2011; Alam et al., 2012). Therefore, supply chain optimization for biomass-based power plants is becoming an important research area (Tallaksen and Simo-Kush, 2014).

With the development of computational tools, mathematical models for optimization were widely used to implement cost-effective biofuel production (Macmillan, 2001; Mentzer, 2001; Rönqvist, 2003; Gunnarsson et al., 2004; Bredström, 2004). As biomass transportation cost accounts for the largest part of the total cost, the developed optimization tools primarily focus on two categories: location selection and biomass transportation cost reduction (Eriksson and Björheden, 1989; Allen et al., 1998; Alam et al., 2012). The location selection models mainly focused on finding the best location for single or multiple processing facilities over large-scale biomass-supply chain (Zhang et al., 2011). The transportation cost reduction models generally aimed to reduce cost for biomass procurement and to estimate the feedstock availability (Ranta, 2002; Ranta, 2005; Panichelli and Gnansounou, 2008). However, as a critical phase in woody biomass supply chain logistics, woody biomass storage was rarely studied (Rentizelas et al., 2009).

Storage is important because of the changing seasonal availability of woody biomass and the varied demand of energy plants throughout the year (Sokhansanj et al., 2006; Lin and Pan, 2013). Meanwhile, different storage methods will produce biomass at various quality levels, which can significantly affect the transportation cost and combustion efficiency (Jirjis, 2005; Casal et al., 2012). The most common way in Northern U.S. to store green biomass is to directly process it into wood chips and store in piles before being utilization (Lin and Pan, 2013). This storage method poses several challenges such as dry matter loss, moisture content increase, and energy content reduction (Fredholm and Jirjis, 1988; Hornqvist and Jirjis, 1999; Jirjis 2001; FRL, 2002; Afzal et al, 2010). Store forest harvesting residue in bundles can produce high quality biomass feedstock with low biomass MC, higher energy content and low ash content (Lehtikangas, 2001; Pettersson and Nordfjell, 2007; Afzal et al., 2010). Yet, the bundling technology is also associated with several problems such as high capital investment and low productivity caused by saw binding, materials handling, twine spool collapse, and slow movement at the harvesting site (Rummer et al. 2004; Leinonen, 2004; Patterson et al., 2008; Harrill, 2010). Compared to wood chips pile and biomass bundles, storing unprocessed

harvesting residue can achieve lower processing cost and effectively reduce biomass MC, thus increasing transportation and conversion efficiency (W.A. Amos, 1998; Lin and Pan, 2013; Lin and Pan, 2015).

Michigan is a state with 84% forest cover, forest resources have been viewed as a widely available and promising resource for energy production in Michigan (Dickmann and Leefers, 2003; Zhang et al., 2011). In Michigan, there are 9 biomass-based power plants with a total amount of 210 MW energy generated annually (Biomass Power Association, 2014). Due to weather, ground conditions, or biological constraints, forest harvesting operations are not always possible. To ensure a cost-effective, year-round reliable supply of high quality biomass feedstock to the power plants, a computer-aided optimized operations system was developed. The objectives of this paper are: 1) to develop an optimized operations system that can increase biomass feedstock quality and minimize the storage and transportation costs; 2) to test the effect of transportation distance and biomass MC on supply chain logistics strategy and the total cost.

## 2. Problem description

### **Feedstock storage and transportation operations**

Since the prediction of biomass MC during storage is based on two previous studies conducted from August to November, the woody biomass is assumed to be harvested at the end of July and be stored from August to November. The selected harvesting site is a natural forest stand with a mixture of hardwood and softwood species, 40 miles away from the feedstock end-user: the Cadillac Renewable Energy. Part of the harvested woody biomass is going to be in-woods chipped, transported to and stored in the Cadillac Renewable Energy to meet its first month demand. The rest of woody biomass is to be stored at the harvesting site as unprocessed residue piles for a certain time and then be chipped and be transported to the Cadillac Renewable Energy based on its continued demand.

### **Feedstock end-user**

The Cadillac Renewable Energy, located in Cadillac, Michigan, has a 38MW energy production capability. It is exclusively designed to use recycled wood waste as its primary fuel source. Average monthly use of woody material (in approximately 45% MC) is about 35,000 green tons in wintertime and around 25,000 tons in other months. There are about 40 logging

companies constantly supplying woody biomass to Cadillac Renewable Energy. Therefore, it is assumed that each supplier needs to deliver 550 dry tons of woody biomass in every month.

### Traditional operation system and optimized operation system

In this study, the traditional operation system refers to the traditional way of handling harvested biomass, where harvested logging residue is directly processed into wood chips and immediately delivered to the feedstock user, then stored in wood chips pile (WCP). In the optimized operation system, one portion of the harvested biomass will be processed right away and delivered to feedstock user, while the rest unprocessed portion is to be stored in the form of logging residues pile (LRP) at the harvesting site. After a certain time of in-woods drying, unprocessed logging residues will be chipped by a mobile chipper and delivered to feedstock end-user.

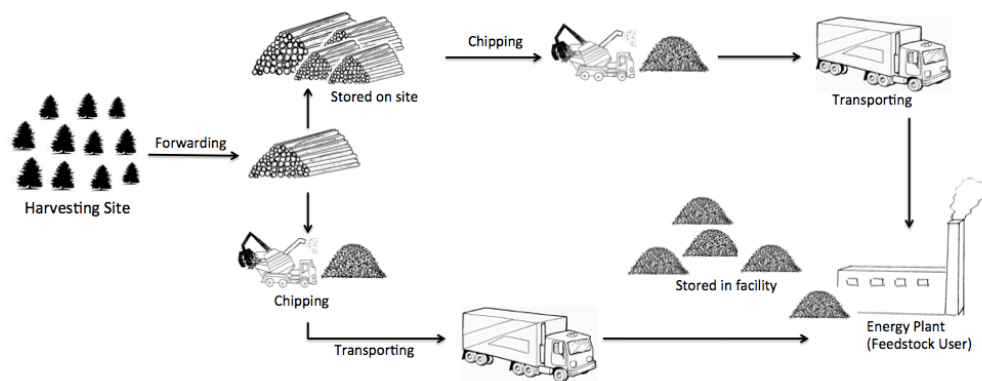


Figure 1. An illustration of the optimized woody biomass supply chain system includes biomass processing, storage and transportation.

### Biomass storage

In the optimized operations system, storage and transportation cost is closely related to the woody biomass MC, which is significantly affected by the storage form. The monthly MC of a wood chips pile is based on the previous study conducted in Michigan from August to November 2013 (Lin and Pan, 2015, Table 1). The monthly MC of logging residue pile is predicted using the formula developed in a previous study and the local weather conditions from August to November 2013 (Lin and Pan, 2013).

Table 1. Monthly Biomass MC (Lin and Pan, 2013; Lin and Pan, 2015)

<b>Biomass MC (%)</b>	<b>Wood Chips Pile (WCP)</b>	<b>Logging Residues Pile (LCP)</b>
<b>August</b>	40.3%	23.8%
<b>September</b>	39.3%	18.1%
<b>October</b>	40.7%	26.1%
<b>November</b>	45.5%	25.9%

### Transportation costs

The transportation distance is set to be 40 miles in the case study. The transportation cost in dollars per green ton is estimated based on the equation that was developed for Lower Peninsula, Michigan (Lautala et al., 2012). The transportation costs associated with different distances are provided in Table 2.

Table 2. Transportation costs with different transportation distances

<b>Transportation distance (miles)</b>	<b>Transportation cost (\$/green ton)</b>
20	5.88
30	6.42
40	6.97
50	7.52
60	8.07

### Holding cost (HC) and additional profit (AP)

In the optimized operation system, part of the fresh harvested biomass is going to be stored as logging residues piles at the harvesting site for air-drying. This will delay the loggers' cash flow and lead to future costs such as machine mobilization and transportation cost. However, it is beneficial for feedstock end-user to use drier wood fuels with higher energy content and lower MC, to increase boiler combustion efficiency. To offer a motivation and

profit for loggers to store biomass in logging residue pile, it is assumed that purchasing price for woody biomass is based on their net energy content, which largely depends on biomass MC. Therefore, drier biomass has higher purchasing price. The standard purchasing price for wood chips is \$23/green ton for woody biomass at around 45% MC (Larry Heibel, personal contact, June 11th, 2014; Nate Verhanovitz, personal contact, June 25th, 2014). The net energy content of the wood (NEC) can be estimated using the equation below:

$$NEC = HHV \times (1 - MC/100) \text{ (Maker, 2004).}$$

Where:

HHV is the higher heating value of the oven dry biomass,

MC is the moisture content of the received biomass.

If the HHV of the woody biomass is assumed to be 8400 BTUs/lb., the NET of 45% MC woody biomass is 4620.00 BTUs/lb. based on the above equation. Therefore, the energy cost in dollar per BTUs can be calculated by dividing standard purchasing price by the net energy content in the wood chips. For biomass with different MC, the purchasing prices are calculated and listed in Table 3.

Table 3. Calculated prices for wood chips based on NEC

<b>U.S. Standard</b>			
<b>Energy Cost (\$/BTUs):</b>			2.48918E-06
<b>Biomass MC (%)</b>	<b>HHV (BTUs/lb)</b>	<b>NEC (BTUs/lb)</b>	<b>Purchasing price (\$/green ton)</b>
60%	8400	3360.00	16.73
55%	8400	3780.00	18.82
50%	8400	4200.00	20.91
45%	8400	4620.00	23.00
40%	8400	5040.00	25.09

35%	8400	5460.00	27.18
30%	8400	5880.00	29.27
25%	8400	6300.00	31.36
20%	8400	6720.00	33.45

### 3. Mathematical model

#### Indices

n: The storage length of the biomass (n=0, 1, 2, 3 months)

#### Variables

$WC_n$  : Weight of biomass harvested in July, stored in wood chips piles (WCP) for n months

$WR_n$  : Weight of biomass harvested in July, stored in logging residue piles (LRP) for n months

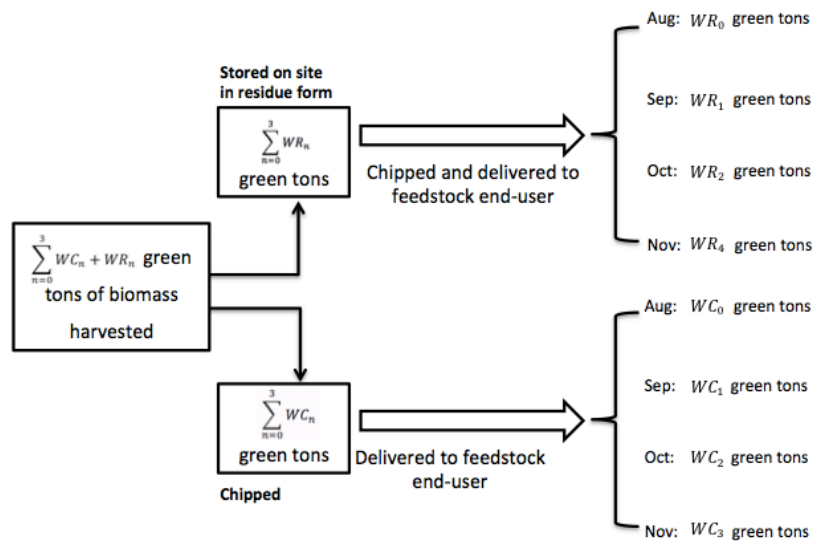


Figure 2. Monthly biomass weight delivered to the feedstock end-user

## Parameters

DB: The monthly biomass demand in green tons (45% MC in wet-basis) for the energy plant

Z: The total cost of processing, storing and delivering the woody biomass

KC: The total chipping cost (\$) for processing all the biomass

KP: The total piling cost (\$) for shaping the logging residues into biomass piles

KMG: The machine mobilization cost (\$) of moving the mobile grinder to the harvesting site

KML: The machine mobilization cost (\$) of moving the loader to the harvesting site

KT: The transportation cost (\$) of delivering chipped products to the feedstock end-user

AP: The additional profit earned by selling drier biomass

MC<sub>Cn</sub>: The MC of biomass harvested in July and stored in wood chips form for n month(s)

MC<sub>Rn</sub>: The MC of biomass harvested in July and stored in logging residues form for n month(s)

HHV: Higher heating value of the woody biomass (BTUs/lb.)

NEC<sub>Cn</sub>: Net energy content of wood chips (BTUs/lb.)

NEC<sub>Rn</sub>: Net energy content of logging residues (BTUs/lb.)

PC<sub>n</sub>: The purchasing price (\$/green ton) of wood chips that were harvested in July and store for n month(s).

PR<sub>n</sub>: The purchasing price (\$/green ton) of logging residues that were harvested in July and store for n month(s).

P<sub>s</sub>: The standard purchasing price (23 \$/green ton) for energy plant to purchase biomass (45% wet-basis).

EC<sub>s</sub>: The purchasing price for 1 BTU of energy (\$/BTUs).

HC: The costs (\$) occur while holding the biomass store in logging residues piles.

## Constraints

Satisfy the monthly demand of the energy plant

$$[(1 - MC_{Cn}) \cdot WC_n + (1 - MC_{Rn}) \cdot WR_n] - (1 - 45\%)DB \geq 0$$

where n =0, 1, 2, 3 months.



## Objective function

The total cost can be expressed as

$$z = KC + KP + KMG + KML + KT - AP + HC$$

where  $AP = \sum_{n=0}^3(PC_n \cdot WC_n + PR_n \cdot WR_n) - PC_0 \cdot \sum_{n=0}^3(WC_n + WR_n)$

$$PC_n = NEC_{Cn} \cdot \frac{2000 \text{ lbs}}{\text{green}} \text{ ton} \cdot EC_s$$

$$NEC_{Cn} = \sum_{n=0}^3 HHV(1 - MC_{Cn})$$

$$PR_n = NEC_{Rn} \cdot \frac{2000 \text{ lbs}}{\text{green}} \text{ ton} \cdot EC_s$$

$$NEC_{Rn} = \sum_{n=0}^3 HHV(1 - MC_{Rn})$$

$$HC = WR_n \cdot PR_1 \cdot r \cdot t \cdot [1 + WR_n \cdot PR_1(1 + r \cdot t) + WR_n \cdot PR_1(1 + r \cdot t)^2 + WR_n \cdot PR_1(1 + r \cdot t)^3] \cdot$$

n=0, 1, 2, 3 months; r=0.03 (yearly interest rate); t=1 month≈0.08 year.

Other values of the parameters are listed in Table 4.

Table 4. Values of the parameters

<b>Site conditions</b>		
Feedstock user	Cadillac Renewable Energy	
Transportation distance (miles)	40	
<b>Parameters</b>	<b>Wood Chips Pile (WCP)</b>	<b>Logging Residues Pile (LCP)</b>
Chipping cost (\$/green ton)	5.00 <sup>(1)</sup>	5.00 <sup>(1)</sup>
Piling cost (\$/green ton) <sup>(4)</sup>	0	4.59 <sup>(2)</sup>
Machine mobilization cost (\$/green ton) <sup>(5)</sup>	2.52 <sup>(3)</sup>	2.52 <sup>(3)</sup>
Total Processing cost (\$/green ton)	7.52	12.11
Transportation cost (\$/ green ton) <sup>(6)</sup>	6.97 <sup>(1)</sup>	6.97 <sup>(1)</sup>

<sup>(1)</sup> Lautala et al., 2012

<sup>(2)</sup> Harrial, 2012

<sup>(3)</sup> Zamora, 2013

<sup>(4)</sup> Assume the chipper will originally has a loader attached; therefore the piling cost of wood chips pile is 0.

<sup>(5)</sup> The mobilization cost includes cost for moving chipper and loader.

<sup>(6)</sup> Transportation cost is 9.75 \$/green ton and additional \$0.15/green ton per mile after 20 miles (Barnes, 2010).

## 4. Results and Discussion

### The optimized operation system

The optimized operation system of continuously supplying Cadillac Renewable Energy with high quality biomass feedstock for 4 months is presented in Table 5. The optimized

operation system favors a shift from WCP form towards LRP form to store biomass for achieving lower MC.

At the end of July, a total of 3079.68 green tons of biomass will be harvested. An amount of 921.69 green tons of biomass will be immediately processed into wood chips and be delivered to Cadillac Renewable Energy to meet its August demand. The rest 2157.99 green tons of biomass will be stored in LRP form in the field. At the end of August, a mobile grinder needs to be moved to the harvesting site to process 671.51 green tons of 1-month air-dried logging residues into wood chips. The wood chips will then be delivered to Cadillac Renewable Energy to meet its September demand. During October and November the similar process will take place. The grinder will grind 744.49 green tons of 2-month field-stored and 741.99 green tons of 3-month field-stored biomass to meet the end-user's monthly demand.

The split costs in each month are listed in Table 5. The highest total cost of \$28,698.57 occurs in July. The chipping cost, piling cost, machine mobilization cost, and transportation cost account for 16.06%, 34.51%, 27.04%, and 22.39%, respectively. The lowest total cost of \$164.96 is in August, when the only cost occurred is the holding cost for not selling the 2157.99 green tons of biomass immediately. From August to November, since there is no need for biomass piling, the total costs only include the chipping cost, the machine mobilization cost, the transportation cost, and the holding cost. From September to November, the monthly total cost varied from \$9,895.48 to \$10,917.60, which mainly depends on the weight of biomass processed and delivered in each month. The total cost of the four months sums up to \$60,630.19. The largest component of the total cost is the transportation cost, which represents 35.40% of the total cost. The holding cost of \$662.24 only accounts for 1.09% due to the relatively small amount of biomass holding.

### **Comparison between optimized operation system and traditional operation system**

The optimized operation system costs the loggers \$6,089.70 more compared to the traditional operation system because of the extra machine mobilization cost and the piling cost associated with establishing logging residue piles (Table 6). However, the higher cost of the optimized operation system can be offset by the additional profit of \$22,204.90 from selling the higher quality biomass feedstock. As the result, the loggers can expect to earn approximately \$16,115.20 more by adopting the optimized operation system.

In the optimized operation system, the total biomass required to satisfy the four-month demand is 3079.68 green tons; while in the traditional operation system, 3764.00 green tons of biomass is required to satisfy the four-month demand. The 684.32 green tons reduction in

green biomass demand is caused by the drier biomass obtained by using logging residues pile as the main storage method.

Table 5. Optimized operation system for selling biomass to Cadillac Renewable Energy

Month	Storage form		Split Cost (\$):				Holding cost (\$):	Total Cost (\$):
	Wood Chips Pile (WCP)	Logging Residues Pile (LCP)	Chipping cost	Piling cost	Machine mobilization cost	Transportation cost		
<b>July</b>	$\sum_{n=0}^3 WC_n = 921.69^{(1)}$	$\sum_{n=0}^3 WR_n = 2157.99^{(2)}$	4608.45	9905.16	7760.78	6424.18		28698.58
<b>Aug</b>	WC <sub>0</sub> =921.69	WR <sub>0</sub> =0.00	0.00	0.00	0.00	0.00	164.96	164.96
<b>Sep</b>	WC <sub>1</sub> =0.00	WR <sub>1</sub> =671.51	3357.53	0.00	1692.19	4680.39	165.36	9895.48
<b>Oct</b>	WC <sub>2</sub> =0.00	WR <sub>2</sub> =744.49	3722.45	0.00	1876.12	5189.10	165.76	10953.44
<b>Nov</b>	WC <sub>3</sub> =0.00	WR <sub>3</sub> =741.99	3709.95	0.00	1869.81	5171.67	166.15	10917.60
<b>Total</b>	921.69	2157.99	15398.38	9905.16	13198.91	21465.34	662.24	60630.06
<b>Total biomass harvested (green tons):</b>								3079.68
<b>Additional Profit (\$):</b>								22204.90
<b>Total cost after Additional Profit (\$):</b>								38425.16
<b>Cost (\$/green ton):</b>								12.48

<sup>(1)</sup> The total weight of green biomass is going to be stored in wood chips pile.

<sup>(2)</sup> The total weight of green biomass is going to be stored in logging residues pile.

Table 6. Traditional operation system for selling biomass to Cadillac Renewable Energy

Month	Storage form		Split Cost (\$):				Holding cost (\$):	Total Cost (\$):
	Wood Chips Pile (WCP)	Logging Residues Pile (LCP)	Chipping cost	Piling cost	Machine mobilization cost	Transportation cost		
<b>July</b>	$\sum_{n=0}^3 WC_n = 3764.00^{(1)}$	$\sum_{n=0}^3 WR_n = 0.00^{(2)}$	18820.02	0.00	9485.29	26235.08		54540.36
<b>Aug</b>	$WC_0 = 921.69$	$WR_0 = 0.00$	0.00	0.00	0.00	0.00	0.00	0.00
<b>Sep</b>	$WC_1 = 906.64$	$WR_1 = 0.00$	0.00	0.00	0.00	0.00	0.00	0.00
<b>Oct</b>	$WC_2 = 927.32$	$WR_2 = 0.00$	0.00	0.00	0.00	0.00	0.00	0.00
<b>Nov</b>	$WC_3 = 1008.35$	$WR_3 = 0.00$	0.00	0.00	0.00	0.00	0.00	0.00
<b>Total</b>	3764.00	0.00	18820.02	0.00	9485.29	26235.08	0.00	54540.36
<b>Total biomass harvested (green tons):</b>								3764.00
<b>Additional Profit (\$):</b>								0.00
<b>Total cost after Additional Profit (\$):</b>								54540.36
<b>Cost (\$/green ton):</b>								14.49

<sup>(1)</sup> The total weight of green biomass is going to be stored in wood chips pile.

<sup>(2)</sup> The total weight of green biomass is going to be stored in logging residues pile.

## Sensitivity analysis

### Effects of transportation distance on the total cost and the optimized operation system

In this study, transportation distance from the harvesting site to Cadillac Renewable Energy was set at 40 miles. In the sensitivity analysis, the range of the transportation distance considered is from 20 miles to 60 miles. The transportation distance has no impact on the biomass storage and transportation strategy and can only affect the total cost through changing the transportation cost. When the distance increases from 20 miles to 60 miles, the total cost after deducting additional profit rises linearly from \$35,056.08 to \$41,806.73 (Fig. 3.). The

sensitivity analysis indicates that every 1-mile transportation distance increase will raise the total cost by \$168.77. The AP earned for different transportation distance is always \$22,204.90 and can cover the cost caused by the distance increase for up to 151 miles. These results suggest that the negative impact of longer transportation distance in the woody biomass supply chain can be offset by the higher biomass quality.

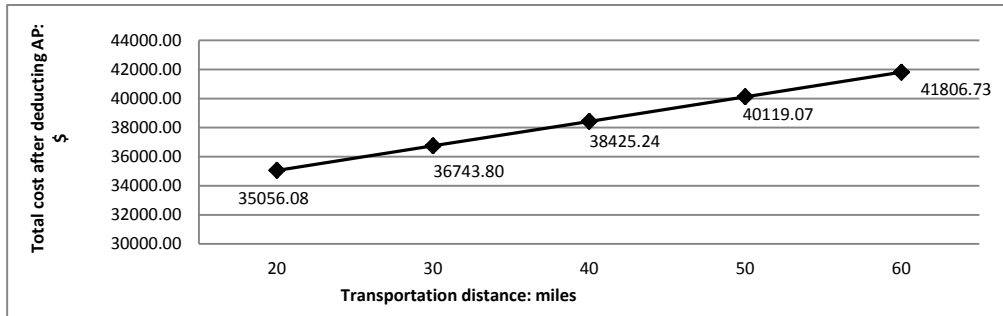


Figure 3. Total cost (include AP) associated with different transportation distances

### Effect of biomass MC on the total cost and the optimized operation system

The effect of biomass MC on the total cost was determined by changing the MC in a 5% increment (Fig. 4). In average, every 1% increase in biomass MC can result in \$760.68 increase in total cost after deducting AP. With every 5% decrease in biomass MC of the fresh harvested biomass, the total cost after deducting AP reduced by \$2976.29. On the other hand, when the biomass MC increases by 5%, 10%, and 15%, respectively, the total cost after deducting AP increases \$3439.78, \$4023.11, and \$4772.51, respectively. This shows the higher the biomass MC is, the higher increase in total cost will be. Therefore, the harvesting operations are suggested to take place in the late spring or summer when initial biomass MC tends to be lower to reduce the total cost.

Through the increase of biomass MC, more biomass is required to satisfy the same energy demand within four month. For different biomass MC, LRP is always the preferred way to store biomass mainly because it can produce higher quality biomass feedstock (Fig. 5). A 5% decrease in biomass MC from the base case can reduce the total biomass weight demand by 203.97 green tons. When the biomass MC increases from the base case to +5%, from +5% to +10% and from +10% to +15%, the total biomass weight demand raises by 235.66 green tons, 275.54 green tons and 326.75 green tons. In average, every 1% increase in biomass MC will raise the total biomass demand by 52.1 green tons.

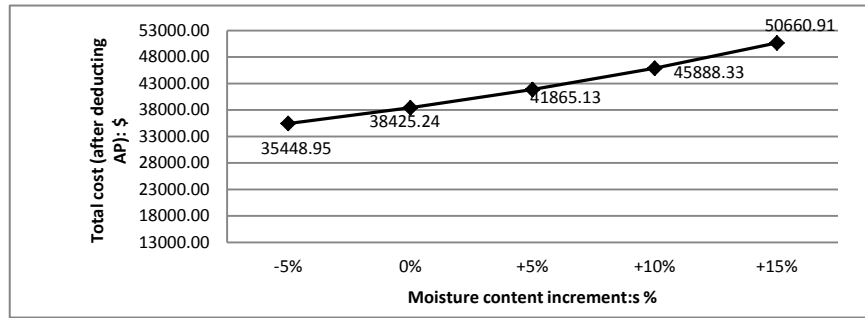


Figure 4. Total cost (after deducting AP) associated with different biomass MC

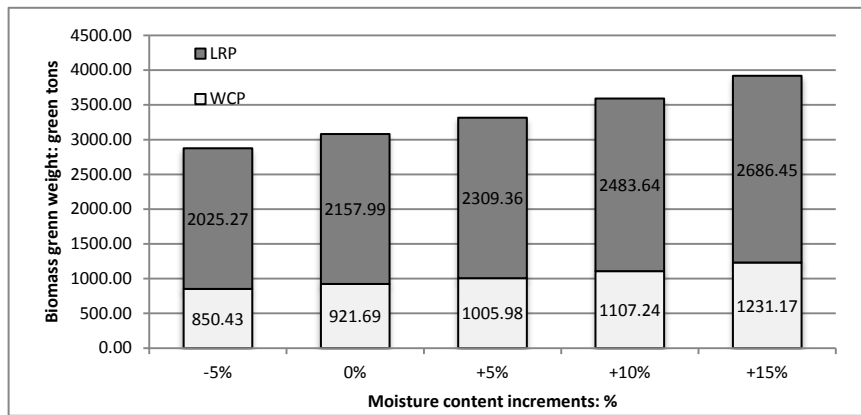


Figure 5. Storage strategy impacted by biomass MC change

## 5. Conclusion

An optimized operation system for biomass storage and transportation was generated using computer-based linear programming technique. The simulation results indicate when using logging residue pile as the major storage form, the extra costs of \$6089.70 due to piling and machine-moving operations can be offset by the \$22204.90 additional profits. In addition, because of the drier biomass achieved in the optimized operation system, the biomass required to satisfied the four-month energy demand is reduced by 684.32 green tons compared to the traditional operation system.

Sensitivity analyses were conducted to evaluate the effect of transportation distance and biomass MC on the optimized operation system and the total cost. The sensitivity analysis indicates transportation distance has no effect on the storage and transportation strategy and only affects the total cost by increasing the transportation cost. Every 1-mile increase in transportation distance will raise the total cost by \$168.77. The additional profit brought by higher quality biomass can offset the increased transportation cost for up to 151 miles. The changes in biomass MC affect both the optimized operation system and the total cost. This impact of biomass MC is concluded to be more significant when it is higher. In average, every 1% increase in biomass MC can result in \$760.68 increase in total cost. In addition, 1% increase in biomass MC will cause 52.1 green tons increase in total biomass green weight to satisfy the four-month energy demand.

In conclusion, this computer-aided optimized operations system can effectively minimize the total cost and improve the efficiency of biomass supply chain logistics while retaining the biomass fuel quality at a higher level.

## 6. References:

- Alam Md. Bedarul, Pulkki Reino, Shahi Chander, Thakur Prasad Upadhyay. 2012. Economic Analysis of Biomass Supply Chains: A Case Study of Four Competing Bioenergy Power Plants in Northwestern Ontario. ISRN Renewable Energy.
- Allen J, Browne M, Hunter A, Boyd J and Palmer H. 1998. Logistics management and costs of biomass fuel supply. *Int J Phys Distrib Logistics Manage* 1998; 28: 463–77.
- Barnes T. 2010. Existing Wood-Based Production and Logistics Infrastructure. MREP Bioenergy & Geothermal Committee Meeting. Michigan Public Service Commission, 6 October 2010, Traverse City Michigan.
- Berndes G, Hoogwijk M and Van Den Broek R. 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass Bioenergy* 2003, 25: 1–28.
- Bredström D., J. T. Lundgren, M. Rönnqvist, D. Carlsson, and A. Mason. 2004. Supply chain optimization in the pulp mill industry—IP models, column generation and novel constraint branches. *European Journal of Operational Research*, vol. 156, no. 1, pp. 2–22.
- Biomass Energy Resource Center. 2011. Wood boiler systems overview. [http://www.biomasscenter.org/images/stories/Wood\\_Boiler\\_Systems\\_electronic.pdf](http://www.biomasscenter.org/images/stories/Wood_Boiler_Systems_electronic.pdf)
- Biomass Power Association. U.S. Biomass Facilities Map. [http://usabiomass.org/docs/biomass\\_map.pdf](http://usabiomass.org/docs/biomass_map.pdf). Visit on September, 2014.



- Casal, M. D., Gil, M. V., Pevida, C., Rubiera, F. and Pis, J. J. 2010. Influence of storage time on the quality and combustion behaviour of pine woodchips. *Energy*, 35(7), 3066-3071.
- U.S. Department of Energy (DOE). 2014. 2014-2018 DOE Strategic Plan. [http://www.energy.gov/sites/prod/files/2014/04/f14/2014\\_dept\\_energy\\_strategic\\_plan.pdf](http://www.energy.gov/sites/prod/files/2014/04/f14/2014_dept_energy_strategic_plan.pdf)
- Dickmann, D. and L. A. Leefers. 2003. *The forests of Michigan*. University of Michigan Press.
- Eriksson, L.O. and R.W. Björheden. 1989. Optimal storing, transport and processing for a forest-fuel supplier. *European Journal of Operational Research* 43, pp. 26-33.
- IEA, 2013. International Energy Association (IEA) database. <http://www.iea.org>. Accessed on April 2015.
- Jager-Waldau A and Ossenbrink H. 2004. Progress of electricity from biomass, wind and photovoltaics in the European Union. *Renew Sustain Energy Rev* 2004;8: 157–82.
- Jirjis, R. 2005. Effects of particle size and pile height on storage and fuel quality of comminuted *Salix viminalis*. *Biomass and Bioenergy*, 28(2), 193-201.
- Lautala, P., R. Stewart, R. Handler and S. Chartier. 2012. Michigan Center of Energy Excellence Frontier Renewable Resources, Kinross Michigan Facility Biomass Transportation Systems Evaluation. <http://www.ncwrpc.org/NorthwoodsRail/wp-content/uploads/2014/04/COEE%20FINAL%20Report%20Draft%201-30-12.pdf>
- Lauri, P., Havlík, P., Kindermann, G., Forsell, N., Böttcher, H., and Obersteiner, M. 2014. Woody biomass energy potential in 2050. *Energy Policy*, 66, 19-31.
- Macmillan I. 2001. Biomass evaluation: including a case study on woodchip utilisation at ardverrick estate, Kinlochlaggan [M.S. thesis]. Department of Mechanical Engineering, University of Strathclyde, Glasgow, UK. [http://www.esru.strath.ac.uk/Documents/MSc2001/ian\\_macmillan.pdf](http://www.esru.strath.ac.uk/Documents/MSc2001/ian_macmillan.pdf).
- Maker, T. M. 2004. *Wood-chip heating systems. A guide for institutional and commercial biomass installations*.
- Mentzer J. T. 2001. *Managing the Supply Chain—Managerial and Research Implications*. Supply Chain Management, J. T. Mentzer, Ed., pp. 437–461, Sage, Thousand Oaks, Calif, USA.
- Gunnarsson H., M. Rönnqvist, and J. T. Lundgren. 2004. Supply chain modelling of forest fuel,” *European Journal of Operational Research*, vol. 158, no. 1, pp. 103–123.
- Panichelli L. and E. Gnansounou. 2008. GIS-based approach for defining bioenergy facilities location: a case study in Northern Spain based on marginal delivery costs and resources competition between facilities. *Biomass and Bioenergy*, vol. 32, no. 4, pp. 289–300.

- Ranta T. 2002. Logging residues from regeneration fellings for biofuel production—a GIS-based availability and supply cost analysis [Ph.D. thesis], Acta Universitatis Lappeenrantaensis 128, Lappeenranta University of Technology.
- Ranta T. 2005. Logging residues from regeneration fellings for bio-fuel production—a GIS-based availability analysis in Finland. *Biomass and Bioenergy*, vol. 28, no. 2, pp. 171–182.
- Rauch P. and M. Gronalt. 2010. The terminal location problem in the forest fuels supply network. *International Journal of Forest Engineering*, vol. 21, no. 2, 2010.
- Rentizelas A., Tolis A. and Tatsiopoulos I.P. 2009. Logistics issues of biomass: the storage problem and the multi-biomass supply chain. *Renewable & Sustainable Energy Reviews*, Vol. 13 (4), pp. 887-894.
- Rönnqvist M. 2003. Optimization in forestry. *Mathematical Programming* July 2003, Volume 97, Issue 1-2, pp 267-284.
- Sokhansanj S, Kumar A and Turhollow AF. 2006. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). *Biomass Bioenergy* 2006; 30: 838–47.
- Tahvanainen T. and A. Perttu 2011. Supply chain cost analysis of long-distance transportation of energy wood in Finland. *Biomass and Bioenergy*, vol. 35, no. 8, pp. 3360–3375.
- Tallaksen J. and Simo-Kush T. 2014. A Case Study in Planning a Renewable Energy Supply Chain: Part II Using Life Cycle Environmental Metrics to Select A Biomass Feedstock. 2014 American Society for Engineering Management Annual Conference, Virginia Beach, VA
- Yamamoto H, Fujino J, Yamaji K. 2001. Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model. *Biomass Bioenergy* 2001;21:185–203.
- Zamora, R. 2013. Economic Optimization of Forest Biomass Processing and Treatment. PhD. Oregon State University, 196 pp.
- W.A. Amos. Report on biomass drying technology. 1998. National Renewable Energy Laboratory, U.S.

# A Mathematical Approach to Biomass Feedstock Logistics Problems

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## Abstract

An important task in forest biomass recovery operations is to select the most cost-efficient feedstock logistics system, given spatial distribution of biomass, road access and available machinery. Notable constraints include inaccessibility of large chip vans to treatment units due to poor road conditions, and frequent, long-distance mobilization of forestry equipment caused by small amount of forest residues spatially dispersed across a large forested landscape. In this study, we attempted to optimize biomass feedstock logistics while taking into account the following options: (1) forwarding residues to a concentration yard where they are stored and ground directly into chip vans and (2) on-site grinding of forest residues and forwarding the ground materials to a concentration yard where the materials are stored and reloaded into large chip vans. A mixed integer programming model coupled with a network algorithm was developed to solve the problem efficiently. The solution includes grinder locations, slash forwarding, in-woods grinding, and chip van transportation operations that minimize the overall costs of forest residue processing and transportation. We present the mathematical model and an application of the model on a study site in southwestern Colorado.

**Keyword:** forest residues, feedstock logistics, mixed integer programming, network algorithm

## 1. Introduction

An important task in forest biomass recovery operations is to select the most cost-efficient feedstock logistics system, given the spatial distribution of biomass, road access and available machinery (Zamora-Cristales and Sessions 2013). Biomass feedstock logistics include all processes from harvesting to transportation operations used to deliver feedstocks to a utilization facility. On-site preprocessing, such as grinding, is usually required to improve transportation efficiency and deliver biomass at desired quality and particle size.

Grinding is often one of the most expensive operations due to high owning costs and low utilization rate of the grinder caused by frequent moves between processing sites. In-woods grinding also becomes inefficient when harvest or restoration treatment units are inaccessible to large chip vans due to narrow and winding forest roads. In such situations, smaller trucks must be used to haul the ground materials or forward unprocessed residues to a concentration yard where they are ground and loaded into large chip-vans. Unsurprisingly, each option involves additional handling costs that further prohibit extraction efforts. Possible alternatives should be analyzed to determine the most cost-efficient biomass feedstock logistics for given residue pile locations, road infrastructure and concentration yard locations.

The objective of this study is to develop a mathematical approach to minimize the overall cost of forest residue grinding and transportation operations across a large forested landscape. We attempt to optimize the biomass feedstock logistics for given harvest units where large chip van access is limited. We take into account the following options: (1) forwarding forest residues to a concentration yard where they are stored and ground directly into chip vans, and (2) on-site grinding of forest residues and forwarding the ground materials to a concentration yard where the materials are stored and reloaded into large chip vans. We refer to these two options as “slash forwarding” and “in-woods grinding”, respectively (Anderson et al. 2012). We also assumed that a grinder can be moved into any of individual landings or given concentration yards. If a grinder is located at a log landing, the landing is called as “concentration landing”. Residues at the landing will be ground and residues from nearby landings can be slash forwarded to the landing where the grinder resides to minimize move-in and move-out costs. In contrast, “concentration yard” is a larger scale, pre-determined area where slash as well as ground materials can be forwarded, stored and loaded onto large chip vans.

## **2. Problem Description**

We formulated the problem as a network problem and solved it using a mixed integer programming approach. We assumed there was a known quantity of forest residues at each landing which serves as an entry node in the network. For the slash forwarding option, the residue volume is forwarded to a nearby concentration landing or concentration yard, ground and transported to the facility. Links b and c in Figure 1 represent slash forwarding operations using small dump trucks. For the in-woods grinding option, the residues could be either processed at their current location (Link a) if the landing serves as a concentration landing, or processed at another landing location or a concentration yard after forwarding the slash. The

ground materials are then transported to nearby concentration yard using small dump trucks (Links d and e) or directly to the bioenergy facility (Links i and j), whichever becomes the least expensive option. All the ground materials stored at a concentration yard will be reloaded onto large chip vans for transportation to the final destination (Links f, g, and h). Different truck configurations and haul costs are used to represent truck transportation options, and appropriate fixed costs are considered for concentration landing and concentration yard to account for site construction and grinder mobilization costs.

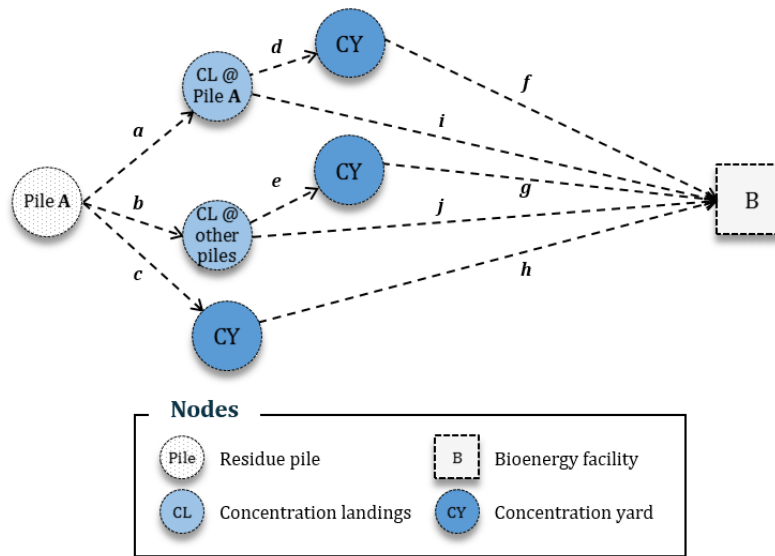


Figure 1. A hypothetical network diagram representing slash forwarding, in-woods grinding, and large chip van transportation options.

### 3. Mathematical Formulation

The network,  $B = (N, L)$ , consists of a set of nodes,  $N$ , representing residue piles, concentration landings, concentration yards and bioenergy facility, and a set of directed links,  $L$ , representing transportation operations with different truck configurations. We used the shortest path algorithm to pre-calculate the least cost routes from the possible pairs of entry and destination nodes existing in the network. These routes are then embedded into the mixed-integer formulation to reduce problem complexity by limiting the number of possible routes. Costs associated with each link in the network are calculated based on bone dry tons (BDT). The sets, decision variables, and parameters of the model are given in Table 1.

Table 1. Sets, decision variables, and parameters of the optimization model.

Sets	
$C$	Set of concentration yards
$K$	Set of bioenergy facilities
$L$	Set of links in the network
$N$	Set of nodes
$P$	Set of material types (slash or ground residue)
$S$	Set of processing equipment system
$R_{uv}$	Set of road segments included in the shortest path from $u$ to $v$
$T$	Set of truck options
$W$	Set of intermediate nodes that are not a residue pile or a bioenergy facility
$Z$	Set of residue pile locations
Decision Variables	
$X_{ij}^{tp}$	Flow (BDT) of material type $p$ transported using truck $t$ on link $ij$
$Y_{kl}$	0, 1 integer variable over road segment $kl$ used for grinder mobilization
$D_u^c$	0, 1 integer variable if location $u$ is used for concentration yard
$D_u^d$	0, 1 integer variable if location $u$ is used for concentration landing
Parameters	
$cp_{ij}^{sp}$	Variable processing cost of system $s$ at location $i$ (\$/BDT)
$ct_{ij}^{tp}$	Variable transportation cost of transporting material $p$ with truck $t$ on link $ij$ (\$/BDT)
$cm_{kl}$	Move-in cost of grinder mobilization on road segment $kl$ (\$)
$cc_u^c$	Consturction cost for consentration yard at location $u$ (\$)
$cc_u^d$	Consturction cost for consentration landing at location $u$ (\$)
$n_{uv}$	Number of road segments included in shortest path from $u$ to $v$
$r_{min}$	Minimum required dry weight of biomass (BDT)

The mathematical formulation of the model is as follows:

$$\text{Min } Z = \sum_{ij \in L} \sum_{kl \in N} \sum_{s \in S} \sum_{p \in P} \sum_{t \in T} (cp_{ij}^{sp} + ct_{ij}^{tp}) \cdot X_{ij}^{tp} + cm_{kl} \cdot Y_{kl} + cc_u^c \cdot D_u^c + cc_u^d \cdot D_u^d \quad (1)$$

subject to:

$$\sum_{j \in L} X_{ij}^{tp} - \sum_{j \in L} X_{ji}^{tp} = \begin{cases} z_i^p & i \in Z(p) \\ -k^p & i \in W(p) \\ 0 & i \in N \end{cases} \quad \forall i \in N, \forall p \in P, \forall t \in T \quad (2)$$

$$M \cdot D_u^c \geq \sum_{u \in C} X_{uv}^{tp} \quad \forall v \in K, \forall p \in P_{grindings}, \forall t \in T \quad (3)$$

$$M \cdot D_u^d \geq \sum_{u \in Z} X_{uv}^{tp} \quad \forall v \in C \cup K, \forall p \in P_{grindings}, \forall t \in T \quad (4)$$

$$\sum_{kl \in R_{uv}} Y_{kl} \geq n_{uv} \cdot D_u \quad \forall v \in K \quad (5)$$

$$\sum_{i \in L} X_{ij}^{tp} \geq r_{min} \quad \forall j \in K, \forall p \in P, \forall t \in T \quad (6)$$

$$D_u, Y_{kl} = \{0,1\} \quad \forall_{klu} \in N \quad (7)$$

$$X_{ij}^{tp} \geq 0 \quad \forall_{ij} \in L, \forall p \in P, \forall t \in T \quad (8)$$

#### 4. Application and Results

The mathematical model was applied to a part of the Uncompahgre National Forest in Colorado. It was estimated that a total of 60,000 BDT of forest residues were available in the study area from 350 log landings. There were two locations identified as possible concentration yards. Road network data were developed with road segments that connect individual log landings to the final bioenergy facility located approximately 12 miles southwest of the study area. The biomass processing equipment fleet includes a horizontal grinder, short dump trucks for forwarding slash and ground materials, loaders, and large chip vans for long distance transportation.

Table 2 shows the summary of equipment and their associated costs used in this study. The machine rate calculations were based on methods in Fight et al. (2003). The productivity of each machine and truck capacity data were adapted from Anderson et al. (2012). The transportation costs were calculated considering the least cost route based on engineered road speed and truck capacity (Wells 2013).

Table 2. List of machines and their cost in the slash forwarding and in-woods grinding operations.

Configuration/machine	Machine rate (\$·SMH <sup>-1</sup> )	Productivity <sup>a</sup> (BDT·SMH <sup>-1</sup> )	Truck capacity <sup>a</sup> (BDT)	Cost (\$·BDT <sup>-1</sup> )
<b>Slash forwarding</b>				
Grapple loader (Caterpillar 322B LL)	82.77	45.72	-	1.81
End-dump trailer	44.78	-	4.60	Calculated
Grapple loader (Caterpillar 325 LL)	92.97	43.43	-	2.14
Horizontal grinder (Peterson 7400)	242.43	41.18	-	5.89
Chip van	87.17	-	23.40	Calculated
<b>In-woods grinding</b>				
Grapple loader (Caterpillar 322B LL)	82.77	27.25	-	3.04
Horizontal grinder (Peterson 4710B)	227.65	26.71	-	8.52
Dump truck	43.56	-	6.83	Calculated
Front-end loader (Caterpillar 966D)	73.18	62.85	-	1.16
Chip van	87.17	-	23.40	Calculated

<sup>a</sup>Adapted from Anderson et al. (2012)

The optimal solution for processing all the residues in the study site indicated that two concentration yards and three concentration landings are to be constructed (Figure 2). Approximately 70% of the total processed residues are transported to the bioenergy facility through concentration yard CY2. Small amounts of forest residues (i.e., slash) forwarded to two concentration landings (CL1 and CL2) located near the exits of the study area are to be delivered directly to the bioenergy facility by short trucks without being transferred to a chip van at a concentration yard. It is noteworthy that another concentration landing CL3 is selected as a grinding location because a large amount of biomass volume (22,224 BDT) warrants improving transportation efficiency.



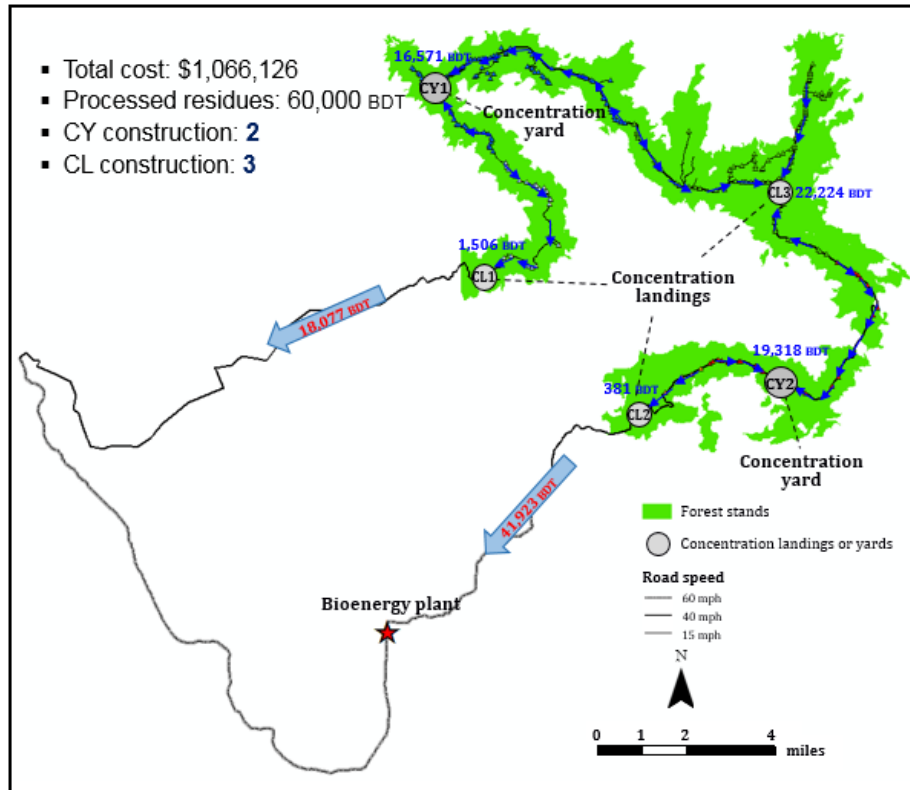


Figure 2. Optimal solution found from the application problem presenting biomass quantity and flow, and selected concentration landings and concentration yards.

## 5. Conclusions

We applied a mixed-integer approach to a biomass feedstock logistics problem where the most cost-efficient grinder locations, slash forwarding, in-woods grinding, and chip van transportation operations need to be determined. We embedded pre-run network solutions into the mixed-integer formulation to solve the challenging problem more efficiently. Further studies will apply this conceptual model to larger landscapes with more realistic settings to demonstrate its applicability and utility in biomass utilization logistics. Forest residues are underutilized due to high processing and transportation costs relative to their value. We hope this study will help improve the efficiency of forest biomass logistics, one of the solutions that make forest biomass utilization economically viable.

## 6. Acknowledgments

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## 7. References

- Anderson, N., W. Chung, D. Loeffler, and J.G. Jones. 2012. A productivity and cost comparison of two systems for producing biomass fuel from roadside forest treatment residues. *For. Prod. J.* 62(3):222-233.
- Fight, R.D., X. Zhang, and B.R. Hartsough. 2003. Users guide for STHARVEST: software to estimate the cost of harvesting small timber. USDA For. Serv. Gen. Tech. Rep. PNW-GTR-582. 12 p.
- Flisberg, P., M. Frisk, and M. Rönnqvist. 2012. FuelOpt: A decision support system for forest fuel logistics. *J. Oper. Res. Soc.* 63(11):1600-1612.
- Wells, L.A. 2013. Spatial distribution and quantification of forest treatment residues for bioenergy production. M.Sc. thesis, Univ. of Montana, Missoula, MT, USA. 107 p.
- Zamora-Cristales, R., and J. Sessions. 2013. RENO: A computerized solution procedure and decision support system for forest biomass recovery operations. In *Proc. of the 36th Annual Meeting of Council on Forest Engineering*, Dodson, B. (ed.).
- Zamora-Cristales, R., J. Sessions, K. Boston, and G. Murphy. 2015. Economic optimization of forest biomass processing and transport in the Pacific Northwest USA. *For. Sci.* 61(2):220-234.
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# Estimating Bioenergy Feedstock Supply and Delivered Costs

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Forest restoration treatments often target low-value, small diameter trees to meet a range of ecosystem-based objectives. These treatments have the potential to produce large quantities of forest residues that are commonly disposed of by on-site burning. Growing interests in the use of these residues has resulted in the development of increasingly efficient conversion technologies to produce energy and bio-based products from forest biomass. However, current methods to estimate feedstock supply and the associated costs of processing and transport on both small and large landscapes are limiting. In this study, we present a new methodology to facilitate spatially explicit estimation of treatment residue volumes across forested landscapes of arbitrary size and locale. An automated stand delineation algorithm was developed to define treatment unit boundaries based on patterns of vegetation in digital aerial photography. A remote sensing model employing digital imagery and FIA plot data was used to attribute treatment units with stand-level descriptions of basal area, tree density, above ground biomass, and quadratic mean diameter. These methods were applied to a 235,000 ha study landscape in southwestern Colorado to assess the quantity and distribution of treatment residue for use in bioenergy production at a nearby facility.

**Keywords:** forest biomass, treatment residue, bioenergy, delivered costs

## 1. Introduction

In recent years the interior west of the United States has experienced growing interests in using forest biomass as a renewable source of energy. Historically, the use of forest biomass has been dominated by the forest products industry for generating heat, steam, and electricity (Guo et al., 2007). However, emerging markets for forest biomass as a fuel and feedstock for

bioenergy applications can be found throughout the U.S. Interests in these potential and emerging markets are closely linked to the increasing risk of significant forest disturbances, such as fire, insects and disease, and by the broad agreement that silviculture using active treatments, including thinning and prescribed fire, is urgently needed to restore historic stand dynamics and improve forest health (Brown et al., 2004). The large potential treatment area throughout the western U.S. presents opportunities to increase the use of renewable energy sources and stimulate local economic development with new bioenergy and bio-based products enterprises that will use the woody biomass byproducts produced by these treatments.

In the 15 Western States there are at least 11 million hectares (ha) that could benefit from some type of treatment to restore healthy ecosystems, protect water and soil quality, and improve forest and rangeland resilience (Rummer et al., 2003). Assuming such management occurs only on forests with annual timber production of at least 21 m<sup>3</sup> ha<sup>-1</sup> per year, an estimated biomass availability of 245 million dry tonnes (t) could result from forest treatments on 4.3 million ha in the west (Western Governors' Association, 2005). The U.S. Department of Energy and USDA Forest Service estimated that an annual supply of 907 million t of biomass would displace 30% or more of domestic petroleum consumption. Of this amount, the continental U.S. could potentially produce 429 million t at \$54.43 t<sup>-1</sup> from forest residue and agricultural waste (US DOE, 2011).

Although national and regional scale assessments of biomass availability suggest a promising future for forest biomass utilization, many questions remain unanswered. The availability of biomass at tactical and operational scales relies on many factors such as current biomass stocks, harvesting systems, terrain, road network, species, forest characteristics, silviculture, ownership, public policy and regulation, local markets and management objectives. These factors are often ignored in large-scale forest biomass supply models that focus on biomass stocks due to the complexity of forest landscapes and the difficulty in modeling spatial and temporal details of forest management activities. There is a need for an integrated framework to provide realistic forest biomass supply and cost of feedstock across a large landscape at tactical resolution that takes into account forest inventory, existing infrastructure, and current forest management objectives applied across multiple scales and time frames.

The focus of this study is to quantify and spatially describe delivered feedstock volumes and costs for multiple management scenarios across landscapes of arbitrary size in ways that characterize operational and annual management decision making. We use state-of-the-art remote sensing and image processing techniques to produce forest stand boundaries and stand descriptive statistics. These outputs are coupled with site specific silvicultural prescriptions across large landscapes to estimate retention, merchantable yield and resulting recoverable

biomass residue volumes that can be transported and used for energy and bio-based products. This approach generates data and information that provide a foundation to evaluate forest biomass utilization at strategic, tactical and operational scales through space and time for alternative treatment scenarios. These methods are applied to a forested landscape in southwestern Colorado to estimate delivered feedstock volumes and costs following currently implemented site specific management regimes.

## 2. Methods

### 2.1 Study site

The study area includes the extent of the Uncompahgre Plateau National Forest (UPNF). The UPNF covers approximately 235,000 ha on the west slope of the Colorado Rocky Mountains (Figure 1). Stretching northwest to southeast for 200 kilometers (km), the plateau ranges in elevation from 1,700-1,800 m in canyon bottoms to upland elevations around 2,500-3,000 m. Three primary vegetation strata occupy the plateau. Pinyon-juniper (*Pinus edulis*, *Juniperus osteosperma*, *Juniperus scopulorum*) cover occurs at the lower elevations ranging from 1,800 to 2,100 m, Gambel oak and Ponderosa pine (*Quercus gambelii*, *Pinus ponderosa*) forests inhabit elevations from 2,200 to 2,700 m and occur in both mixed and pure stands. The upland zone is dominated by aspen (*Populus tremuloides*), mixed-conifer and spruce-fir (*Picea engelmannii*, *Abies lasiocarpa*) forests.

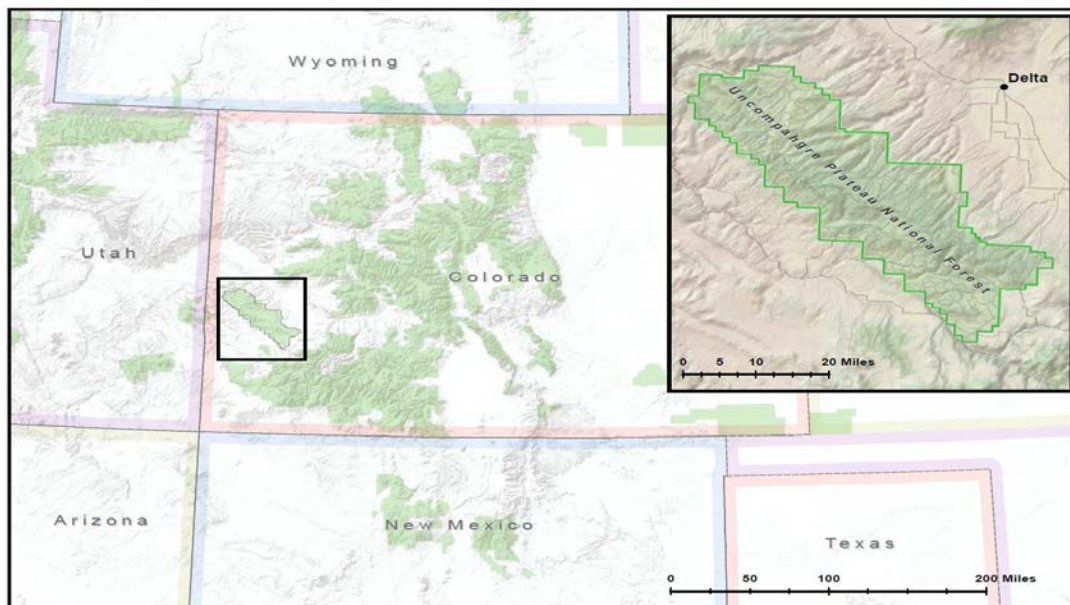


Figure 1: Study site: Uncompahgre Plateau National Forest in southwestern Colorado

Approximately 70% of the UPNF is in fire regime condition class 2 or 3 (Hardy et al., 2001; Schmidt et al., 2002) suggesting that these areas exhibit fuel conditions that are conducive to uncharacteristic, high intensity fires. The potential for these disturbance events have initiated active restoration management across the plateau to reduce fuel loading in mixed-conifer and Ponderosa pine, increase diversity in age, size and seral conditions in spruce-fir, regenerate damaged aspen stands from sudden aspen decline, and mitigate pinyon-juniper encroachment into native grasslands and sagebrush ecosystems.

## **2.2. Imagery**

Imagery of the National Agricultural Imagery Program (NAIP) was used to estimate forest characteristics and define potential treatment units. NAIP acquires aerial digital orthophotos during the agricultural growing seasons and the imagery is publicly available within a year of acquisition. The imagery has a 1 m ground sample distance (1 m spatial resolution) with a horizontal accuracy of within 6 m at a 95% confidence level (USDA-FSA- APFO, 2011) and a temporal resolution of 2 to 5 years. The default spectral resolution is natural color (RGB) with an option to include the near infrared band. The configuration used in this study was a 3 band composite including near infrared, green and blue bands (Color-infrared).

## **2.3. Stand delineation**

An automated segmentation algorithm (Wells, 2014), or so called Stand Delineation Algorithm (SDA), was developed in this study to delineate forest landscapes into operational-level treatment units. The SDA employs a series of image filtering techniques and the mean-shift algorithm (Fukunaga and Hostetler, 1975) to decompose NAIP imagery into individual forest stands which are defined in silviculture as “a contiguous group of trees sufficiently uniform in age-class distribution, composition and structure, and grown on a site of sufficiently uniform quality to be a distinguishable unit” (Helms, 1998). These processes are embedded in a subspace, multi-scale framework to circumvent computational limitations associated with large scenes of high resolution imagery. The algorithm uses USGS 12 digit hydrological unit boundaries (sub-watersheds) as initial subspace geometries. New geometries created by the segmentation process within each sub-watershed are stored in a vector database and used to further subset the image in the next iteration. As objects become smaller, finer resolutions are used for segmentation locating features that may not be visible at coarser scales. The algorithm

can also be parameterized to comply with minimum and maximum treatment unit area constraints. Minimum and maximum treatment unit area constraints for the study area were 2 and 40 ha respectively.

#### **2.4. Stand characteristics**

Stand characteristics such as basal area, tree density, and above ground biomass are estimated for each treatment unit using the Forest Characteristics Model (FCM) (Hogland et al., 2014). The FCM is a two-tiered remote sensing model where the first stage performs a probabilistic classification of identifiable patterns (e.g. tree canopy, shadow, grass, or water) within NAIP imagery. The classification is the result of a polytomous logistic regression scheme employing a collection of texture derivatives of the imagery as explanatory variables. The classification output and texture derivatives of the classification are then summarized for the spatial extent of a FIA field plot and related to plot estimates of basal area, tree density, and above ground biomass using multivariate linear regression. The result is a multiband raster dataset where each pixel (1 m<sup>2</sup>) represents mean plot estimates of forest characteristics for each species group. Above ground biomass estimates are derived from equations found in Jenkins et al. (2003) and thus can be used to calculate stump, bole, top, and foliage biomass components. Quadratic mean diameter (cm) is added to the dataset post hoc by  $[BA/(k \times n)]^{1/2}$  where BA is basal area (m<sup>2</sup> ha<sup>-1</sup>), n is tree density (stems ha<sup>-1</sup>), and k = 0.00007854 (foresters constant).

#### **2.5. Modeling silvicultural prescriptions**

Three quantifiable silvicultural prescriptions were developed to model removal and retention of biomass on candidate treatment units. Prescriptions were 1) stocking-based thinning, 2) aspen regeneration, and 3) restoration in Ponderosa pine and applied to spruce-fir, aspen/aspen-pine, and Ponderosa pine respectively [see Wells (2013) for more information on prescription development]. These prescriptions are generalized and adapted from the current forest plan for the Uncompahgre National Forest (UPNF Current Forest Plan, 2012) and from a management plan assembled by the Uncompahgre Plateau Collaborative Restoration Project (UPCRP). Management planning documents provided detailed information regarding current conditions, including problems with forest health, reference conditions, and desired future conditions. Stands that are assigned a silvicultural prescription are a subset of the accessible treatment units (stands within 610 m of existing roads, or assumed skidding distance) and

classified as candidate treatment units, which are defined as stands that are included in the selection pool as potential treatment units but may or may not receive treatment under a given scenario.

$$TR = (B_{ag} - B_{sr}) \left( 1 - \left( \text{Exp}(\beta_0 + \frac{\beta_1}{D_q}) \right) \right) r$$

## 2.6. Treatment residue

Residue was estimated for each candidate treatment unit by first subtracting the removed biomass from the total above ground biomass then subtracting gross merchantable yield. The amount of removed biomass was determined by the silvicultural prescription, and the gross merchantable yield was calculated by using a component ratio estimator for stem wood and stem bark based on quadratic mean diameter and tree length from a 30 cm stump to a 10 cm top diameter (Jenkins et al., 2003). Total treatment residues were reduced by 30% to account for leakage during transport from stump to landing and the recovery rate of the residue at the landing. Equation 1 was used to calculate treatment residue (TR) where  $B_{ag}$  is above ground biomass,  $B_{sr}$  is silviculturally retained biomass (biomass units in dry tons per hectare),  $\beta_0$  and  $\beta_1$  are the species-specific component ratio coefficients for stem wood and stem bark,  $D_q$  is the quadratic mean diameter for the stand and  $r$  is the reduction factor of leakage and recovery rates (0.7). Residue extraction was assumed to take place after the removal of the commercial component and residue was allowed time to dry to a moisture content of 30% (Han et al., 2010).

## 2.7. Operations costs

The harvesting system for each treatment was assumed to be mechanical felling with a feller-buncher followed by whole-tree skidding where the tops and limbs of the removed trees were transported with the bole to a road side landing designated for each unit. The extraction operation was assumed to be road-side processing and biomass grinding since all candidate treatment stands were selected to be within the maximum skidding distance of 610 m to unit centroid from the existing road network. A marginal cost approach was used to calculate forest operations costs (Puttock, 1995). This approach considers biomass to be a byproduct of the production of higher value products such as sawlogs, and fully allocates harvest costs of felling, extraction, processing, road construction, and stumpage to these products. Therefore the costs begin accruing with the collection of residues at the roadside. Handling, processing and loading



costs for residues were calculated following methods from Anderson (2011) by averaging the results from 40 scientific studies examining biomass removal from timber harvest, fuel treatments, and other residue related operations resulting in \$31.14 t<sup>-1</sup>.

Transportation costs (\$ t<sup>-1</sup>) were calculated for each candidate treatment unit and optimized round trip delivery times from each unit to the potential bioenergy facility were calculated using a GIS coverage of all UPNF roads. A non-spatial transportation network optimization program was used to determine the least cost route for each unit based on engineered road speed (Chung and Sessions, 2003). Other variables used to calculate transportation costs were load time and unload time each assumed to be 0.5 hr, non-fuel trucking (operator) cost set at \$48.03 hr<sup>-1</sup> (ATRI, 2013), a specialized trucking premium of \$12.00 hr<sup>-1</sup>, \$1.04 L<sup>-1</sup> for diesel fuel price (US EIA, 2013), average fuel economy of 1.98 km L<sup>-1</sup>, average truck speed (km hr<sup>-1</sup>) which depends on the engineered road speed of the shortest path distance for each unit, lubrication price set at 10% of the diesel fuel price assumed to correlate perfectly with diesel fuel price, van capacity of 27.22 t, and biomass moisture content of 30%.

## **2.8. Feedstock volume and delivered costs**

A 10 year management simulation was carried out to estimate delivered feedstock volume and costs under current site specific management objectives. For each year in the simulation a set of treatment units were selected and the residue volume and delivered feedstock costs for each treatment unit were calculated and stored. The selection of units in the simulation was based on a prioritization scheme which placed higher importance on stands that needed treatment according to the characteristics of the stand and the assigned silvicultural prescription metrics. The annual treatment area constraint was set according to a management planning documents developed by the US Forest Service and UPCR. Stocking-based prescriptions were constrained to 850 ha yr<sup>-1</sup>, aspen regeneration prescriptions constrained to 587 ha yr<sup>-1</sup>, and pine restoration constrained to 445 ha yr<sup>-1</sup> totaling to 1882 ha yr<sup>-1</sup>. Once a unit was selected for treatment it was no longer considered a candidate treatment unit for the duration of the simulation. The annual delivered volumes and costs were calculated for each prescription designation.

### 3. Results

Operations costs were calculated for all accessible stands across the study area. These costs represent handling, processing and loading cost as well as round trip transportation cost to the bioenergy facility. The distribution of operations costs was bell shaped and range from \$34.77 t<sup>-1</sup> to \$51.13 t<sup>-1</sup> with a mean of \$42.57 t<sup>-1</sup>. These costs correlate perfectly with travel distance to the bioenergy facility since in-woods operations costs were fixed.

Figure 2 displays outputs from the remote sensing model and management simulation. Figure 2.a shows the distribution of above ground biomass (agb) across the accessible treatment units where blue is low agb and red is high. 13,887 stands of the total 25,538, or 54% of the total area, were considered accessible stands for treatment. These stands are represented by the gray area in Figure 2.b and 2.c. Figure 2.b shows units that are considered candidate treatment units in the simulation. The remaining accessible stands were given a “no treatment” prescription because they 1) currently meet desired future conditions, 2) are in early seral stage, or 3) are composed of a species group that is not targeted or has high biomass logistics costs. These stands totaled to 46,840 ha with 20,228 ha, 8,102 ha and 18,510 ha in stocking-based, regeneration and restoration respectively. Although candidate treatment units composed 20% of the total area, the above ground biomass within these stands included 30%, or 5,936,049 t of the total 20,126,833 t on the landscape. This was due to the silvicultural prescriptions targeting over-stocked mixed-conifer, pine, and aspen stands that naturally have high above ground biomass relative to other forest types occupying the study area. The units that are selected to be treated in the simulation are shown in Figure 2.c.

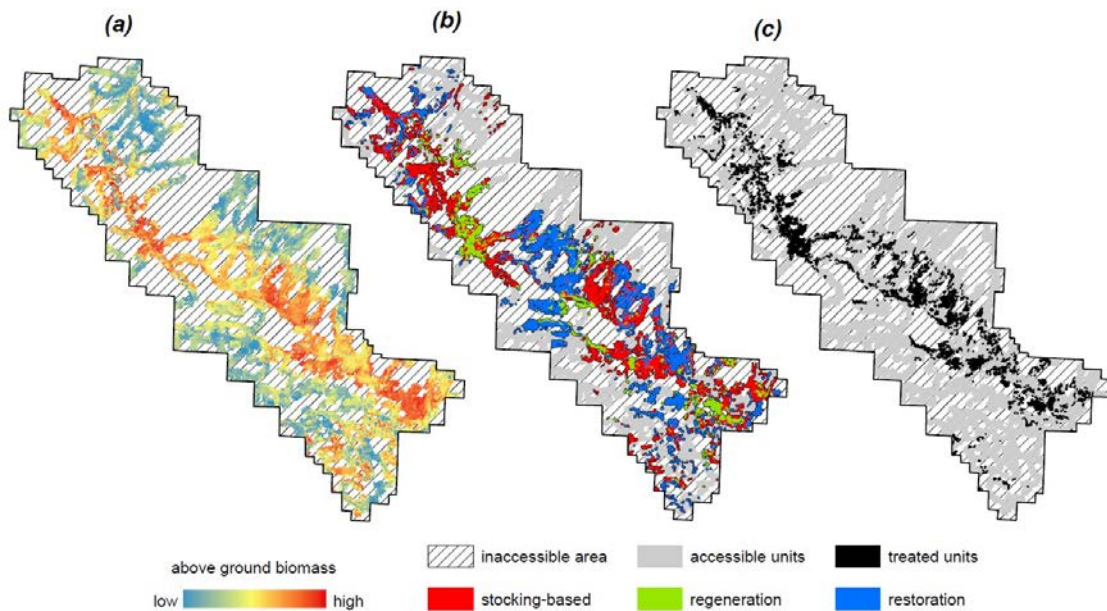


Figure 2: Maps illustrating model outputs. (a) Distribution of above ground biomass across the study area, (b) candidate treatment units by silvicultural prescription, (c) units selected for treatment.

The 10 year management simulation resulted in 18,564 treated ha and 463,727 t of available treatment residue. Year 6 had the largest range of delivered costs of \$34.18 to \$50.91 t<sup>-1</sup>. The lowest average delivered costs was \$42.02 t<sup>-1</sup> during year 2 and the highest during year 10 at \$42.98 t<sup>-1</sup>. The average delivered cost for the 10 year simulation was \$42.54 t<sup>-1</sup>.

Table 1: Area treated, pretreatment above ground biomass, removed biomass, treatment residue, and available feedstock per year.

Year	area	agb	removed	residue	feedstock
1	1,861	392,094	193,936	73,851	51,696
2	1,827	354,698	191,331	73,060	51,142
3	1,870	337,680	184,988	70,060	49,042
4	1,832	317,217	178,741	67,721	47,405
5	1,874	311,540	181,018	68,600	48,020
6	1,867	294,931	174,711	66,021	46,215
7	1,874	277,972	165,494	62,355	43,649
8	1,867	265,062	160,152	60,196	42,137
9	1,836	257,877	160,792	60,622	42,434
10	1,856	239,137	158,033	59,983	41,988

Table 1 shows results from the 10 year management simulation. The outputs from the simulation included area treated during each year and components of the cumulative biomass volumes for the treated area. Components include above ground biomass, representing the total biomass in the treated area prior to the intervention, the amount of biomass removed by the treatment, estimated merchantable volume, total treatment residue (removed minus merchantable) and the amount of recoverable residue at the landing (feedstock).

Table 2: Area treated and treatment residue at each delivered costs category

delivered cost (\$ t <sup>-1</sup> )	Area (ha)	Feedstock (t)
< 40	3,153	56,924
40 – 45	25,627	524,154
45 – 50	14,915	321,812
> 50	3,144	58,015

Table 2 shows categorized delivered costs for all candidate treatment units. Nearly 55% (524,154 t) of the residues within the candidate treatment area are available at \$40- 45 t<sup>-1</sup> and roughly 33% (321,812 t) of residues are available at \$45-50 t<sup>-1</sup>.

#### 4. Discussion

Although the area constraints were held constant throughout the simulation, the available residue generally decreased over the 10 year period (table 1). This was a result of treatment prioritization targeting higher stocked stands in the beginning of the simulation. It is worth noting that this decreasing trend is likely to persist if the simulation is continued for a longer planning horizon. This is in part due to the absence of forest growth in the presented methodology, however it is primarily attributable to the treatment prioritization schemes that were based on ecological goals: restorative management regimes that target overstocked stands tend to produce large amounts of treatment residue including non-merchantable small-diameter trees. The long-term management goal of restoration means that more acres of forest will be changed from current overstocked conditions to a state that more closely represents historic reference conditions, especially if periodic low-intensity natural and prescribed fires are used as a management tool to maintain understory conditions where appropriate. It is expected that available residue volumes will continue to decrease as the forests approach desired future conditions.

These results can be used to prioritize treatments early on in the development of a bioenergy supply chain to initiate markets by allocating efforts to residues available at relatively low costs. As markets develop, managers can begin to incorporate the acreage allocation constraints to meet forest-wide desired future conditions. Potential end users can use this information to evaluate feedstock prices that would result in different levels of feedstock supply and production.

## **5. Conclusion**

The integration of the stand delineation algorithm and the forest characteristics model coupled with site specific silvicultural prescriptions and operational planning presents the opportunity to carry out detailed spatial analysis for a diverse array of resources on very large landscapes. As demonstrated in this study, the methodology can be employed to assess the feasibility of biomass utilization, assist silvicultural decisions, and facilitate operational planning at strategic, tactical, and operational scales. The ability to not only estimate residue quantities, but also map the spatial distribution of stand-level residues following alternative management regimes is an essential tool in areas with limited history of industrial biomass utilization and uncertainties in biomass markets. This information is useful to stakeholders across the biomass supply chain, including land managers, contractors, and end users.

Research is still needed to fill the knowledge gap regarding residue leakage from stump to landing and recovery rates at the landing, as well as site specific forest operations costs. Although this study assumed a 70% reduction rate to account for stump to landing leakage and recovery at the landing, this can vary significantly depending on species, time since harvest, level of stand mortality, and other variables. An improved model would incorporate forest growth in temporal simulation, allowing more accurate estimates well beyond the 10-year time frame used in this study. This improvement would broaden the planning horizon to better understand the sustainability of biomass flows, as well as the long-term viability of supplying bioenergy and biofuels facilities with biomass from forest restoration treatments. Future studies could use this methodology to optimally locate bioenergy facilities in the region in ways which would reduce feedstock procurement costs, and determine the scale at which they could operate sustainably and in balance with forest management regimes that meet a broad range of social, economic and ecological objectives.

## 6. Acknowledgments

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## 7. References

- R.T. Brown, J Agee, and J. Franklin. Forest restoration and fire: principles in the context of place. *Conservation Biology*, 2004.
- W. Chung and J. Sessions. Network 2000: a program for optimizing large fixed and variable cost transportation systems. in *Proc. of the Eighth Symposium on Systems Analysis in Forest Resources*, Arthaud, G.J., 2003.
- Fukunaga and Hostetler. The estimation of the gradient of a density function, with applications in pattern recognition. *IEEE Transactions on information theory*, 1975.
- Z. Guo, C. Sun, and D.L. Grebner. Utilization of forest derived biomass for energy production in the U.S.A.: status, challenges, and public policies. *International Forestry Review*, 2007.
- H. Han, J. Halbrook, F. Pan, and L. Salazar. Economic evaluation of a roll-off trucking system removing forest biomass resulting from shaded fuelbreak treatments. *Biomass and Bioenergy*, 2010.
- C. Hardy, K. Schmidt, J.P. Menakis, and R. Sampson. Spatial data for national fire planning and fuel management. *International Journal of Wildland Fire*, 2001.
- J.A. Helms. *The dictionary of forestry*. Society of American Foresters, 1998.
- J. Hogland, N.M. Anderson, W. Chung, and L.A. Wells. Estimating forest characteristics using naip imagery and arcobjects. *Proceedings of the 2014 ESRI Users Conference; July 14-18, 2014, San Diego, CA*. Redlands, CA: Environmental Systems Research Institute., 2014.
- J. Jenkins, D. Chojnacky, L. Heath, and R. Birdsey. Nation-scale biomass estimators for united states tree species. *Forest Science*, 2003.
- G. Puttock. Estimating cost for integrated harvesting and related forest management activities. *Biomass and Bioenergy*, 1995.
- B. Rummer, J. Prestemon, D. May, P. Miles, J. Vissage, R. McRoberts, G. Liknes, W.D. Shepperd, D. Ferguson, W. Elliot, S. Miller, S. Reutebuch, J. Barbour, J. Fried,

B. Stokes, E. Bilek, and K. Skog. A strategic assessment of forest biomass and fuel reduction treatments in Western States. USDA Forest Service, Research and Development, 2003.

K. Schmidt, J.P. Menakis, C. Hardy, W. Hann, and D. Bunnell. Development of coarse-scale spatial data for wildland fire fuel management. U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station. Gen. Tech. Rep., 2002.

US DOE. Us billion-ton update: biomass supply for a bioenergy and bioproducts industry. Oak Ridge National Laboratory, 2011.

USDA-FSA-APFO. National Agricultural Imagery Program. U.S. Department of Agriculture Farm Service Agency - Aerial Photography Field Office. Salt Lake City, Utah, 2011.

L.A. Wells. Spatial distribution and quantification of forest treatment residues for bioenergy production. Thesis, College of Forestry and Conservation, University of Montana, 2014.

Western Governors' Association. Western regional biomass energy program. [www.westgov.org/wga/initiatives/biomass/](http://www.westgov.org/wga/initiatives/biomass/), 2005.

## VIII. Concurrent Session 3A – Logging Operations and Site Disturbances

### **An Approach for Estimating Erosion from Stand Level Forest Operations in the Southeastern United States Piedmont Physiographic Region**

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Since passage of the Federal Water Pollution Control Act of 1972, states have developed and implemented forestry best management practices (BMPs) to protect water quality during and after forest operations. Forestry BMPs in the southeastern United States are typically non-regulatory although some states have a hybrid of both non-regulatory and regulatory BMPs. Studies have shown that forestry BMPs are effective if implemented properly. Evaluations of BMP effects on erosion and sediment are typically conducted by researchers using direct measures of erosion, erosion models, or in stream sediment samples and relatively few studies have evaluated sediment control improvement attributable to operational categories of BMPs. Our goal was to develop a simple approach using an excel spreadsheet to estimate erosion that occurs from forest operations in the Piedmont physiographic region that could also be used by forest managers to identify areas of where alternative BMPs might be beneficial. Erosion and sediment delivery ratios were estimated based on only two previous estimates from the Piedmont physiographic region. No new data was collected, rather we used erosion estimates associated with specific BMP categories such as timber harvesting, forest roads, skid trails, log decks, stream crossings, SMZs, prescribed burning, mechanical site preparation, and chemical site preparation. We also used previous research that reported erosion and sediment delivery with and without BMPs implemented on forest operations. Such information should be beneficial to forest managers, landowners, and agency personnel with limited research resources who wish to estimate the effects of various BMP implementation rates.

**Keywords:** Erosion, sediment, forestry best management practices, Piedmont

#### **1. Introduction**



Forestry BMPs were formulated due to the passage of the Federal Water Pollution Control Act (FWPCA) of 1972 and its subsequent amendments. Section 208 of the FWPCA required states to establish forestry BMPs for silvicultural operations to control nonpoint source pollution (NPSP) associated from these operations (Phillips and Blinn 2004, Grace 2005). NPSP is associated with surface runoff which occurs during rainfalls and snowmelts and results in erosion and sedimentation. State forestry agencies were required to develop either regulatory, quasi-regulatory, or non-regulatory forestry BMP guidelines to reduce and control surface runoff (Ice et al. 2004). The southeastern United States consists primarily of non-regulatory and quasi-regulatory BMP guidelines (Aust and Blinn 2004, Shepard 2006).

Sedimentation from forest operations is the main pollutant that occurs from forest operations (Yoho 1980, Fulton and West 2002, U.S. EPA 2005). Forest operations in the Piedmont and Coastal Plain region of the southeast United States primarily consist of intensively managed forests (Fox 2000, Allen et al. 2005). Intensively managed forests can produce higher erosion and sedimentation rates than naturally regenerated forests and can influence water quality (Aust and Blinn 2004, Grace 2005). Forest roads, skid trails, and site preparation are the greatest impacts to water quality due to bare soil being exposed (Fulton and West 2002, Grace 2005). Forestry BMPs applied to these areas can reduce water quality impacts. There is currently no consolidated database or simple method for forestry organizations in the southeastern United States to access information on forestry BMP studies and their effectiveness in controlling erosion. The objective of this project is to develop an approach to estimate potential erosion from forest operations and to include past literature on these operations for the Piedmont region.

## **2. Methods**

Literature (1999-present) pertaining to forestry best management practices, erosion, sedimentation, and sediment delivery in the Piedmont physiographic region were accessed using the Virginia Tech Library database and Google Scholar and reviewed. Erosion rates and sediment delivery ratios were recorded from relevant literature. No new data was collected. Majority of the erosion rates were converted from Mg/ha/yr and kg/ha/yr to tons/ac/year. Microsoft Excel was used to reference the past literature and to develop an erosion estimation approach.

## Erosion Estimation Approach

The erosion estimation approach was subdivided by different forest operations (clearcut, forest roads, decks, skid trails, stream crossings, and streamside management zones (SMZs)). Microsoft Excel was used to formulate the erosion estimation approach (Table 1). In order to estimate erosion for a forest operation, area of the operation (acres) and an erosion rate (tons/ac/yr) are needed for input into the appropriate excel cells. Area of the operation will need to be known, but an appropriate erosion rate can be selected from the range of erosion rates included in the table based on the manager's knowledge of the site and operations.

The range of erosion rates come from existing literature on forestry BMPs in the Piedmont region and are divided into forest operation categories. The supporting literature is provided in an additional excel sheet so that the user can examine specific erosion rates for different forest operations (Table 2). This excel sheet (Table 2) is designed for the user to input an erosion estimate number for a specific forest operation category (included in Table 2) and excel will update the sheet with the literature for that specific operation. The forest operation categories and supporting literature reviewed include: (1) clearcut (Williams et al. 1999, Christopher and Visser 2007, Fraser et al. 2012, Barrett 2013), (2) clearcut with stand establishment (Williams et al. 1999, Fraser et al. 2012), (3) log decks (Christopher and Visser 2007, Barrett 2013), (4) forest roads (Christopher and Visser 2007, Barrett 2013, Brown et al. 2013, Lang et al. 2015), (5) skid trails (Christopher and Visser 2007, Sawyers et al. 2012, Wade et al. 2012a, Wade et al. 2012b, Barrett 2013, Wear et al. 2013), (6) stream crossings (Christopher and Visser 2007, Aust et al. 2011, Barrett 2013), (7) SMZs (Ward and Jackson 2004, Lakel et al. 2010, Barrett 2013), and (8) biomass operations (Barrett 2013). Data from the past literature include (if available): treatment(s), area of operation (acres), erosion with BMPs (tons/ac/yr), erosion without BMPs (tons/ac/yr), sediment delivery ratio, and the literature citation. These studies used a variety of methods to either measure or predict erosion (and sometimes sediment delivery). Erosion models used in the supporting literature included the Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), and Water Erosion Prediction Project (WEPP).

Only applicable forest operations require input into the erosion estimation approach. Once the area of operation(s) and erosion rate(s) are input into the estimation approach, total operational area and estimated potential erosion rate are output. Total operational area is the sum of the area over all the applicable (input) operations. The estimated potential erosion rate is first calculated by multiplying each applicable area of operation by the erosion rate for that specific operation. These values are then summed over all applicable operations and divided by

the total operational area to get an estimated potential erosion rate for the forest operation site. The formulas for total operational area and estimated potential erosion rate are shown below:

$$Total\ operational\ area = \sum area\ of\ operation(s)$$

$$Estimated\ potential\ erosion\ rate = \frac{\sum(area\ of\ operation \times erosion\ rate)}{total\ operational\ area}$$

Table 3. Piedmont region erosion estimation approach in Microsoft Excel. Input variables would be area (acres) of each applicable forest operation and erosion rate (tons/ac/yr) for that operation. Erosion rate ranges are based on past literature from the Piedmont region. Equations in excel output the total operational area and estimated potential erosion rate (tons/ac/yr).

Forest operation	Area of operation (ac)	Erosion rate (tons/ac/yr)	Range of erosion rates (tons/ac/yr)
Clearcut	(input)	(input)	0.07-0.48
Forest Roads	(input)	(input)	0.05-11.88
Decks	(input)	(input)	0.04-6.4
Skid trails	(input)	(input)	0.18-66.20
Stream crossings	(input)	(input)	0.04-84.09
SMZs	(input)	(input)	<0.13

Total operational area =  acres

Estimated potential erosion rate =  tons/ac/yr

Table 2. Past literature on forestry BMPs, erosion, and sedimentation can be referenced for the erosion rate inputs in Table 1. The user will input the number corresponding to the forest operation of interest (on bottom of table). The excel sheet will output past literature for the selected forest operation. The output (if available) from the literature include treatment(s), area of operation (acres), erosion with BMPs (tons/ac/yr), erosion without BMPs (tons/ac/yr), sediment delivery ratio, and the citation of the literature

Number	Forest operation	Area (ac)	Erosion with BMPs	Erosion without BMPs	Sediment delivery ratio	Citation
(input)	forest operation category (output)		tons/ac/yr			
	treatment (output)	(output)	(output)	(output)	(output)	(output)
	-	-	-	-	-	-
	-	-	-	-	-	-

Number (input)	Forest operation category
1	Clearcut only
2	Clearcut with stand establishment techniques
3	Decks/landings
4	Forest roads
5	Skid trails
6	Stream crossings
7	SMZs
8	Biomass operations

### 3. Discussion

This approach was conducted for the Piedmont physiographic region and is not intended for use outside of the region. The Piedmont was chosen for this trial approach due to the number of recent studies (1999-present) that have been conducted in the region. Other

physiographic regions in the southeastern United States do not appear to have as many studies or as recent studies that represent current management practices. The Piedmont region allowed for a more complete estimate of potential erosion that can occur from forest operations. This approach is based on literature from forestry BMP studies on erosion rates and sediment delivery from forest operations that either measured erosion rates or predicted erosion rates using models such as USLE, RUSLE, and WEPP. Wade et al. (2012b) compared all three erosion prediction models to measured sediment trap data and found that all three models could be useful for hazard evaluation and BMP inspections. These models provide relevant estimates of erosion from forest operations.

There are some potential concerns that users should consider before using the erosion estimation approach. The number of studies for each forest operation category are small, particularly for some operation categories (log decks/landings and biomass harvesting). Additional studies in these areas are needed to improve this approach for estimating erosion from forest operations. Also, only two studies in the Piedmont region documented sediment delivery ratios (Ward and Jackson 2004, Lakel et al. 2010). Sediment delivery ratios need to be further evaluated on different forest operations. Finally, this method is intended only for use by forest managers attempting to identify where additional BMP implementation may be beneficial and the approach should not be used to model erosion at the landscape scale.

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#### **5. References**

- Allen, H.L., T.R. Fox and R.G. Campbell. 2005. What is ahead for intensive pine plantation silviculture in the south? *Southern Journal of Applied Forestry* 29(2):62-69.
- Aust, W.M. and C.R. Blinn. 2004. Forestry best management practices for timber harvesting and site preparation in the eastern United States: an overview of water quality and productivity research during the past 20 years (1982–2002). *Water, Air and Soil Pollution: Focus* 4(1):5-36.

- Aust, W.M., M.B. Carroll, M.C. Bolding and C.A. Dolloff. 2011. Operational forest stream crossings effects on water quality in the Virginia Piedmont. *Southern Journal of Applied Forestry* 35(3):123-130.
- Barrett, S.M. 2013. Operational characteristics, erosion potential, and implementation of forestry best management practices on biomass harvesting operations. PhD dissertation, Virginia Tech, Blacksburg, VA. 149 p.
- Brown, K.R., W.M. Aust and K.J. McGuire. 2013. Sediment delivery from bare and graveled forest road stream crossing approaches in the Virginia Piedmont. *Forest Ecology and Management* 310(2013):836-846.
- Christopher, E.A. and R. Visser. 2007. Methodology for evaluating post harvest erosion risk for the protection of water quality. *New Zealand Journal of Forestry* 52(2):20.
- Fox, T.R. 2000. Sustained productivity in intensively managed forest plantations. *Forest Ecology and Management* 138(1):187-202.
- Fraser, N., R. Jackson and D. Radcliffe. 2012. A Paired Watershed Investigation of Silvicultural Best Management Practices Revisited: BF Grant Memorial Forest, Georgia. *Forest Science* 58(6):652-662.
- Fulton, S. and B. West. 2002. Forestry impacts on water quality. Southern Forest Resource Assessment. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, General Technical Report SRS-53:501-518.
- Grace, J.M. 2005. Forest operations and water quality in the south." *Transactions of the American Society of Agriculture and Biological Engineers* 48(2):871-880.
- Ice, G., L. Dent, J. Robben, P. Cafferata, J. Light, B. Sugden and T. Cundy. 2004. Programs assessing implementation and effectiveness of state forest practice rules and BMPs in the West. *Water, Air and Soil Pollution: Focus* 4(1):143-169.
- Lakel, W.A., W.M. Aust, M.C. Bolding, C.A. Dolloff, P. Keyser and R. Feldt. 2010. Sediment trapping by streamside management zones of various widths after forest harvest and site preparation. *Forest Science* 56(6):541-551.
- Lang, A., W.M. Aust, M.C. Bolding and K.J. McGuire. 2015. Sediment deposition from forest roads at stream crossings as influenced by road characteristics. *Proceeding of Seventeenth Biennial Southern Silvicultural Research Conference*.
- Phillips, M.J. and C.R. Blinn. 2004. Best management practices compliance monitoring approaches for forestry in the eastern United States. *Water, Air and Soil Pollution: Focus* 4(1):263-274.

- Sawyers, B., M. Bolding, W. Aust and W. Lake. 2012. Effectiveness and implementation costs of overland skid trail closure techniques in the Virginia Piedmont. *Journal of Soil and Water Conservation* 67(4):300-310.
- Shepard, J.P. 2006. Water quality protection in bioenergy production: the US system of forestry Best Management Practices. *Biomass and Bioenergy* 30(4):378-384.
- U.S. EPA. 2005. National management measures to control nonpoint source pollution from forestry. United State Environmental Protection Agency. 276pp.
- Wade, C.R., M.C. Bolding, W.M. Aust and W.A. Lakel 2012a. Comparison of five erosion control techniques for bladed skid trails in Virginia. *Southern Journal of Applied Forestry* 36(4):191-197.
- Wade, C., M. Bolding, W. Aust, W. Lakel and E. Schilling. 2012b. Comparing sediment trap data with the USLE-Forest, RUSLE2, and WEPP-Road erosion models for evaluation of bladed skid trail BMPs. *Transactions of the American Society of Agriculture and Biological Engineers*. 55(2):403-414.
- Ward, J.M. and C.R. Jackson. 2004. Sediment trapping within forestry streamside management zones: Georgia Piedmont, USA. *Journal of the American Water Resources Association* 40(6):1421-1431.
- Wear, L.R., W.M. Aust, M.C. Bolding, B.D. Strahm and C.A. Dolloff. 2013. Effectiveness of best management practices for sediment reduction at operational forest stream crossings. *Forest Ecology and Management* 289(2013):551-561.
- Williams, T.M., D.D. Hook, D.J. Lipscomb, X. Zeng and J.W. Albiston. 1999. Effectiveness of best management practices to protect water quality in the South Carolina Piedmont. *Proceedings of the Tenth Biennial Southern Silvicultural Research Conference*.
- Yoho, N.S. 1980. Forest management and sediment production in the South--a review. *Southern Journal of Applied Forestry* 4(1):27-36.

# Site Disturbance and Soil Impacts Resulting from Mechanized Thinning of Upland Hardwood Stands in Southeastern Kentucky

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A large scale silvicultural trial was designed to examine the effectiveness of five treatments in reducing the potential future impacts of gypsy moth infestation and oak decline on upland hardwood forests in the Daniel Boone National Forest in southeastern Kentucky. Three of the five prescriptions were implemented with a mechanical harvesting system. The system consisted of a swing-to-tree feller buncher, chainsaw limbing and topping in the woods and skidding with a grapple skidder. The three mechanically harvested prescriptions were shelterwood with reserves, thinning to B-line, and woodland thinning. Each prescription was designed to test the effectiveness of varying degrees of basal area reduction in limiting the impact of gypsy moth infestation and oak decline. After harvesting was complete the point transect method was used to measure site disturbance caused by the harvesting operations. An assessment of soil response was conducted in one area that was subjected to the most intense thinning – shelterwood with reserves. This treatment thinned each stand to 10 – 25 ft<sup>2</sup>/ac to create a 2 aged stand. Primary soil variables measured included bulk density and soil strength in both pre- treatment and post treatment condition. Bulk density within the soil profile increased in response to thinning. Conversely, soil strength was reduced after thinning that may be the result of higher moisture levels. Soil bulk density increased in response to traffic intensity, as measured by the site disturbance survey, but the reverse was noted for soil strength. The impact of trafficking on carbon and nitrogen was also evaluated by monitoring nitrogen mineralization and carbon efflux. Disturbance intensity influenced nitrogen mineralization while carbon efflux was detected on a limited basis.

**Keyword:** Site Disturbance, Soil Impact, Thinning, Bulk Density, Soil Strength, Kentucky

## 1. Introduction

A large scale study was implemented in 2007 to assess the effectiveness of five different silvicultural treatments in limiting the impacts of gypsy moth and oak decline on the Daniel Boone National Forest in southeastern Kentucky.



Previous research suggests that the impact of oak decline and gypsy moth infestations can be limited by preparing the forest before stress introduction. Silvicultural treatments aimed at decreasing competition and increasing regeneration and tree vigor have been shown to lessen the impacts of oak decline and gypsy moth infestations.

The original study implemented four silvicultural treatments and a control to test their effectiveness against oak decline and the gypsy moth. The study was being conducted by a multidisciplinary research team composed of USDA Forest Service and university researchers. Research included studies of not only the silvicultural effects, but also the effects on wildlife, soils, and the harvesting methods and equipment.

This paper focuses on assessing harvest productivity and soil site impacts of the harvesting systems used to implement the silvicultural prescriptions including tabulation of soil surface disturbances and changes in soil physical properties of a portion of the most intense thinning operation.

## **2. Study Areas**

The study was implemented on the London Ranger District of the Daniel Boone National Forest in Southeastern Kentucky. The harvesting units are located west of London in the Cold Hill area with oak and hickory dominated stands ranging in age from 70 to 150 years. The units are generally located on broad ridges with some moderate side slopes (up to 30 percent). Soils are highly weathered, low fertility Ultisols. Stand density before harvest ranged from 100 to 120 ft<sup>2</sup>/ac and 140 to 160 stems/ac.

The study was designed as a randomized complete block. There are two site types (dry-mesic and dry-xeric) and five treatments (table 1): shelterwood with reserves, oak shelterwood, B-line thinning, oak woodland, and a control (Schweitzer et al., 2008). There are three replicates for a total of 30 units equaling almost 600 acres. Eighteen of the 30 units were mechanically harvested, six of the units were treated chemically and the remaining six were retained undisturbed as controls. Harvesting began in May 2007 and was completed in August 2009.

Table 4.-Treatments on the research study examining sustaining oak systems amid threat of gypsy moth infestation and oak decline research study on the Daniel Boone National Forest.

TREATMENT	PRESCRIPTION
1. Control	No burn, no disturbance
2. Shelterwood w/ Reserves	10-15 ft <sup>2</sup> /ac residual BA <sub>1</sub> , mechanical harvest
3. Oak Shelterwood	60-75 ft <sup>2</sup> /ac residual BA, herbicide treatment
4. Thinning to B-line	Gingrich's Stocking Chart, mechanical harvest
5. Woodland Thinning	30-50 ft <sup>2</sup> /ac residual BA, mechanical harvest

<sup>1</sup>BA = Basal Area

### 3. Methods

A mechanical tree-length harvesting system was used to harvest all units. The system consisted of a feller buncher, grapple skidder and a knuckleboom loader. Trees larger than 23 inches d.b.h. (diameter at breast height) were felled with a chainsaw. All limbing and topping was performed with a chainsaw in the stand. Products removed from the units included hardwood sawtimber and biomass logs. A biomass log was any material greater than 3 inches in diameter, reasonably straight, at least 10 feet long and that did not meet merchantability specifications of a saw log.

The Forest Operations Research Unit of the USDA Forest Service in Auburn, Alabama measured the productivity and efficiency of the harvesting system and its impact on the stand. This data along with the amount of timber removed from each unit allowed for the calculation of unit productivity and an estimate of cost and efficiency. Soil surface disturbances caused by the harvesting operations were assessed using the point transect method (McMahon, 1995). A total of 9 mutually exclusive disturbance classes were used. Each sample point was further classified by a location type (table 2) Additional soil surface disturbance classes were tabulated on a portion of Unit 31, a shelterwood with reserves thinning operation.

Table 5.-Disturbance classes and location types used to describe harvesting impacts.

DISTURBANCE CLASS	LOCATION
-Undisturbed	-Landing
-Disturbed w/ litter in place	-Primary skid trail
-Litter removed & topsoil exposed	-Secondary skid trail
-Litter removed & mineral soil exposed	-Stand area
-Litter & soil mixed	-Road
-Soil exposed > 4 inches	-Other (stream bed, SMZ)
-Non-soil (stumps, rocks, logs, etc.)	
-Logging slash	
-Soil deposited on top of ground	

An assessment of soil response to a thinning operation was conducted by measuring select soil physical properties in a select area of one thinning treatment: shelterwood with reserves. This treatment had the potential for the greatest impact on soil resources due to the higher basal area removals. Three blocks were established that each measured approximately 1,000 ft<sup>2</sup> (40 x 25) feet along a hillslope of approximately 25 % with two side by side and the third on the lowest portion of the slope. A grid system was superimposed on each block and sampling points laid out in a 4 x 8 foot grid for a total of 15 grid points per block. At each grid point, a soil core approximately 24 inches in length and 2 inches in diameter was removed, sectioned in 4 inch increments, dried at 105 o C for 48 hours. Dry weights were recorded for each depth increment and final bulk density (BD) and soil moisture contents (SMC w/w) were calculated (Blake and Hartge, (1986). Prior to core removals, soil strength (SS) measurements were conducted by inserting a recording cone penetrometer to a depth of 16 inches and tabulated in 1 inch increments. The resulting data were compiled into cone index values for each 4 inches of soil depth.

Soil data related to BD and SS by depth were analyzed by using a mixed model (PROC MIXED) approach that tested main effects of harvest condition: preharvest vs. postharvest and disturbance class by depth and their interaction.

#### 4. Results and Discussion

The research study required that the harvesting be completed with a mechanical harvesting system. The harvesting crew initially consisted of a rubber-tired feller buncher, a tracked swing-to-tree feller buncher, two grapple skidders and a knuckleboom loader. The rubber-tired feller buncher was equipped with a shear felling head with the assumption that smaller biomass material could be felled more effectively with such a machine. However, after a few weeks the contractor decided that it was better to do all felling with the tracked feller buncher. To balance system productivity both the rubber-tired feller buncher and one of the grapple skidders were removed from the crew. Later in 2007, the tracked feller buncher was replaced with a similar machine with a disc saw. This machine remained with the crew for the remainder of the study. Adverse (wet) weather conditions resulted in the extension of the harvesting well beyond the desired completion date of the end of the second growing season (winter 2008). The wet weather and the resulting slower harvesting productivity led to the decision to add a second harvesting crew (contractor 2) in June 2008. The second harvesting contractor was similarly equipped as the first. In early 2009, the first harvesting crew (contractor 1) stopped participating in the timber harvesting.

In an effort to complete the harvesting by the end of the second growing season the harvesting crews were allowed to work through the normal winter shutdown period (December to April). The crews were closely monitored and not allowed to exceed site disturbance limits set by the Forest Service. Working through the winter months did speed up harvesting but included extended periods of idle time when conditions were too wet. Of the 18 units harvested, 9 were completed by contractor 1, 8 were completed by contractor 2 and 1 unit was started by contractor 1 and finished by contractor 2.

The shelterwood with reserves units averaged 27 acres and took an average of 10 weeks to harvest. The woodland thinning and thinning to B-line units averaged 28 and 26 acres in size and took an average of 7 and 6 weeks respectively to harvest. Woodland thinning Unit 20 took 4 months to harvest. This unit was started by contractor 1 and then later finished by contractor 2. The unit was the largest unit in the study (48 ac) and consisted of several long thin ridge tops which contributed to the extended time to harvest.

Tons per acre removed varied, as expected, by treatment with an average of 77 tons/ac on the shelterwood units, 25 tons/ac on the B-line thinning units and 42 tons/ac on the woodland thinning units. Table 3 shows the removal percentage for each treatment. The thinning treatment, which had the lowest tons per acre removed also had a much lower percentage of Basal Area (BA) removed compared to the percentage of Stems Per Acre (SPA) removed. The percentage of biomass tons removed was also much lower than the percentage

of sawlog tons removed. These results indicate that more small stems were removed in the thinning treatment and this resulted in lower harvesting productivity. The shelterwood treatment, on the other hand, had high percentages of both BA removed and SPA removed indicating a heavier removal across all stem diameters. The product removal percentages were close to being equally split between biomass and sawlogs. Average productivity by treatment decreased as the percent of biomass removed increased. The shelterwood treatments had the highest harvesting productivity (3.98 tons/PMH) and the least percent of biomass removed (54 percent) and the thinning treatments had the lowest harvesting productivity (2.60 tons/PMH) and the highest percentage of biomass removed (78 percent). Figure 1 shows the tons/ac removed for each treatment.

Table 3.-Percentages of Basal Area, Stems/Acre and tons removed.

Treatment <sup>1</sup>	Percent Removed		Percent Removed (tons)	
	BA <sup>2</sup> (ft <sup>2</sup> )	SPA <sup>3</sup>	Biomass	Sawlogs
2. Shelter	78	87	54	46
4.Thin	32	60	78	22
5.WThin	43	68	65	35

<sup>1</sup>See Table 1 for Treatment Descriptions, <sup>2</sup> Basal Area, <sup>3</sup> Stems/acre

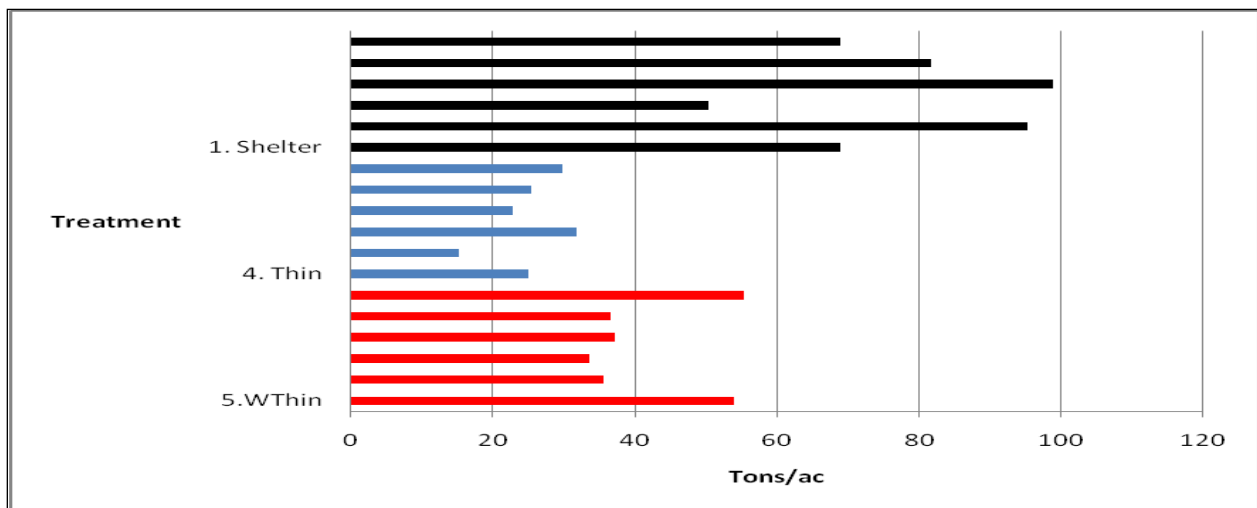


Figure 1.-Tons/ac removed from harvest units by treatment.

Site soil disturbances were tabulated on all harvested units. The disturbance categories are combined into 5 main disturbance types to highlight differences among treatments (Figure 2). The category “Soil exposed” combines the three disturbance classes “Litter removed & topsoil exposed”, “Litter removed & mineral soil exposed”, and “Litter & soil mixed” from Table 2. The “Slash” disturbance class was included to illustrate the amount of biomass left in the units and combines the disturbance classes “Slash” and “Non-soil”. “Non-soil” accounted for a very small percentage of data points of which the majority was downed logs. Eighteen percent of the shelterwood with reserves units were classified as “Slash”, while 9 percent and 11 percent of the thinning to B-line and woodland thinning units, respectively, were classified as “Slash”. “Slash” was defined as any piled limbs and tops located at the survey point.

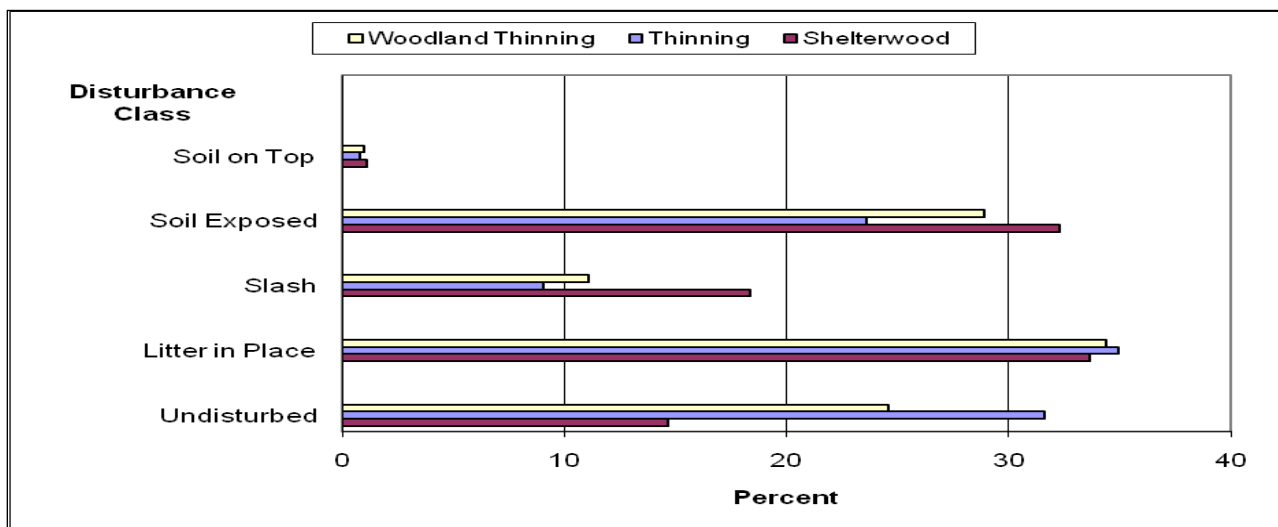


Figure 2.-Percent of area in various disturbance classes.

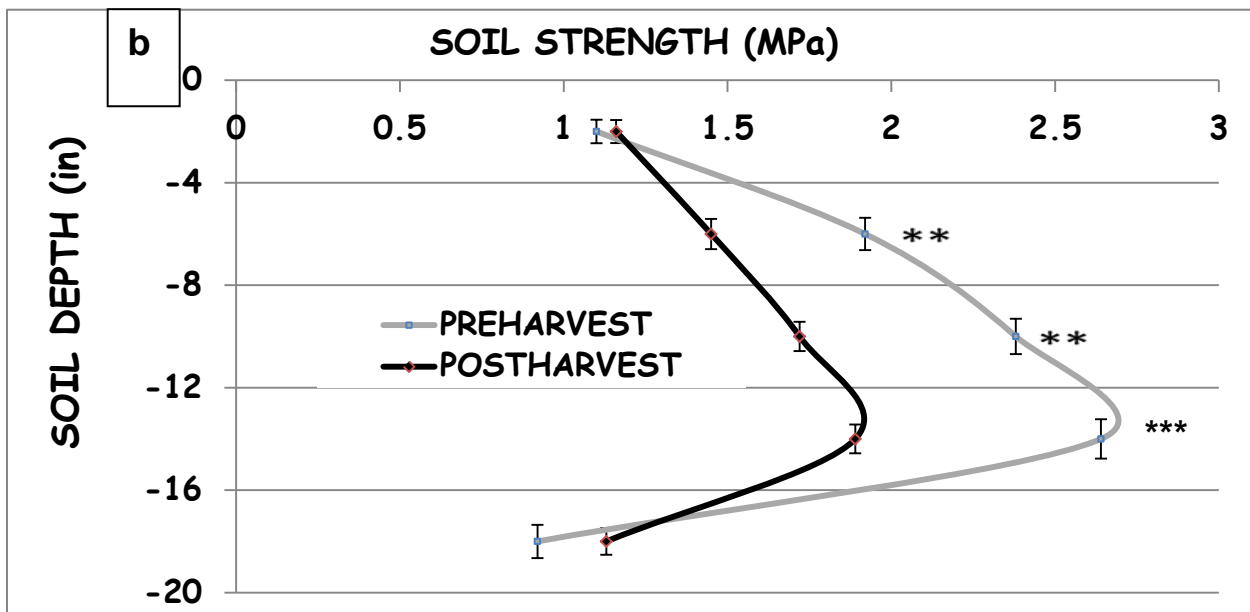
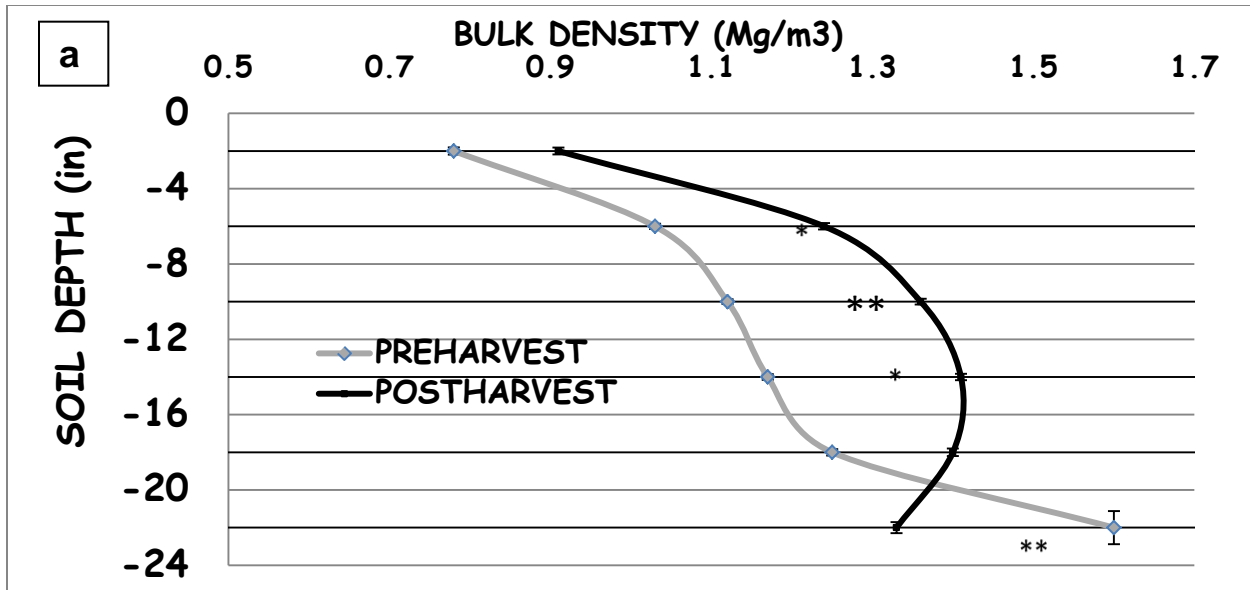
“Soil Exposed” ranged from 24 percent on the thinning to B-line units to 32 percent on the shelterwood with reserves units. “Litter in Place” and “Undisturbed” combined, accounted for 49, 59, and 67 percent in shelterwood with reserves, woodland thinning and thinning to B-line, respectively. Thinning to B-line units had the highest percent area in undisturbed and litter in place which reflects the least average volume of timber removed (25 tons/ac).

Final soil disturbance class tabulation of the area evaluated for soil response (Unit 31) noted the presence of 5 classes: undisturbed (UND), disturbed with litter in place (TWL), soil exposed > 4 inches partitioned into ruts < 6 inches (RUTSLT6) and ruts greater than 6 inches (RUTSGT6) and top soil exposed (TSE). The percentage of each class included UND – 17,8%, TWL – 66.7%, RUTLT6 – 8.9%, RUTGT6 – 4.4%, and TSE – 2.2%. The highest percentage of

disturbance was TWL which matched the overall result for shelterwood with reserves followed by UND. More soil was exposed (TSE) in the overall tabulation compared to the soil evaluation site.

Bulk density increased in response to machine trafficking as indicated by postharvest increases relative to preharvest conditions (Figure 3a). The increase was significant at several depth increments throughout the soil profile: 5% level for the 8 – 12 and 20 - 24 inch soil layers while significance was detected at the 10% level in the 4 – 8 and 12 – 16 inch soil layers. The final BD levels over the depths evaluated may be an indication of the formation of a hardpan in response to harvest trafficking. In comparison, SS was reduced under postharvest conditions and differences were observed to be significantly different in subsoil layers between 4 and 16 inch soil layers, especially in the 12 – 16 inch layer (Figure 3b). Contrary to BD results, SS declined in response to harvesting operations with SS levels lowered in subsurface layers; the reduction in SS may mitigate the impact of a hardpan layer in subsurface layers.

Pre and post harvest BD values were compared to BD levels derived from a moisture-density compaction test (Proctor). Surface compaction levels of both conditions were less than 1.0 Mg m<sup>-3</sup> that was lower than peak levels estimated at 1.53 Mg m<sup>-3</sup>. Similarly, BD levels measured in the immediate subsurface layer (4 – 8 in) were estimated to be approximately 1.1 and 1.3 Mg m<sup>-3</sup>, respectively, and less than the 1.77 Mg m<sup>-3</sup> estimated from the Proctor test. Soil strength levels greater than 2.5 MPa in the 12 – 16 in subsoil layer may limit root exploration and proliferation (Taylor et al., 1966)

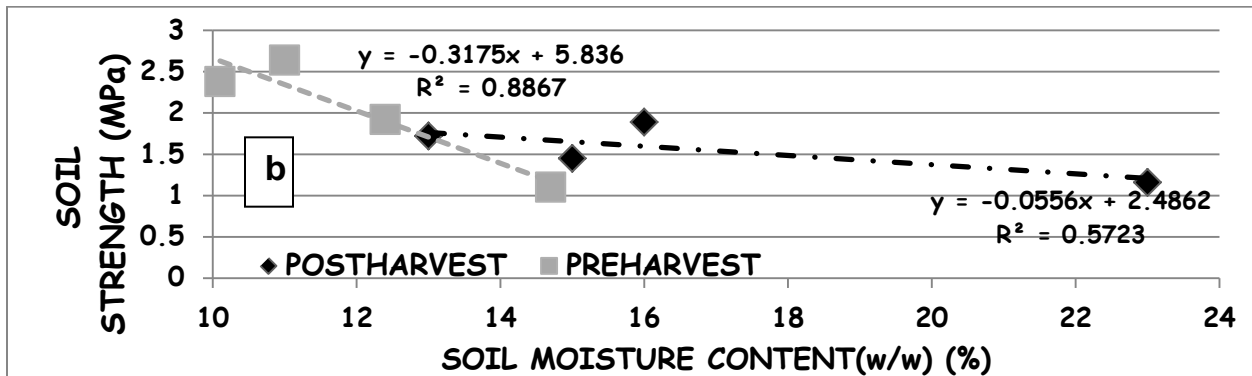
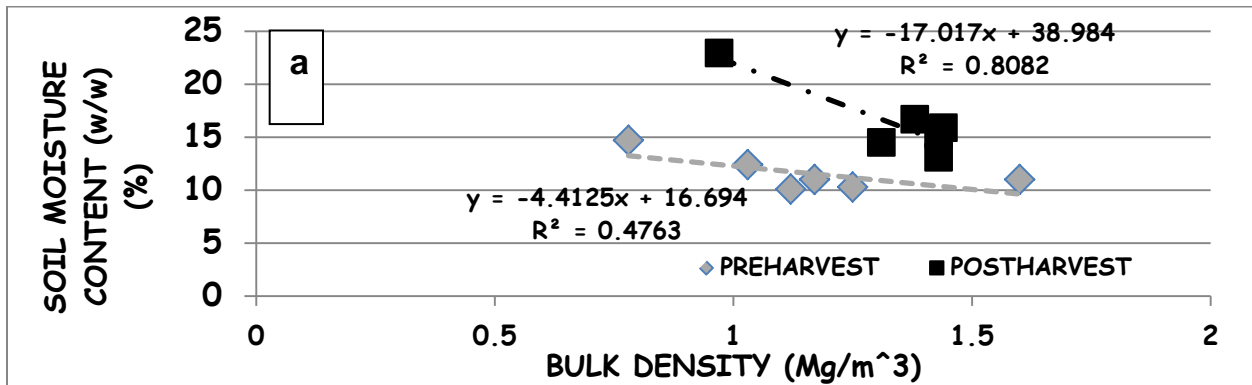


(Figure 4 a-c). Bulk density increases occur at the expense of soil structure, decreasing pore size and volume, in turn affecting water and air infiltration and retention. Soil moisture contents narrowly ranged between 10 and 15% under pre-harvest conditions over a wide range of BD values (~0.8 to 1.6 Mg/m<sup>3</sup>) versus elevated moisture contents under postharvest conditions over a slightly smaller range of BD (Figure 4a). This may be an indication of decrease in soil volume with a rearrangement of soil pore volume and size that retained a greater amount of soil moisture (Amppooter et al., 2010). The relationship between BD and SMC was



stronger ( $r^2 = 0.81$ ) under postharvest conditions compared to preharvest as a result of compactive forces on soil structure.

Soil strength measurements are influenced by SMC as evidenced by the relationship depicted in Figure 4a. Preharvest SS increased in response to reductions in SMC ( $r^2=0.89$ ) while SS measurements in post harvest (13 – 23%) indicated SMC were sufficient to minimize its influence on SS levels although the relationship was weaker ( $r^2 =0.57$ ). Elevated soil moisture conditions facilitate SS measurements by reducing the influence of specific soil conditions, e.g. BD, soil texture, etc. (Ayers and Perumpral, 1982). This is further confirmed by the relationship in Figure 4b in which elevated preharvest BD levels were strongly related to elevated SS levels ( $r^2=0.99$ ) while this relationship was not as strong under post harvest conditions ( $r^2=0.87$ ) presumably due to the increase in SMC with increased BD levels.



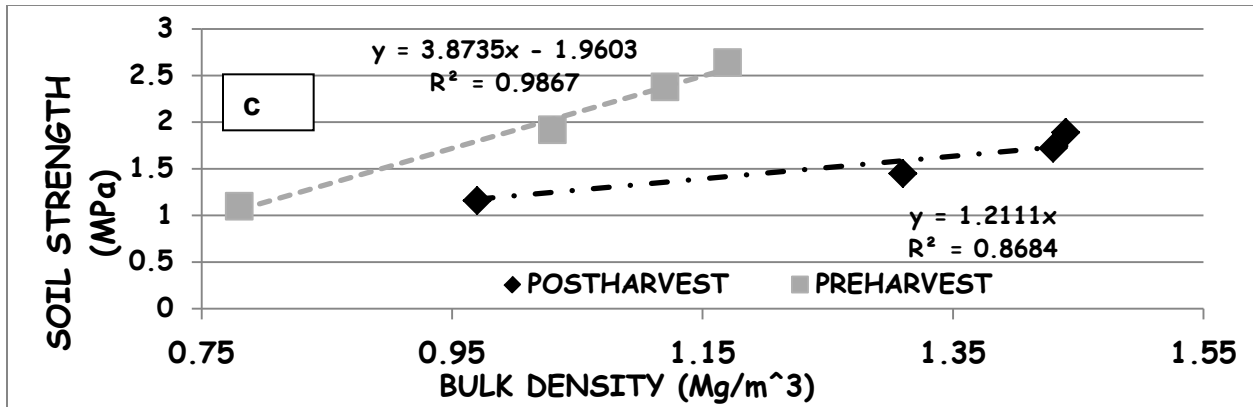


Figure 4 a – c. Relationship among bulk density (BD), soil moisture content (SMC w/w), and soil strength (SS) in response to a thinning operation, Kentucky.

Further assessment of machine impacts was conducted through the tabulation of surface soil disturbance classes (Figure 5). The disturbance class related to TWL was most often tabulated in the study area and may indicate a minimum of soil damage.

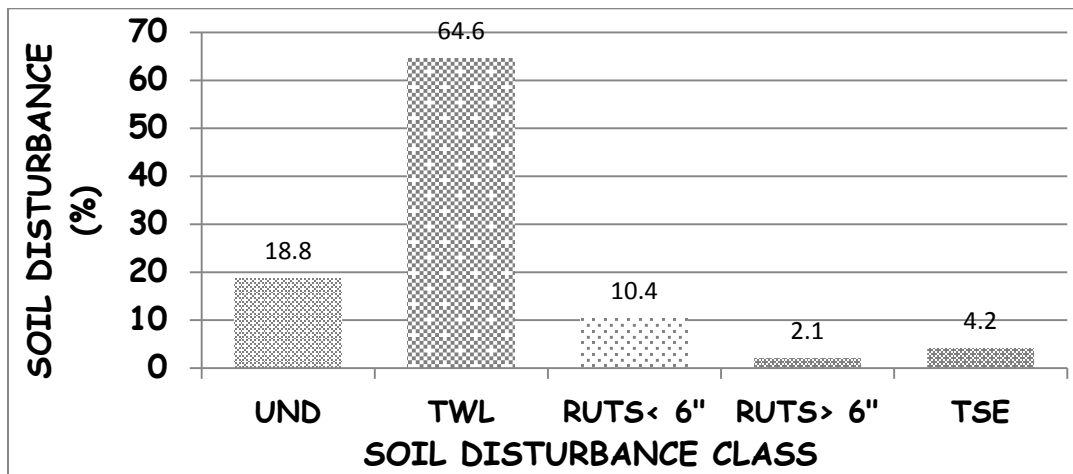


Figure 5. Soil disturbance classes of a study site in response to a thinning operation, Kentucky.

Examination of soil properties by disturbance class was limited to three classes: UND, TWL, and RUTLT6 due to their prevalence in the study site (Figures 6a & b). Surface BD was elevated in response to surface exposure (RUTLT6) followed by TWL and UND, respectively (Figure 6a). Subsoil BD increased with depth in all classes, and may be an indication of the formation of hardpan development, especially TWL. No significant differences were detected.

Soil strength levels were higher in UND compared to RUTLT6 and TWL which might not have been expected (Figure 6b). This may be due to less soil moisture contained in UND resulting in more resistance to penetration during SS measurements. Less soil moisture was associated with BD in UND, the lower SMC contributing to higher SS levels of BD when compared to TWL and RUTLT6.

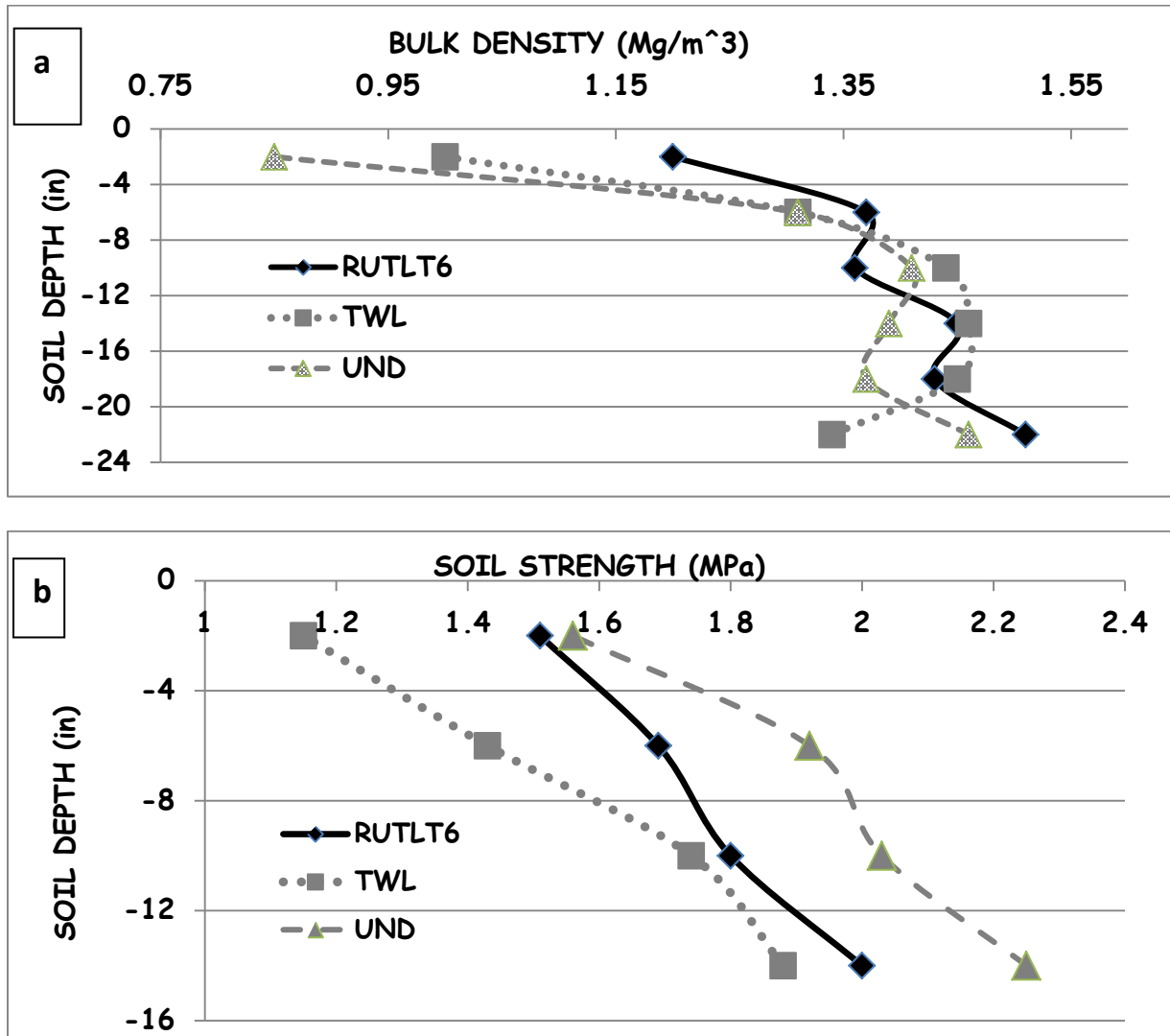


Figure 6 a & b. Soil bulk density (BD) (a) and soil strength (SS) (b) response to soil disturbances during thinning, Kentucky.

## 5. Conclusions

The longevity of this study (May 2007 – August 2009), the addition of a second harvesting contractor (and subsequent retraction of the first contractor), changing personnel and machines within crews, and adverse weather conditions all complicated the analysis of this study.

Soil disturbance resulting from mechanized ground-based harvesting appeared to be related to the volume removed. More removal was associated with higher levels of soil disturbance and more coverage of logging residues. The amount of stand area impacted by skid trails was relatively low, averaging between 12 percent and 16 percent of total area. This range is in-line with those measured by other studies.

Machine trafficking induced changes in soil physical properties related to BD, SMC and SS as would be expected. Bulk density increased in response to trafficking but final BD levels were lower than maximum levels predicted by Proctor tests. Soil strength declined in response to trafficking, which was atypical and attributed to increased soil moisture levels after trafficking.

Soil disturbances were limited primarily to UND and TWL with a smaller proportion tabulated as RUTLT6, RUTGT6 and TSE. Bulk density levels were elevated in each disturbance class with depth but no significant differences were detected. Soil strength declined in response to disturbance with TWL levels showing a greater difference in the upper 8 inches.

## 6. References

- Ayers, P.D. and J.V. Perumpral. 1982. Moisture and density effects on cone index. *Trans of ASAE* 25: 1169-1172.
- Blake, G.R. and K.H. Hartge. 1986. Bulk Density. IN: Klute, A. (ed), *Methods of Soil Analysis, Part 1*, 2nd edition. American Society of Agronomy, Madison, WI.
- Hatchell, G. E., C. W. Ralston, and R. R. Foil. 1970. Soil disturbance in logging. *Journal of Forestry*. Vol. 68. No. 12. Pg. 772-775.
- Kochenderfer, J. N. 1977. Area in skidroads, truck roads, and landings in the central appalachians. *Journal of Forestry*. Vol. 75. No. 8. Pg.507-508.
- McMahon, S. 1995. Accuracy of two ground survey methods for assessing site disturbance. *Journal of Forest Engineering*. Vol. 6. No. 2. Pg. 27-33.
- Mitchell, W. C., and G. R. Trimble, Jr. 1959. How much land is needed for the logging transport system. *Journal of Forestry*. Vol.57. No. 1. Pg. 10-12

- Schweitzer, C. J., S. Clark, G. Gaines, P. Finke, K. Gottschalk, and D. Loftis. 2008. Integrating land and resource management plans and applied large-scale research on two national forests. In: Integrated restoration of forested ecosystems to achieve multiresource benefits: Proceedings of the 2007 national silviculture workshop. Deal, R. L. Tech. Ed. Gen. Tech. Rep. PNW-GTR-733. Portland, OR: U.S. Department of Agriculture. Forest Service. Pacific Northwest Research Station. Pg. 127-134.
- Taylor, H.M., Gene M. Roberson, and Jessie J. Parker, Jr. 1966. Soil strength-root penetration relations for medium to coarse textured soil materials. Soil Science 102:18-22.

## **Soil response to skidder and dozer traffic as indicated by soil stress residuals**

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Ground based timber extractions are common harvesting systems in the United States as well as other timber producing countries. Machine movements during harvesting may result in areas in which soils have been negatively impacted leading to increased erosion and soil compaction. This is especially true of primary skid trails that have been established to facilitate tree removals. Several techniques have the potential to reduce soil compaction including corduroying skid trails with slash or using equipment exerting lower ground pressures. Typical measures of compaction include bulk density and mechanical resistance. However, bulk density measurements require destructive sampling and are time consuming while mechanical resistance measurements are highly variable due to soil moisture content, bulk density, and operator consistency. Therefore, we established a research project designed to accomplish two objectives: 1) compare and contrast conventional measures of soil compaction with a newer technique using soil stress residuals, and 2) compare the effects of slash versus bare soil on skid trails trafficked by a rubber-tired grapple skidder and a dozer. The project will be located within an upland hardwood/pine stand in the Ridge and Valley physiographic region. The initial pilot study indicated that soil stress residuals as an indication of compaction level increased by approximately 25% after 1 pass, 12% after 2 passes, and less with subsequent passes (6 total). Comparison of the newer technique of soil compaction measurement with existing techniques, as well as the effects of cover and equipment type on compaction, will be discussed.

### **1. Introduction**

Ground-based systems are commonly used for timber harvesting in the southeastern United States. These systems rely on equipment to fell, transport, and process timber

(Simmons, 1979). Forest machinery is heavy and traffics a portion of mechanically harvested sites. Depending on soil characteristics and site conditions, forest machinery can significantly change soil properties. It is often desirable to characterize the change in soil properties before and after a harvest. After soil series and moisture content are determined, traditional soil properties including bulk density, mechanical resistance, porosity, and saturated hydraulic conductivity can be analyzed (Greacen, et. al, 1980).

The forest industry is growing in the Appalachian Mountain region and harvesting is occurring more often and impacting more forest lands. Despite intensive research on many aspects of timber harvesting in the Appalachians, knowledge regarding changes in soil characteristics due to harvest are limited (Wang, et. al, 2007). The project was designed to provide information about two different types of machinery, cover type, and the number of machinery passes associated with overland skidding in the mountains.

## **2. Methods**

### **2a. Field Site**

A harvest was conducted on the Fishburn Forest, Virginia Tech's research forest, in spring 2015. The study site was located adjacent to a log landing that provided an ideal area for data collection without impacting harvest operations. The site was located on a continuous 7% grade atop a small ridge. The forest was an upland oak system consisting of chestnut, white and scarlet oaks with some white pine interspersed. The forest floor inside the study area was not disturbed during initial project installation. The study site is located on a Berks-Clymer complex where soils are silt loam in texture, moderate to well drained, and shallow in depth containing many coarse fragments. Depth to shale or sandstone bedrock is shallow; 27 – 49 inches (USDA, 1985).

The study site was located next to an existing ridge road in an area of un-trafficked forest. Trees and brush were cut and removed by hand to create three travel lanes. Equipment was not permitted to enter the study area during preparations to ensure the first two sets of measurements were representative of zero and one machine pass. The study site measured 120 ft by 40 ft and consisted of two travel lanes and a return lane adjacent to the study site. Each travel lane was divided into six 20 ft long by 20 ft wide segments. The rubber-tired skidder (skid) was assigned to one travel lane and the tracked skidder (dozer) was assigned to the other. Both machines used the existing ridge road as a return lane to exit the study area and line up for another pass. Within each travel lane, three segments were assigned to be left bare, and three segments were covered with slash. Slash was considered to be woody debris left on

site and was piled to an initial depth of ~ 3 ft. Slash is a commonly used best management practice to reduce soil disturbance by providing cover, provide weight distribution, and aid in machinery movements (VDOF, 2011). This setup allowed for comparison of machine, cover type, and number of machinery passes on soil quality. Figure 1 below shows the study site layout. The arrows represent the direction of travel for each lane. Each small block is a 20 ft by 20 ft segment. Machine type is identified by “Skid” or “Dozer,” numbers represent segments, and cover type is “Bare” or “Slash.”

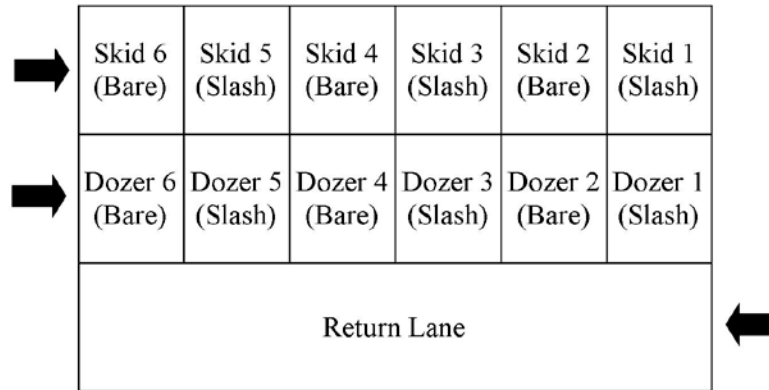


Figure 1. Study site layout; arrows represent travel direction, “Skid” or “Dozer” represent machine type, numbers represent segment, and “Bare” or “Slash” represent cover type.

Data collection occurred following zero, one, three, six, nine, and twelve passes. Each time sampling occurred, soil cores were extracted, mechanical resistance was measured, and soil moisture was recorded. Soil cores were collected using standard bulk density hammers paired with two 2 in x 2 in metal rings. Two cores were extracted from each lane segment to a depth of 4 – 5 in after each set of passes. The cores were capped and bagged for storage and transport. A Rimik CP20 recording cone penetrometer was used to record mechanical resistance. The penetrometer was set to record in kilopascals associated with every 25 mm (1 in) change in depth of soil. Three sets of mechanical resistance measurements were taken in a triangular pattern surrounding the soil core sampling location. Soil moisture was measured using a Campbell Scientific Hydro-Sense TDR moisture meter. Two readings were taken near the soil core location after each set of passes for each segment. See Figure 2 below for the sampling layout for each 20 ft by 20 ft segment as well as sample location for each set of passes. The zero pass samples were taken between the tracks and samples for passes one, three, six, nine, and twelve were taken from within the trafficked areas as shown. Zero pass represented initial conditions.



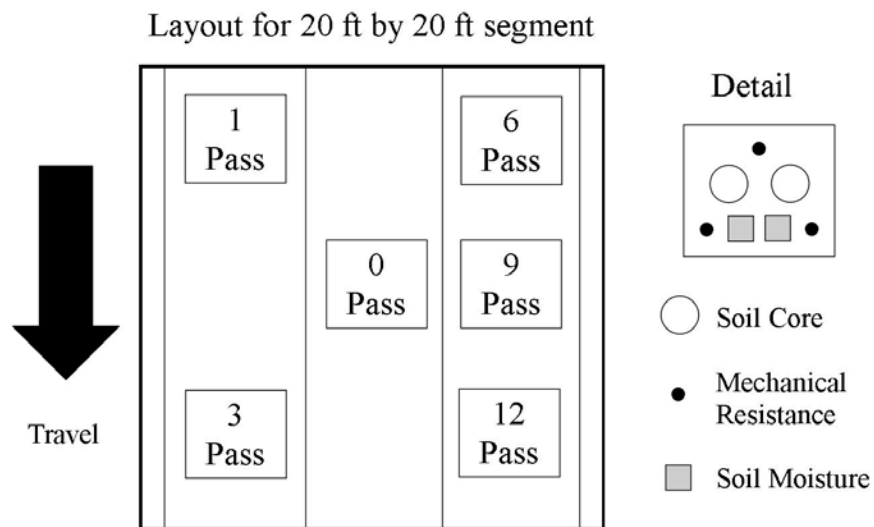


Figure 2. Sampling scheme used for each 20 ft by 20 ft segment.

## 2b. Machinery

The skidder is vital to ground-based timber operations and makes the most passes through the harvest area. The skidder is utilized on job sites regardless of the method of felling because it is the machine that transports cut timber from the woods to a landing or collection point (McGonagill, 1978, Simmons, 1979). A small dozer was used to represent a tracked skidder and a grapple skidder was used to represent a rubber-tired skidder. It was impractical to actually pull a complete turn of logs through the course because of disturbing the slash and contaminating the bare treatments. To replicate loaded passes, a weight constructed of metal pipe filled with concrete was suspended from the dozer's fire plow and the skidder's grapple. The goal was to simulate the butt weight of a turn of logs. The weight was 1412 lb and suspended with 60 lb of chain and binders. It was assumed that the ground supports the majority of the weight of a turn of logs and the machinery only supports a finite amount of each turn.

The dozer was a 1986 John Deere 450E with a fire plow attached to the rear. The dozer was equipped with standard metal tracks. Each track measures 82.2 in long and 18.0 in wide. Both tracks result in a contact area of 2959 in<sup>2</sup>. The standard dozer has an operational weight of 15350 lb. These specifications result in a ground pressure of 5.2 psi (John Deere, 1985). For the actual measurements in the study, the fire plow, weight, and bindings were added. The

450E weighed 17500 lb including the fire plow. This combined with the suspended weight resulted in a total weight of 18972 lb and a ground pressure of 6.4 psi. Figure 3 below depicts the bulldozer with attached weight.



Figure 3. John Deere 450 dozer.



Figure 4. CAT 525D skidder.

The wheeled skidder was a 2014 Caterpillar 525D with dual arch grapple, winch, and front blade. The skidder was equipped with single Firestone Forestry Special size 30.5 L – 32 (20) rubber tires. From published Firestone specifications (Bridgestone Americas Tire Operations LLC, 2015), each of the four tires has a flat plate area of 378 in<sup>2</sup>. Total ground contact area supporting the machine is 1512 in<sup>2</sup>. From the Carter Caterpillar dealership, the 525D skidder used in the study weighed 45249 lb (Caterpillar, 2014). The addition of the suspended weight brings the total equipment weight to 46721 lb. This results in a ground pressure of 30.9 psi. Figure 4 above shows the CAT 525D skidder with the attached weight.

## 2c. Laboratory and Data Analysis

Soil cores were analyzed for saturated hydraulic conductivity, macro and micro porosity, and bulk density. For each set of measurements taken during the experiment, two soil cores were extracted. The two cores provided two samples used to calculate a representative average for each soil property for each set of passes. Mechanical resistance data was downloaded from the Rimik CP20 recording penetrometer as a data file and analyzed in software. Soil moisture data was recorded by hand in the field and input into software for analysis.

Saturated hydraulic conductivity was determined using the constant head technique. Soil cores were completely saturated by immersing them in water for a minimum of 24 hours. The cores were removed from immersion and placed in an apparatus that maintained a

constant head of water. The amount of water that passed through a soil core and the associated time were recorded. Samples that exhibited pipe flow were not included in analysis. The Berks – Clymer complex has a maximum permeability of 6.0 in/hr, or 15.24 cm/hr (USDA, 1985). Knowing that the soil contained numerous coarse fragments combined with professional judgment, samples were excluded due to pipe flow at a threshold of 150 cm/hr. This value preserved the data set while staying within the known magnitudes of silt structured materials. According to Coduto (1999), the maximum magnitude of flow through silt materials is 0.01 cm/s, and 150 cm/hr corresponds to 0.04 cm/s. Soil cores that failed to produce the minimum flow of water for measurement were assumed to be impermeable. A flow rate of 0.0001 cm/hr was assigned to these samples. The Berks – Clymer complex has a minimum permeability of 0.6 in/hr, or 1.52 cm/hr, but contains pockets of clays that are impermeable (USDA, 1985). According to Coduto (1999), the minimum magnitude of flow through silt materials is 10-8 cm/s, and 0.0001 cm/hr corresponds to  $2.7 \times 10^{-8}$  cm/s.

Micro and macro porosity were determined using a tension table setup and a drying oven. For the apparatus used, a tension of 50 cm of water in equilibrium with the water in the soil core results in macro pores being empty leaving water in micro pores. Soil cores were immersed in water for a minimum of 24 hours to achieve full saturation. The cores were then placed on the tension table and allowed to rest for 24 hours to come to equilibrium with the 50 cm applied tension. The equilibrium weight of the cores was recorded and then the cores were baked in a drying oven at 105° C for a minimum of 24 hours to determine oven dried weight. Equilibrium weight was compared to oven dried weight to determine the percentage of micro pores. Macro pores were assumed to be the difference between total porosity and the percentage of micro pores. Total porosity was calculated based on corrected bulk density and an assumption of 2.65 g/cm<sup>3</sup> density of coarse fragments.

Bulk density was determined for each core based on cylinder volume and oven dried weight which were both determined from previous porosity analysis. Analysis of several cores showed that the soil contained a large amount of coarse fragments, so bulk density values were corrected. Samples were corrected following the methods found in the Soil Survey Field and Laboratory Methods Manual (2014). Soil cores were oven dried, ground with mortar and pestle, sieved, and rinsed. The remaining fragments were oven dried and weighed. This method accounted for both the weight and volume occupied by the coarse fragments.

Mechanical resistance data was recorded as a Rimik CP20 recording cone penetrometer passed through the soil profile. The device recorded penetration resistance in kilopascals for every 25 mm of depth into the soil. The unit was used to record three samples of data for each set of experimental data collection. The three samples were averaged to form one

representative set of mechanical resistance data for each part of the experiment. The 25 mm depth increment proved to be too finite for analysis. Following a process similar to those in Bolding, et al. (2009), the mechanical resistance values were regrouped into depth classes: 25 – 100 mm, 125 – 200 mm, 225 – 300 mm, 325 – 400 mm, 425 – 500 mm, and 525 – 600 mm. The first depth class was compared to the soil core data as it results from the same part of the soil profile; the depth class corresponds to 1 – 4 in below the surface and soil cores were taken from 4 – 5 in below the surface. Two volumetric soil moisture measurements were taken with each set of collected data. These values were averaged to provide a single representative value.

JMP statistical software was used to organize and analyze data (SAS Institute Inc., 2012). As this is a preliminary review of the data, mean values of parameters were used. The experiment was designed to allow for separate analysis of each type of machinery for changes in bulk density, hydraulic conductivity, and porosity. Raw values for each soil property were compared to the initial existing condition yielding the magnitude and direction of change of a given property. This method of analysis accounted for initial variation of plots.

### **3. Results and Discussion**

The rubber tired skidder and dozer had an impact on the visual appearance of the soils and cover of the experimental site. The skidder created deep ruts with obvious soil displacement whereas the dozer did not. Slash treatments were compressed and limbs and branches were broken forming a mat. Results are presented separately for the skidder and the dozer because of the major difference in magnitude of weight.

A major objective of the study was to determine if cover type on an overland skid trail impacts changes in soil characteristics due to traffic. The average change in each soil property was compared to initial conditions for the entire 12 passes observed. In terms of saturated hydraulic conductivity both the skidder and the dozer experienced a larger loss in conductivity for slash treatments than bare. The magnitude of the decrease in conductivity for slash was 2 to 3 times that of the bare treatment. Cover type did not have an impact on changes in bulk density. Bulk densities after 12 passes were greater than those of the initial conditions. The skidder resulted in an increase of 0.2 g/cm<sup>3</sup> while the dozer resulted in an increase of 0.05 g/cm<sup>3</sup>. Both machines decreased the total porosity of the soils, but the skidder resulted in three times the loss. Cover type did not result in major differences in total porosity change. Micro porosity was increased by trafficking the soil and slash cover did not impact changes in micro porosity for the skidder. For the dozer, bare treatments experienced double the increase in micro pores than the slashed treatments. Cover type did not have a major impact on changes

in macro porosity, but in both cases bare treatments experienced a slightly greater loss of macro pores. The skidder caused three times the loss of macro pores than the dozer. For the skidder, bare treatments experienced an increase of 5.8% in water content while slash treatments only saw an increase of 2.3%. The dozer resulted in a loss of 1.1% in water content for bare treatments while slashed treatments water content increased by 0.4%. These results are summarized in Table 1 on the following page.

Table 1. Average results for comparison of cover type by machine for soil properties over the entire 12 passes; reported values are changes from initial conditions.

Machine	Cover	Saturated Hydraulic Conductivity	Bulk Density	Porosity	Micro Porosity	Macro Porosity	Volumetric Water Content
		cm/hr	g/cm <sup>3</sup>	%	%	%	%
Skidder	Bare	-6.50	0.18	-6.90	2.00	-8.90	5.80
	Slash	-11.10	0.16	-6.20	2.00	-8.20	2.30
Dozer	Bare	-4.40	0.05	-1.70	1.70	-3.40	-1.10
	Slash	-13.10	0.05	-1.80	1.00	-2.80	0.40

Within a given cover type for each machine, the number of passes of machinery were compared to changes in soil properties. There was major change after the first pass for the skidder and appreciable change for the dozer between three and six passes.

The skidder experienced a major loss in hydraulic conductivity after the first pass for both bare and slashed treatments. There was a loss of 19.7 cm/hr for bare treatments and a loss of 14.6 cm/hr for slashed treatments. After three passes, both cover types experienced a rebound in hydraulic conductivity. Bare treatments saw an increase of 8.9 cm/hr above initial conditions whereas slash treatments recovered to 6.2 cm/hr below initial conditions. From six to twelve passes under both cover types, the skidder reflected a loss in hydraulic conductivity comparable to that after the first pass. Slashed treatments saw greater loss of saturated hydraulic conductivity than bare treatments. Changes in saturated hydraulic conductivity were closely related to macro porosity. When macro porosity declined significantly, saturated hydraulic conductivity did as well. For bare treatments 11.2% of macro pores were lost after one pass with rebound to a loss of 7.9% after three passes. After three passes, the loss of macro pores remained constant around 11.0%. For slashed treatments macro pores were reduced by 9.8% after one pass and remained constant around 11.0% loss for passes three through twelve. Bulk density increased by 0.2 g/cm<sup>3</sup> after the first pass for both cover types and remained relatively consistent for the remainder of passes from six to twelve. No major trends emerged

for change in micro porosity and volumetric water content. For both cover types, values increased with traffic and then remained relatively constant.

Cover played a more significant role for the dozer. Bare treatments experienced major changes after one pass, but did not experience appreciable change under slashed conditions until three to six passes. In terms of saturated hydraulic conductivity, the dozer lost 4.1 cm/hr after one pass, rebounded to 0.3 cm/hr after three passes, and reflected losses of about 8.0 cm/hr from six to twelve passes. For slashed conditions no major loss was found after one pass, but a loss of 12.5 cm/hr occurred after three passes. Slash experienced significant losses after six and twelve passes of 25.3 and 26.6 cm/hr respectively. Macro porosity was related to a saturated hydraulic conductivity. Under bare conditions, the dozer lost 2.3% of macro pores after one pass. Loss gradually increased to between 6.0 and 7.0% loss after twelve passes. Slashed treatments experienced a slight increase in macro pores of 1.7% after one pass followed by losses from three to twelve passes. The slashed treatment lost 8.6% of macro pores after twelve passes. Bulk density was increased by 0.06 g/cm<sup>3</sup> after three passes for bare treatments and reached a consistent value of 0.1 g/cm<sup>3</sup> for passes nine and twelve. Bulk density did not increase to 0.06 g/cm<sup>3</sup> until six passes for slashed treatments. Micro porosity increased with traffic on average for bare and slashed treatments, but no major patterns were apparent. Volumetric water content did not exhibit any apparent pattern as values reflected both an increase and decrease in volumetric water content. Table 2 below provides detailed information about each machine, cover type, and the associated changes in soil properties.

Table 2. Results for soil properties based on machine, number of passes, and cover type; values reported are changes from initial conditions.

Machine	Passes	Cover	Saturated Hydraulic Conductivity	Bulk Density	Porosity	Micro Porosity	Macro Porosity	Volumetric Water Content
			cm/hr	g/cm <sup>3</sup>	%	%	%	%
Skidder	0	Bare	0.00	0.00	0.00	0.00	0.00	0.00
	1	Bare	-19.68	0.18	-6.94	4.29	-11.24	6.17
	3	Bare	8.91	0.17	-6.35	1.58	-7.94	7.33
	6	Bare	-19.65	0.22	-8.53	2.94	-11.47	6.50
	9	Bare	-5.46	0.27	-10.29	1.23	-11.52	9.00
	12	Bare	-2.83	0.24	-9.14	1.85	-10.99	5.83
	0	Slash	0.00	0.00	0.00	0.00	0.00	0.00
	1	Slash	-14.58	0.18	-6.83	2.93	-9.76	1.67
	3	Slash	-6.15	0.18	-6.75	2.62	-9.37	1.17

	6	Slash	-16.29	0.28	-10.63	1.02	-11.65	2.67
	9	Slash	-13.16	0.21	-7.83	2.86	-10.69	3.33
	12	Slash	-16.43	0.13	-4.88	2.64	-7.52	5.00
Dozer	0	Bare	0.00	0.00	0.00	0.00	0.00	0.00
	1	Bare	-4.10	-0.02	0.62	2.91	-2.29	0.17
	3	Bare	0.26	0.06	-2.13	1.27	-3.40	-2.00
	6	Bare	-7.41	0.02	-0.80	1.56	-2.36	-1.50
	9	Bare	-9.11	0.11	-4.22	2.69	-6.91	-1.50
	12	Bare	-6.22	0.10	-3.79	1.63	-5.42	-1.67
	0	Slash	0.00	0.00	0.00	0.00	0.00	0.00
	1	Slash	0.39	-0.03	1.35	-0.32	1.67	1.50
	3	Slash	-12.49	0.04	-1.46	1.27	-2.73	-1.17
	6	Slash	-25.28	0.06	-2.21	2.74	-4.94	0.17
	9	Slash	-14.60	0.06	-2.37	-0.14	-2.23	-0.67
	12	Slash	-26.64	0.16	-6.16	2.44	-8.60	2.67

Mechanical resistance data was analyzed for the effect of cover over the 12 passes of the experiment. Mechanical resistance values are presented from the two uppermost depth classes; 25 – 100 mm (depth class 1) and 125 – 200 mm (depth class 2). These depth classes correspond to the same depth as the extracted soil cores. As with the other soil characteristics, the reported numbers show the change from initial conditions.

For the skidder in depth classes 1 and 2, cover had a major effect. Bare treatments in depth class 1 experienced an increase of 385.0 kPa while slashed treatments experienced only an 85.0 kPa increase. The same held true for depth class 2. Bare treatments mechanical resistance increased by 607.2 kPa while slash treatments only increased by 382.0 kPa. The dozer followed the same trends, but the magnitudes of the increases were slightly lower. For bare treatments in depth class 1 the mechanical resistance increased by 378.7 kPa while slashed treatments increased by 73.7 kPa. For the bare dozer treatments in depth class 2, there was an increase of 490.0 kPa and there was an increase of 84.5 in the slash treatments. Table 3, below, reports the average change in mechanical resistance based on machine type and cover.

Table 3. Average results for comparison of cover type by machine for mechanical resistance over 12 passes; reported values are changes from initial conditions.

Machine	Cover	Mechanical Resistance, 25 - 100 mm	Mechanical Resistance, 125 - 200 mm
		cm/hr	g/cm <sup>3</sup>
Skidder	Bare	384.97	607.19
	Slash	84.99	382.01
Dozer	Bare	378.70	490.00
	Slash	73.75	84.47

Mechanical resistance data from depth classes 1 and 2 was analyzed based on machine type, cover type, and number of passes. Traffic resulted in increased mechanical resistance values. The skidder and dozer showed major fluctuations in mechanical resistance for slash treatments. Table 4 shows the change in mechanical resistance for two depth classes based on machine, number of passes, and cover type.

For depth class 1 and 2 bare treatments, the skidder caused significant increases in mechanical resistance for the first three passes. For passes six through twelve, mechanical resistance dropped and maintained a consistent value. Depth class 1 reached a maximum of 710.9 kPa after three passes and leveled out around 350.0 kPa. Depth class 2 reached a maximum of 1102.6 kPa and leveled out around 600.0 kPa. For depth class 1 with slash the skidder caused a decrease after the first and sixth pass, but the overall change was an increase of 230.0 kPa after twelve passes. A maximum of 822.5 kPa was reached with slash cover for depth class 2 after three passes. Values dropped to 274.0 kPa increasing to 402.0 kPa by twelve passes.

The dozer did not exhibit any clear pattern for bare treatments regardless of depth. Values of mechanical resistance increased and decreased throughout the study. The magnitude of change at the second depth class was larger than the first. At depth class 1 for slash treatment with the dozer, mechanical resistance values decreased for the first three passes and then increased to 356.3 kPa at six passes. Values decreased after nine passes, but showed an increase of 448.6 kPa after twelve. Depth class 2 for the dozer with slash experienced decreases in resistance over 200.0 kPa after passes one and nine. All other passes increased with a maximum of 507.7 kPa after 12 passes.



Table 4. Results for mechanical resistance based on machine, number of passes, and cover type; values reported are changes from initial conditions.

Machine	Passes	Cover	Mechanical Resistance, 25 - 100	Mechanical Resistance, 125 - 200	
			mm kPa	mm kPa	
Skidder	0	Bare	0.00	0.00	
	1	Bare	582.41	754.83	
	3	Bare	710.94	1102.61	
	6	Bare	391.86	504.03	
	9	Bare	290.91	686.46	
	12	Bare	333.72	595.22	
	0	Slash	0.00	0.00	
	1	Slash	-118.03	431.25	
	3	Slash	236.75	822.50	
	6	Slash	-101.28	274.86	
	9	Slash	263.33	361.47	
	12	Slash	229.16	402.00	
	Dozer	0	Bare	0.00	0.00
		1	Bare	335.20	525.94
3		Bare	513.92	480.78	
6		Bare	394.81	692.45	
9		Bare	672.89	779.75	
12		Bare	355.39	461.09	
0		Slash	0.00	0.00	
1		Slash	-182.97	-209.64	
3		Slash	-33.00	134.41	
6		Slash	356.33	314.33	
9		Slash	-146.42	-239.95	
12		Slash	448.55	507.67	

#### 4. Summary and Conclusions

Trafficking associated with overland skidding changed all of the soil properties that were analyzed. Some results were as expected, but others seemed contradictory. For both types of machinery, visible ruts were present following the study. The heavy grapple skidder created deep ruts with obvious soil movement and displacement. The lighter dozer created shallow uniform ruts. Jansson et. al (1998) reported the same types of rutting associated with wheeled versus tracked machinery. Wang et. al (2007) noted that under wet conditions, or in cases where soil moisture is increased, heavy machinery may displace rather than compact soil. This phenomenon was noted by Sheridan (2003) in which traffic increased soil water content leading to soil displacement rather than continued compaction.

Changes in soil properties occurred within the first loaded pass for both machines regardless of cover type except for the dozer with slash treatment (effects occurred after three to six passes in this case). For overland skid trails experiencing traffic levels of twelve passes, wheeled skidders will increase bulk density by 0.2 g/cm<sup>3</sup> and tracked skidders will increase bulk density by 0.05 g/cm<sup>3</sup> in the mountains on silt loam soils. These results are similar to those found by Wang et. al (2007). Increases in bulk density were found after a single loaded pass on mountain soils with a slight decrease after four passes to a constant value. This finding is similar to the skidder data from this experiment. Mechanical resistance of soils was increased after one pass, but effects were slightly diminished after more intense trafficking. Sheridan (2003) found increases in mechanical resistance following two passes for tracked machines and ten passes for rubber-tired machines. Sheridan reported significant losses of saturated hydraulic conductivity following traffic by heavy machinery. Jansson et. al (1998) reported that both tracked and wheeled machines increase bulk density and decrease macro porosity. This finding supports the relationship found between saturated hydraulic conductivity and macro pore space found in this experiment.

When soil properties are analyzed over the entire twelve passes, interesting and unexpected relationships between bare and slash cover are apparent. Slashed treatments experienced a loss in saturated hydraulic conductivity two to three times that experienced by bare treatments. Cover did not impact changes in bulk density or total porosity. The experiment did show the rubber-tired skidder resulted in three times the reduction of pore space than the dozer. This is likely a result of the weight difference. Cover did not result in any difference in the increase in micro pore space for the rubber-tired skidder. The tracked vehicle saw double the increase in micro pores on bare treatments than slash. Loss in saturated hydraulic conductivity was directly tied to loss of macro pore space. Bare treatments saw a greater loss of macro pore space than slashed. Cover played a major role in changes in mechanical resistance. Bare treatments exhibited much higher soil strength than slashed treatments.

More research is needed to understand the role of slash as a means of soil protection. Slash is an encouraged method for protecting exposed soils from erosion (VDOF, 2011). Although slash provides cover, this study showed that slash does not alleviate the effects of traffic on the underlying soil profile. The results that showed slash as inadequate soil protection from this study may be influenced by project design and installation. Wood et. al (2003) found that common failures associated with slashed roads were caused by large diameter slash and slash placement. Large logs can be forced into the soil surface. These results were common after heavy traffic or during turning. Slash roads should be constructed of evenly distributed small diameter material. Eliasson et. al (2007) had similar findings to our experiment. Although

slash was expected to reduce rutting and prevent compaction, they found no significant relationship between slash cover and reduced changes in soils. They suspected that excess traffic leads to breakage, thinning, and ultimate failure of slash roads. Wood et. al (2007) found that slash reduced negative changes in the top soil consistent with our findings of less change in mechanical resistance within the upper depth classes.

Even though direct comparison cannot be made between machines because of the difference in weight, it was striking that many of the soil properties were changed almost as much by the small dozer as the massive rubber-tired skidder. Researchers including Sheridan (2003) have found this. They did not find major differences between rubber-tired and tracked vehicles. Despite the major differences in ground pressure, tracked vehicles are subject to higher amounts of vibration. The larger contact area with vibration actually works to tamp the soil or cover leading to changes in soil properties.

## 5. References

- Bolding, M., L. Kellogg, and C. Davis. 2009. Soil Compaction and Visual Disturbance Following and Integrated Mechanical Forest Fuel Reduction Operation in Southwest Oregon. *International Journal of Forest Engineering*, Vol. 20, No. 2.
- Bridgestone Americas Tire Operations LLC. 2015. Forestry Special with CRC (WTP). Bridgestone, United States. Available online at: <http://commercial.firestone.com/en/agriculture/product/for-spec>; accessed July 2015.
- Caterpillar. 2014. 525D/535D/545D/555D Wheel Skidders. Caterpillar, United States. Available online at: <http://s7d2.scene7.com/is/content/Caterpillar/C10307331>; accessed July 2015.
- Coduto, D.P. 1999. *Geotechnical Engineering Principles and Practices*, Prentice-Hall, Englewood Cliffs, NJ. Available online at: <http://www.fhwa.dot.gov/engineering/geotech/pubs/05037/05d.cfm>; accessed July 2015
- Greacen, E. and R. Sands. 1980. Compaction of Forest Soils: A Review. *Australian Journal of Soil Resources*, Vol. 18.
- Jansson, K. and J. Johansson. 1998. Soil changes after traffic with a tracked and a wheeled forest machine; a case study on a silt loam in Sweden. *Forestry*, Vol. 71, Issue 1.
- John Deere. 1985 450E Long Track Bulldozer Specifications. John Deere, United States. Available online at: <http://murphyused.com/images/specs/99.pdf>; accessed July 2015.
- McGonagill, Keith L. 1978. *Logging Systems Guide*. Juneau, Alaska: Dept. of Agriculture, Forest Service, Alaska Region. SAS Institute Inc. 2012. JMP Pro 10.0.2.

- Sheridan, G. 2003. A comparison of rubber-tyred and steel-tracked skidders on soil physical properties. *Australian Journal of Soil Research*, Vol. 41.
- Simmons, Fred C. 1979. *Handbook for Eastern Timber Harvesting*. Broomall, Pa: U.S. Dept. of Agriculture, Forest Service, Northeastern Area, State & Private Forestry. Soil Survey Staff. 2014. *Soil Survey Field and Laboratory Methods Manual*. Soil Survey Investigations Report No. 51, Version 2.0. U.S. Department of Agriculture, Natural Resources Conservation Service. Available online at: [http://www.nrcs.usda.gov/Internet/FSE\\_DOCUMENTS/stelprdb1244466.pdf](http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1244466.pdf); accessed July 2015.
- United States Department of Agriculture. Soil Conservation Service, and Virginia Polytechnic Institute and State University. 1985. *Soil Survey of Montgomery County, Virginia*. Washington, D.C.: The Service. Virginia Department of Forestry. 2011. *Virginia's Forestry Best Management Practice for Water Quality*. Fifth edition.
- Wood, M., A. Moffat, and P. Carling. 2003. Improving the Design of Slash Roads Used to Reduce Soil Disturbance During Mechanised Harvesting of Coniferous Forest Plantation in the UK. *International Journal of Forest Engineering*, Vol. 14, No. 1.

# Sedimentation Reduction and Cost of Best Management Practices for Forest Road Ditches

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Sediment is one of largest nonpoint source pollutants in the US and is the leading pollutant from forest operations. Forest roads with operational ditches at stream crossings approaches have the potential to increase sedimentation without careful application of best management practices (BMPs) and have been a central issue in recent court cases. Forestry BMPs have proven effective for erosion control, but few studies have quantified sediment delivery reduction from various levels of BMPs for forest ditches. This project was designed to evaluate the effectiveness and cost of the following operational roadside ditch BMPs: 1) bare soil (Bare), 2) grass seeded only (Seed), 3) grass seeded with erosion control mulch mat (Mat), 4) check dams (Check), and 5) completely rocked (Rock). Sediment delivery was measured from 14 logging haul road ditch segments during Pre-harvest, Harvest, and Post-harvest periods using silt fence and sediment pins. Costs of BMP implementation were greatest for Rock followed by Check, Mat, and Seed treatments, respectively. Sediment delivery rates were greatest directly following ditch reconstruction and BMP implementation. Smaller increases in sediment delivery were observed following cutslope collapses (during Pre-harvest) and road surface maintenance (during Post-harvest). Bare, Check, and Rock treatments had the greatest mean sediment delivery rates (7.52, 5.53, and 1.94 Mg ha<sup>-1</sup> yr<sup>-1</sup>, respectively) and were significantly greater than Mat and Seed treatments (0.10 and 0.08 Mg ha<sup>-1</sup> yr<sup>-1</sup>, respectively). Thus implementing cost effective ditch BMPs that provide adequate cover and fit site specific situations is recommended to reduce sediment delivery from ditched stream crossing approaches.

**Keywords:** best management practices, sediment delivery, ditches

## 1. Introduction

Sediment is the leading pollutant from forest operations (Yoho 1980, Binkley and Brown 1993, Aust and Blinn 2004, Anderson and Lockaby 2011). Forest roads, stream crossings, skid

trails, and landings are potential sources of bare soils caused by traffic disturbances. These operation components provide necessary access, yet they often pose issues of cost and water quality concerns (Anderson and Lockaby 2011). Minimum standard construction and maintenance are often necessary to attain economic efficiency for forest operations (Groover et al. 2010). Subsequently, roads tend to have exposed soils, lack surface roughness, and are prone to erosion (Kochenderfer and Helvey 1987). The compacted surfaces generate runoff quickly, which can lead to increased erosion and sedimentation (Swift and Burns 1999, McBroom et al. 2008). Therefore forestry best management practices (BMPs) were developed to address erosion associated with silvicultural access (Aust and Blinn, 2004).

Ditching is a common road component that may connect runoff to streams when water is not properly controlled and dispersed. Managing runoff on and near approaches to stream crossings is of particular importance as they serve as breakthroughs through streamside management zones (SMZs) (MacDonald and Coe 2007, Aust et al. 2011, Lang et al. 2015). Stream crossings can be a significant source of sediment from forest operations (Aust et al. 2011). Ditching along stream crossing approaches may further increase sediment delivery potential by concentrating flow and increasing water velocity. The Virginia Department of Forestry recommends dispersing runoff into undisturbed areas of SMZs at a minimum of 7.6 m (25 feet) before stream crossings (VDOP 2011). However, their recommendations do not include in-ditch BMPs and few field studies have measured sediment delivery contributions from operational ditches with and without BMPs.

The level of sediment delivery from ditches has entered the public's consciousness through legal controversy over the forestry silvicultural exemption under the Clean Water Act (Boston 2012). Normal ongoing silviculture operations that follow federal and state BMPs, do not alter hydrology, and do not introduce toxins have a generalized permit known as a "silvicultural exemption". This exemption allows forestry activities from having to obtain National Pollution Discharge Elimination System (NPDES) permits (point source pollution permits) under the Clean Water Act. The National Environmental Defense Center (NEDC) filed a lawsuit challenging the silviculture exemption in 2006. NEDC alleged that runoff from forest roads collected by ditches and conveyed into the nations waters should be constituted as an industrial point source pollutant and therefore requires a NPDES permit. This case eventually reached the Supreme Court in 2013 where the exemption was upheld, but further litigation is possible (MacCurdy and Timmons 2013). Regardless of the litigation, it is clear that quantitative evaluations of feasible and cost-effective ditch BMPs can aid in the refinement of forestry BMPs for water quality protection.

The objectives of this research were to measure sediment delivery rates from four in-ditch BMPs and a bare ditch control during Pre-harvest, Harvest, and Post-harvest time periods and assess the associated cost of BMP implementation. The ditch management practices evaluated were: 1) bare soil (Bare), 2) grass seeded only (Seed), 3) grass seeded with erosion control mulch mat (Mat), 4) two check dams (Check), and 5) completely rocked (Rock).

## **2. Methods**

### **Study Site**

The study site was located on the Virginia Tech Fishburn forest in the Ridge and Valley physiographic region of Montgomery County, Virginia. Mean temperatures range from a low of -16.1°C to a high of 25.6°C. The mean annual rainfall amount is 119 cm. Approximately 475 m of haul road was designed by a professional forester and constructed by the National Guard Combat Engineers in the early 1980's. The 4 m wide road has a crowned template with a ditch on one side and contains seven cross drains with a mean percent slope of 10.9. This road served as the main access for a 12.5 ha (31 ac) timber harvest from November of 2014 to March 2015 during which 37 loaded log trucks traveled across the instrumented road.

### **Road Maintenance and Use**

Ditches were reconstructed in June of 2014 with a John Deere 450 bulldozer and New Holland TN650 farm tractor to improve ditch function, road drainage, and trafficability. The bulldozer moved soil and organic debris away from culvert inlets, which exposed mineral soil. The tractor, equipped with a rhino blade, was used to grade the road-ditch transition. Ditches were reconstructed according to site specific situations, but all were cleared to approximately 30.4 m past each cross drain. The haul road was trafficked with tractor trailer log trucks periodically during the Harvest period. Heavy traffic created ruts reaching 0.5 m in depth in several locations. In April 2015, a bulldozer was used to re-grade the road surface and remove rutting, but did not directly disturb the ditches. The road surface was re-graveled later in April with 143 Mg of crush and run.

### **Treatments**

Treatments were installed directly following ditch reconstruction. Two silt fences catchment areas were installed upslope of each cross drain (Robichaud and Brown 2002). One

silt fence was installed next to the culvert inlet and the other 15.2 m from the previous silt fence (Figure 1). One treatment was applied to both ditch sections at each of the 7 cross drains (14 total experimental units). Ditch and road dimensions were measured after installation using a total station (Sokkia total station model SET-520, Tokyo, Japan).

Bare treatments served as the control and were left uncovered. Seed treatments were applied by hand, spreading pelletized lime and a native seed mixture of orchard grass (72 kg ha<sup>-1</sup>), annual rye (28 kg ha<sup>-1</sup>), and white clover (2.2 kg ha<sup>-1</sup>). Mat treatments received the same seed mixture and were covered with an erosion mat interlaced with straw. Erosion mats were secured within the ditch by landscape staples. Number 1 surge (8.9 – 10.2 cm) was used for Check and Rock treatments. The number 1 surge was purchased from a local quarry and delivered on site. Both Rock and Check treatments were applied using the frontend loading bucket of the farm tractor. Two rock check dams (~1.5 m length) were applied to each Check treatment according to Virginia BMP spacing guidelines for check dams. Ditch segments with Rock treatments were layered with rock for 15.2 m, but did not fill the ditch up to the road level.



Figure 1. Two experimental units at one cross drain, separated by silt fence. The closest two check dams and silt fence are the second experimental unit. Picture was taken Pre-harvest (June 2014).



## Sediment Measures

A network of sediment pins were installed upslope of the silt fence to allow for periodic measurement of sediment deposit depths. Similar methods have been used by Ward and Jackson (2004), Lakel et al. (2010), and Brown et al. (2013) to estimate erosion and sediment delivery. Sediment depths were determined by measuring pin heights with a 1/16th inch tape measure. Sediment depths were measured seven times over five months prior to harvest activity (Pre-harvest), four times over four months during harvest (Harvest), and five times over 2.5 months following harvest activity (Post-harvest).

Bulk densities were collected from each catchment area containing sediment deposits following the core method (Blake and Hartge 1986). Sediment volumes ( $m^3$ ) were calculated by multiplying depositional area ( $m^2$ ) by elevation gain (m). Sediment volumes were converted to a sediment load (Mg) by multiplying bulk density (Mg  $m^{-3}$ ) of the trapped sediment by sediment volumes ( $m^3$ ) (Brown et al. 2013). Sediment loads were then divided by the drainage area and time in order to obtain an annual erosion rate (Mg  $ha^{-1} yr^{-1}$ ). Daily rainfall data were obtained from Virginia Tech airport weather station (software, VWS V14.00), which is located approximately 11 km from the study area.

## Statistical Analysis

This study was analyzed as a completely randomized design. Due to unequal variance and non-normally distributed data, non-parametric analyses were used. Kruskal-Wallis statistical test was used to detect time and treatment differences in mean sediment delivery rates. Spearman correlations were used to assess correlations between measured road components and sediment delivery. Data were analyzed for to statistical significance using JMP statistical software.

## 3. Results

Cost of BMP treatments was cheapest for seed (\$9.00), followed by Mat (\$24.00), Check (\$45.40), and Rock (\$119.50) (Table 1). Cost estimates were based on material, labor, and machine time per 15.2 m ditch section. Manual labor and machine time pay rates were assumed to be \$20 and \$60 per hour, respectively.

Table 1. Itemized cost of BMP treatments per 15.2 m ditch section.

Treatment	Materials	Cost	Time	Cost	Total
Bare	n/a	n/a	n/a	n/a	\$0. <sup>00</sup>
Seed	Seed	\$3. <sup>00</sup>	Manual labor (0.25 hrs)	\$5. <sup>00</sup>	\$9. <sup>00</sup>
	Lime	\$1. <sup>00</sup>			
Mat	Seed	\$3. <sup>00</sup>	Manual labor (0.5 hrs)	\$10. <sup>00</sup>	\$24. <sup>00</sup>
	Lime	\$1. <sup>00</sup>			
	Straw mat	\$10. <sup>00</sup>			
Check	#1 surge stone	\$5. <sup>40</sup>	Manual labor (0.5 hrs)	\$10. <sup>00</sup>	\$45. <sup>40</sup>
			Tractor machine time (0.5 hrs)	\$30. <sup>00</sup>	
Rock	#1 surge stone	\$44. <sup>50</sup>	Manual labor (0.75 hrs)	\$15. <sup>00</sup>	\$119. <sup>50</sup>
			Tractor machine time (1 hrs)	\$60. <sup>00</sup>	

Results of the Wilcoxon multiple comparison test indicated significant differences among time periods ( $p = 0.0115$ ). Pre-harvest had the greatest mean sediment delivery rate ( $5.72 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ) and was significantly different from Harvest ( $0.43 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ,  $p = 0.0007$ ), but not significantly different than Post-harvest ( $1.15 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ,  $p = 0.5526$ ). The Post-harvest period was significantly different from Harvest ( $p = 0.0004$ ). Increased rates in the Pre-harvest period were likely caused by ditch reconstruction, which disturbed and exposed bare mineral soils within ditches. A pronounced increase in sediment delivery rate was observed on the fourth measurement following ditch reconstruction (September 16th). During this measure, cutslope collapses were noted on Bare, Check, and Rock ditch sections (Figure 2). For the Harvest period, road ruts caused by heavy traffic disconnected the travel surface from ditches and reduced the total area of runoff contribution. Subsequently, sediment delivery rates were lower. The road was re-graded and graveled between mid-and late April (Post-harvest), but did not directly disturb ditches. Greater sediment delivery rates during Post-harvest, compared to Harvest, were likely caused by temperature change, increased rainfall (March 19th measure), and road surface maintenance (April 30th measure) (Figure 2).

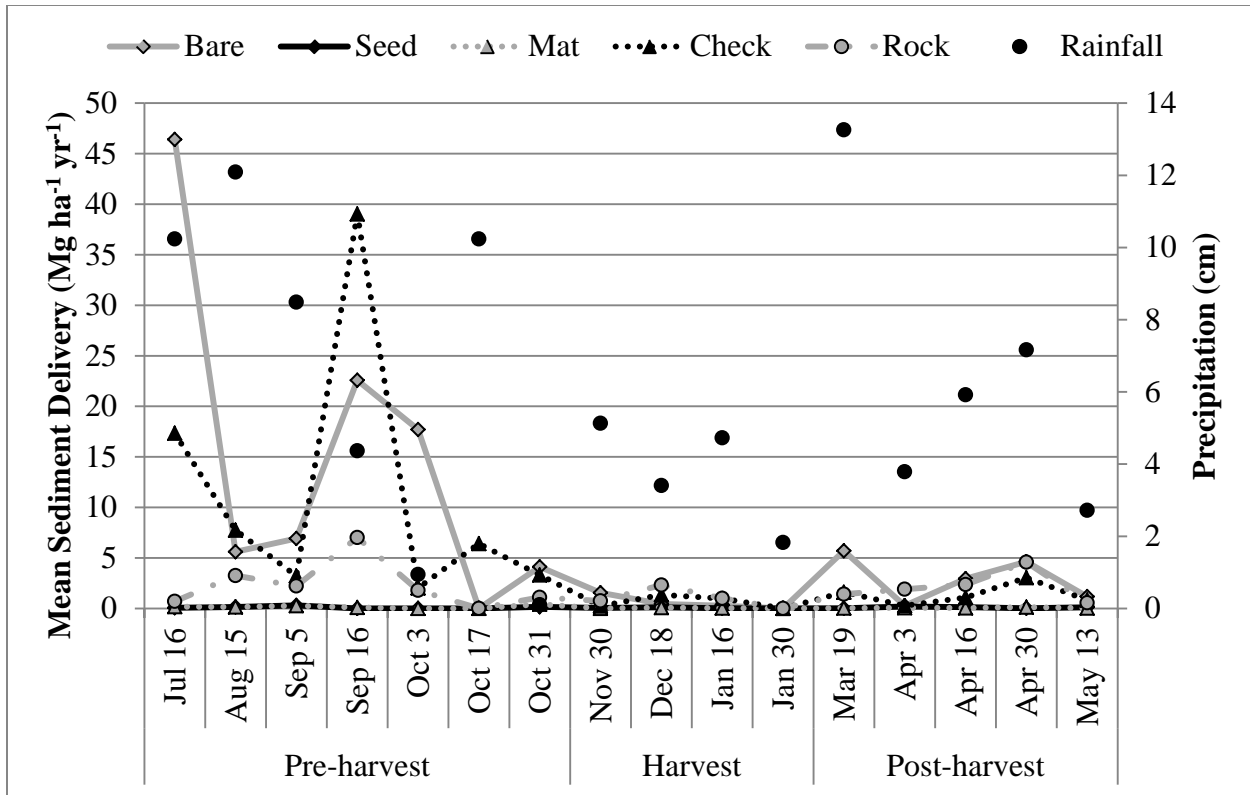


Figure 2. Mean sediment delivery rate ( $\text{Mg ha}^{-1} \text{ yr}^{-1}$ ) per repeated measurement and harvest period by BMP treatment. The secondary y-axis depicts precipitation totals corresponding to the repeated measurement. Treatments were established in June 2014 and measured through May 2015.

Significant differences were detected among ditch treatments for mean sediment delivery rate using Wilcoxon methods ( $p = 0.0121$ ). Mean sediment delivery rate was greatest for Bare ( $7.52 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ) followed by Check ( $5.53 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ), and Rock ( $1.94 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ) treatments. Mat ( $0.10 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ) and Seed ( $0.08 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ ) treatments were most effective at reducing sediment delivery. Mean sediment delivery rates for Bare, Check, and Rock treatments were not significantly different from each other, but were significantly greater than Seed and Mat treatments ( $p < 0.001$ ). Both Seed and Mat treatments germinated quickly due to ideal site conditions and were resilient to erosion throughout the study. Bare and Check treatments had the greatest initial sediment delivery rates ( $46$  and  $17 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ , respectively) following reconstruction (July 16th measure). Sediment delivery rates rapidly decreased by the second and third measurements for Bare and Check treatments, even with increased rainfall from the second measure (Figure 2). Cutslope collapse on Bare, Check, and Rock treatments likely caused increased sediment delivery rates (Figure 2). Overall, Rock treatments did not further reduce sediment delivery rates. Rocks provided high soil coverage

within ditch, but the installation process introduced loose dust and additional soil. Treatments with seed were the least costly and provided the lowest mean sediment delivery rates. However, the ideal growing conditions for grass led to high germination, which should not be assumed for other sites.

Several physical characteristics of each ditch section were measured (Table 2). Ditch lengths ranged from 14.6 to 23.9 m. In-ditch mean slopes ranged from 7.4 to 16.1 percent. Mean slopes from the road edge to ditch bottom (crown slope) ranged from 17.2 to 32.6 percent. Maximum cutslope heights ranged from 1.0 to 2.6 m. The steepest cutslope grade ranged from 31.7 to 102.5 percent. Drainage area, which comprised the visual area of the road prism draining to the ditch, ranged from 19.1 to 61.2 m<sup>2</sup>. Spearman’s correlations showed that total sediment delivery was most highly correlated with the steepest cutslope grade (-0.6703, p = 0.0087). Total sediment delivery was also correlated with cutslope area (-0.6396, p = 0.0138), cutslope height (-0.5545, p = 0.0396), and drainage area (-0.4901, p = 0.0752). Cutslope dimensions had significant negative correlations and were opposite of what was expected. These data reflect inadequate cutslope stabilization on smaller and gentler cutslopes.

Table 2. Physical characteristics of each ditch section on Cassidy Ridge haul road on the Fishburn Forest in Blacksburg, VA.

Site ID	BMP treatment	Ditch length (m)	Mean ditch slope (%)	†Mean road-ditch slope (%)	Cutslope height (m)	Cutslope grade (%)	Drainage area (m <sup>2</sup> )
1a	Rock	15.6	7.8	29.8	1.3	58.4	23.6
1b	Rock	23.9	8.6	17.2	1.1	57.1	52.2
2a	Check	15.3	7.4	30.1	1.0	40.0	21.2
2b	Check	14.9	12.9	23.4	1.2	50.8	25.4
3a	Bare	15.4	15.2	32.6	2.0	31.7	19.1
3b	Bare	15.9	12.4	20.0	1.1	68.8	22.2
4a	Mat	15.3	11.1	29.6	2.2	80.6	42.6
4b	Mat	16.5	9.1	23.9	2.2	85.3	44.6
5a	Check	15.5	10.6	27.3	2.2	73.8	44.5
5b	Check	16.1	9.3	32.4	2.3	67.6	48.1
6a	Seed	14.6	9.7	23.4	2.3	73.9	44
6b	Seed	17.2	9.2	20.7	2.2	69.3	47
7a	Mat	15.1	16.1	24.5	2.6	102.5	44
7b	Mat	18.8	13.4	25.9	2.4	70.4	61.2

†Mean road-ditch slope represents the percent slope from the travel surface edge to ditch bottom.

#### 4. Discussion

Sediment delivery measurements generally decreased with time since last disturbance, which has been well documented throughout the literature and is commonly employed in soil erosion models. In this study, log truck traffic during Harvest, compared to road maintenance activities in Pre- and Post-harvest periods, did not significantly increase sediment delivery from haul road ditches. However, Aust et al. (2011) found that water quality parameters were most negatively affected during crossing installation and during harvest activities. These findings may better reflect the entire road prism and indicate that rutting and traffic can also be detrimental to water quality. Rutting of the road surface can cause rill erosion, which may lead to increased sediment delivery rates (Luce and Black 1999). These studies emphasize BMPs implementation during all harvest periods rather than waiting until harvest closure. Properly implemented BMPs can reduce sediment delivery rates and in some cases reduce erosion rates within the range of natural mixed hardwood stands (Yoho 1980).

BMPs should be implemented according to site specific situations. Seeding may reduce erosion effectively, but its use alone is cautioned as adequate germination is needed. Seeding with mulch mat provides additional coverage and may be warranted on less fertile ground. Rock is an expensive BMP and requires careful installation to reduce additional sediment input. Furthermore, completely rocked ditches on highly erosive sites may cause the ditch to fill and can reduce the time between necessary ditch maintenance.

Overall, sediment delivery rates were considerably lower than other forest operation studies. Wade et al. (2012) measured erosion rates on closed bladed skid trails in the Piedmont of Virginia and reported rates ranging from 137.7 to 3.0 Mg ha<sup>-1</sup> yr<sup>-1</sup> for bare soil with water bar and mulch with water bar, respectively. Sawyers et al. (2012) also measured erosion rates on closed overland skid trails in the Piedmont of Virginia and reported rates ranging from 24.2 to 3.3 Mg ha<sup>-1</sup> yr<sup>-1</sup> for bare soil with water bar and mulch with water bar, respectively. Both studies had similar slope ranges to this study, however higher percent bare soil was likely associated with the lower standard skid roads. Brown et al. (2013) measured sediment delivery rates on traffic surfaces of legacy stream crossing approaches in the Virginia Piedmont. They report sediment delivery rates from 34 to 287 and 10 to 16 Mg ha<sup>-1</sup> yr<sup>-1</sup> for bare and graveled approaches, respectively. Mean sediment delivery rates from ditches with and without BMPs in this study ranged from 7.5 to 0.1 Mg ha<sup>-1</sup> yr<sup>-1</sup>. The lower rates found in this study are the result of having a properly located, designed, and road with higher road standards that limit and cover drainage areas.

## 5. Conclusions

All ditch BMPs offered some erosion control and reduced sediment delivery compared to the Bare control. Maintenance activities that directly disturbed soil within ditches increased sediment delivery rates. However rutting during harvest activities may increase erosion from the road surface. Grass BMP treatments were most effective at reducing sediment delivery from ditches. The use of ditch BMPs should be implemented on stream crossing approaches because the probability of sedimentation is greater. In combination with BMPs that provide cover and cutslope stabilization, drainage areas should be limited to prevent excessive concentrated flow within ditches. Thus implementing ditch BMPs according to site specific situations is recommended to reduce sediment delivery.

## 6. Literature cited

- Anderson, C.J., and B.G. Lockaby. 2011. Research gaps related to forest management and stream sediment in the United States. *Environ. Mgt.* 47(1):303-313.
- Aust, W.M., and C.R. Blinn. 2004. Forestry best management practices for timber harvesting and site preparation in the eastern United States: an overview of water quality and productivity research during the past 20 years (1982-2002). *Water, Air, and Soil Poll. Focus* 4:5-36.
- Aust, W.M., M. Carroll, M.C. Bolding, and C.A. Dolloff. 2011. Operational forest stream crossing effects on water quality in the Virginia Piedmont. *South. J. Appl. For.* 35(3):123-130.
- Binkley D., and T.C. Brown. 1993. Forest practices as nonpoint sources of pollution in North America. *J. Amer. Water Res. Assoc.* 29:729-740.
- Blake, G.R., and K.H. Hartge. 1986. Bulk density. P. 363-367. In *methods of soil analysis, Part 1, physical and mineralogical methods*, Klute A. (ed.) Amer. Soc. Agron. Inc. and Soil Sci. Soc. America, Inc. Madison, WI.
- Boston, K. 2012. Impact of the ninth circuit court ruling (Northwest Environmental Defense Center v. Brown) regarding forest roads and the Clean Water Act. *J. For.* 110(6):344-346.
- Brown, K.R., W.M. Aust, and K.M. McGuire. 2013. Sediment delivery from bare and graveled forest road stream crossing approaches in Virginia Piedmont. *For. Ecol. Mgt.* 310:836-846.
- Groover, M.C., M.C. Bolding, J.L. Conrad, W.S. Ford, and W.M. Aust. 2010. Estimating construction and closure costs of minimum standard forest roads, bladed skid trails, and water crossings. In *proceedings from COFE*. p7.

- Kochenderfer, J.N., and J.D. Helvey. 1987. Using gravel to reduce soil losses from minimum-standard forest roads. *J. Soil Water Cons.* 42:46-50.
- Lang, A.J., W.M. Aust, M.C. Bolding, S.M. Barrett, K.J. McGuire, and W.A. Lakel, III. 2015. Streamside management zones compromised by stream crossings, legacy gullies, and over harvest in the Piedmont. *J. Amer. Water Res. Assoc.* 1-12.
- Luce, C.H., and T.A. Black. 1999. Sediment production from forest roads in western Oregon. *Water Res. Research.* 35(8):2561-2570.
- MacCurdy, M.G., and D.L. Timmons. 2013. Questions remain for the timber industry after Supreme Court's decision in *Decker v. Northwest Environmental Defense Center*. *Environ Law.* 43:827-846.
- MacDonald, L.H.D., and D. Coe. 2007. Influence of headwater streams on downstream reaches in forested areas. *For. Sci.* 53(2):148-168.
- McBroom, M.W., R.S. Beasley, M. Chang, and G.G. Ice. 2008. Storm runoff and sediment losses from forest clearcutting and stand re-establishment with best management practices in East Texas, USA. *Hydro. Proc.* 22(10):1509-1522.
- Robichaud, P.R., and R.E. Brown. 2002. Silt fences: an economical technique for measuring hillslope soil erosion. USDA For. Serv., Gen. Tech. Rep. RMRS-GTR-94, Rocky Mountain Research Station.
- Swift, L.W., Jr., and R.G. Burns. 1999. The three Rs of roads. *J. For.* 97(8):40-44.
- Virginia Department of Forestry. 2011. Virginia's Forestry Best Management Practices for Water Quality: Technical Manual. Fifth ed. Virginia Dept. of Forestry, Charlottesville.
- Yoho, N.S. 1980. Forest management and sediment production in the south - a review. *South. J. Appl. For.* 4(1):27-36.

## IX. Concurrent Session 3B – Biomass Processing Logistics

### Using Pre-commercial Thinning Residues as a Woody Biomass Feedstock: An Economic Feasibility Analysis

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Pre-commercial thinning (PCT) is a stand treatment sometimes used in the southeast to mitigate southern pine beetle outbreak risk and increase individual stem diameter growth. Conventional PCT treatments typically incur an added management cost to landowners. Residues from PCT are usually left on site and remain unutilized. If harvestable volumes of biomass exist in PCT stands, harvesting PCT biomass may be financially preferable to conventional PCT treatment for landowners. However, little is known about realistic volumes available for harvest in PCT stands. Additionally, most research regarding biomass harvesting has placed emphasis on older pine stands with less emphasis on operations in young, small-diameter southern pine stands. Inventories of PCT stands in the 5-7 and 8-12-year old age groups were completed in Virginia to determine standing biomass quantities prior to thinning. We then inventoried a 15-year old pine stand and completed a harvesting case study on a first commercial thinning of the stand to determine machine productivity and harvesting costs of utilizing small-diameter stems for biomass in “near-PCT” conditions. Results of the PCT stand inventory showed standing biomass volumes of 14.47 gt/acre and 39.63 gt/acre for the 5 – 7 and 8 – 12 age groups compared to a standing volume of 57.91 gt/acre in the 15-year old first commercially thinned stand. Total cut-and-haul costs of the operation were \$23.46/gt, higher than delivered prices for biomass in the region. However, if payments to a logger are less than the cost of conventional PCT treatment, harvesting PCT biomass may be financially preferred for landowners.

**Keywords:** pre-commercial thinning, biomass, utilization, feasibility



## 1. Introduction

Throughout the southeast US, southern pine beetle (SPB) can have a devastating effect on southern pine stands. It is estimated that over 1 billion ft<sup>3</sup> of timber mortality losses were caused by the most recent SPB outbreak between the years of 2000 and 2002 (Coulson and Klepzig 2011). Densely stocked southern pine stands, caused by prolific natural regeneration (Grano 1969, Mann and Lohrey 1974), can increase stand susceptibility to SPB outbreak (Hedden and Billings 1979, Nowak et al. 2008). To mitigate SPB infestation and spread, pre-commercial thinning (PCT) has proven to be an effective silvicultural method (Burkhart et al. 1986, Belanger et al. 1993). In Virginia, PCT is typically accomplished manually with the use of brush saws (VDOF 2015), leaving thinned stems on site that are not utilized for any forest products (Perlack et al. 2011). Since PCT traditionally incurs an added management cost to landowners, some states offer cost-share programs to help combat the expense, such as the Virginia Department of Forestry's Pine Bark Beetle Prevention Program (VDOF PBBPP) (Watson et al. 2013). The VDOF PBBPP provides private landowners a 60% cost-share offering to help reduce the added management cost of PCT. Pine stands enrolled in the program must be no older than 15-years old and contain an average density of at least 800 stems/acre prior to thinning.

As woody biomass energy remains viable in the southeast US, currently unutilized PCT residues may provide additional feedstock for biomass energy facilities. Previous studies have identified PCT residues as a potential source for woody biomass energy (Perlack et al. 2011, Staudhammer et al. 2011). However, limited information exists on the volumes available for harvest in PCT stands. Several harvesting case studies have analyzed the productivity and costs of utilizing small-diameter stems for biomass (Bolding and Lanford 2005, Mitchell and Gallagher 2007, Pan et al. 2008), although these case studies have commonly taken place in pine stands 20 years and older, outside the age range of conventional PCT treatments. Therefore, the stand densities and volumes in these studies would reasonably differ from what would be expected in a traditional PCT stand.

The objectives of this study were to 1) complete an inventory of PCT stands to estimate potentially harvestable biomass, 2) perform a harvesting case study to estimate machine costs associated with utilizing small-diameter stems for biomass, and 3) assess the feasibility of utilizing PCT biomass based on regional prices for biomass and the results from the inventory and case study.

## 2. Methods

To attain estimates of woody biomass volume in PCT stands, we inventoried 241 plots across 18 pine stands enrolled in the VDOF PBBPP. Circular 1/250th fixed-acre plots were used to complete the inventory, practical for this application considering PCT stands can exceed densities of 5,000 stems/acre (Grano 1969, Lohrey 1977). A combination of equations was used to calculate biomass in units of green tons/acre. Measured plots were divided among two age groups (5 – 7 and 8 – 12-years old) to compare differences in volume and density.

The inventory of the 15-year old loblolly pine stand was completed using 46-1/10th fixed-acre plots. The thinning prescription used was a combination row and select thinning to reduce the initial stand density of 723 pine stems/acre down to a residual 330 stems/acre. All stems removed were chipped for biomass and no merchandising took place. Equipment used for the harvesting case study included three Tigercat 718 feller-bunchers, two Caterpillar 535C skidders, and one Peterson 4300 mobile chipper. All equipment operators were regarded as well-experienced. Activity and elemental time studies were employed to observe harvesting equipment and attain productivity information to calculate harvesting costs using the machine rate method (Miyata 1980) combined with the Auburn Harvest Analyzer (AHA) (Tufts et al. 1985).

## 3. Results

Results of the PCT stand inventory showed standing pine volumes of 14.45 and 39.63 gt/acre in the 5-7 and 8-12 age groups, while the inventory of the 15-year old case study site determined a volume of 57.91 gt/acre (Figure 1). Stand densities of pine for the 5 – 7 and 8 – 12 age groups were 3,120 and 4,420 stems/acre, respectively, while density for the 15-year old site was 723 stems/acre, much lower than the density of the PCT stands (Figure 2).

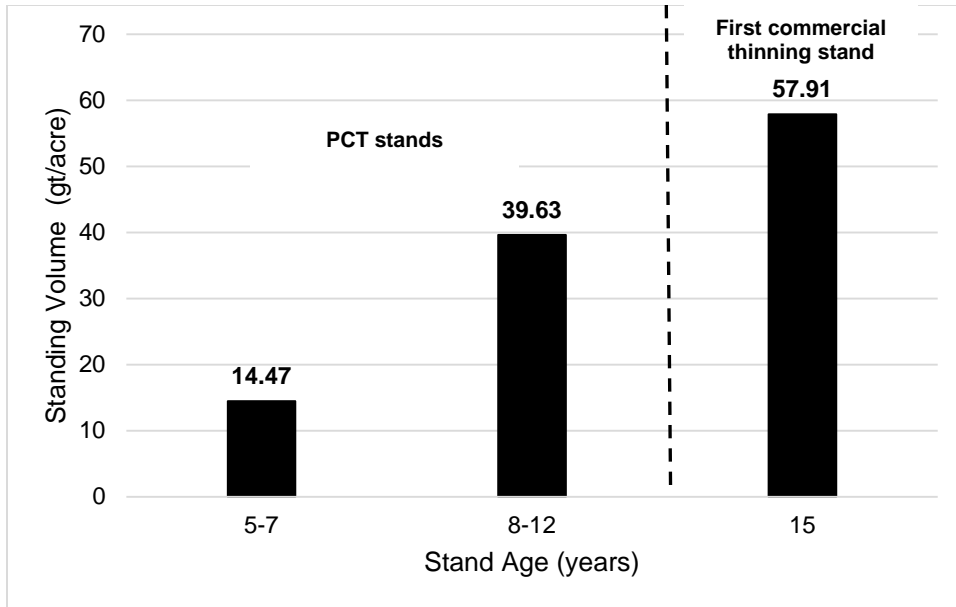


Figure 1. Standing pine volumes of inventoried PCT stands and first commercial thinning stand

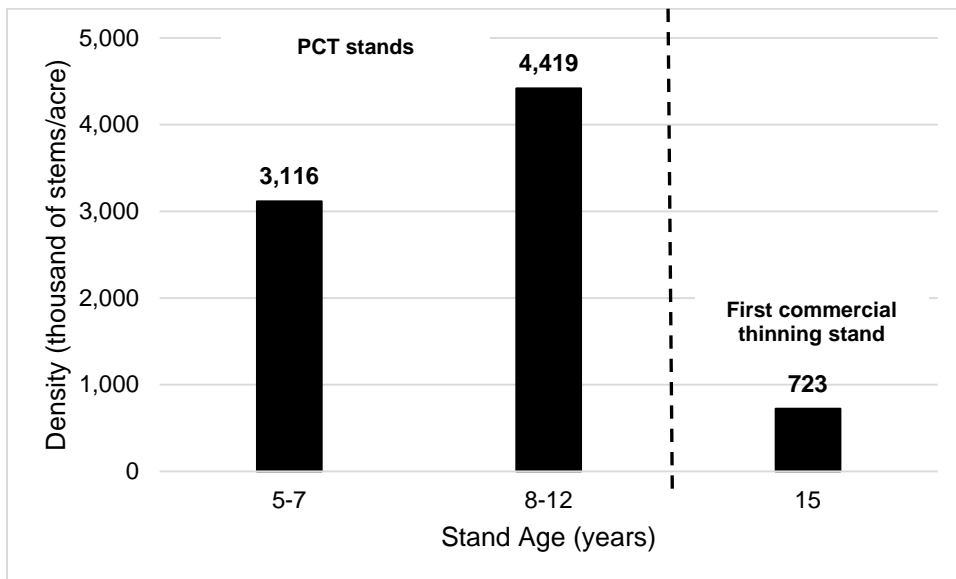


Figure 2. Pine density of inventoried PCT stands and first commercial thinning stand

Based on the volumes of the 8-12 age group and the 15-year old case study site, commercial volumes of biomass may exist in PCT stands at the upper age limit for treatment. Considering partial harvest volumes in the southeast are commonly around 30 gt/acre (Baker et al. 2012), harvestable volumes from PCT stands may be profitable for loggers. However, the volume in Baker et al. 2012 is likely based on roundwood and not biomass, therefore, we would

reasonably expect a lower amount of volume to come from the small-diameter stems in PCT stands.

After compiling productivity information, total harvesting costs for the case study, as determined by the AHA, were \$23.46/gt (Table 1). Individual function costs were \$6.94/gt for hauling, \$5.12/gt for felling, \$4.67/gt for chipping, and \$4.34/gt for skidding. The relatively high cost of the felling function was likely accrued to the high number of machines (3 feller-bunchers) used throughout the study. This total cut-and-haul cost was higher than the regional average delivered biomass price of \$17.35/gt (Timber Mart South 2014).

Table 1. Total harvesting costs in case study

	Per Green Ton
On-board truck (felling, skidding, and chipping)	<b>\$16.52</b>
Total cut-and-haul (felling, skidding, chipping, and hauling)	<b>\$23.46</b>
Delivered chip price (Timber Mart South 2014 3 <sup>rd</sup> Quarter)	<b>\$17.35</b>

Depending on the harvesting costs associated with utilizing PCT biomass, landowners may have an opportunity to reduce the added management cost of conventional PCT treatment. If revenues minus costs for a logger harvesting PCT biomass are less than the cost of a conventional PCT treatment to a landowner, harvesting PCT biomass would be financially preferable for the landowner.

#### 4. Conclusion

An inventory of PCT stands was completed with 241 plots spread across 18 southern pine stands enrolled in the VDOF PBBPP followed by an inventory of a 15-year old southern pine stand that was commercially thinned for biomass-only with conventional logging equipment. Results of the PCT stand inventory showed volumes of 14.47 and 39.63 gt/acre for stands in the 5 – 7 and 8 – 12-year old age groups. The inventory of the case study stand showed a standing pine volume of 57.91 gt/acre and the total cut-and-haul costs of the operation were \$23.46/gt.

This study showed that while the volume in a PCT stand may be less than a first commercially thinned stand, there may be a potential opportunity to harvest PCT biomass

rather than use conventional PCT treatment. If harvesting costs are wholly or partially outweighed by the delivered price of biomass, management costs to the landowner can potentially be reduced or even turned into a profit.

To further assess the feasibility of utilizing PCT biomass for energy, additional research regarding PCT stand biomass volumes and harvesting productivities is needed. Additional inventories of PCT stands would help to provide better estimates of harvestable biomass. Other production studies conducted in pine stands in the more traditional PCT age range (e.g. less than 15-years old) would provide for more realistic estimates of the harvesting costs associated with utilizing and harvesting PCT biomass.

## 5. Literature Cited

- Baker, S., Greene, D., and T. Harris. 2012. Impact of timber sale characteristics on harvesting costs. In Proc. Southern Forest Economics Workshop, Charlotte, North Carolina. pp. 94-105.
- Belanger, R. P., Hedden, R. L., and P. L. Lorio. 1993. Management strategies to reduce losses from the southern pine beetle. *Southern Journal of Applied Forestry*, 17(3):150-154.
- Bolding, M. C. and B.L. Lanford. 2005. Wildfire fuel harvesting and resultant biomass utilization using a cut-to-length/small chipper system. *Forest Products Journal*, 55(12):181-189.
- Bolding, M. C., Kellogg, L. D., and C.T. Davis. 2009. Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon. *Forest Products Journal*, 59(3):35-46.
- Burkhart, H. E., Haney, H. L., Newberry, J. D., Leuschner, W. A., Morris, C. L., and D.D. Reed. 1986. Evaluation of thinning for reduction of losses from southern pine beetle attack in loblolly pine stands. *Southern Journal of Applied Forestry*, 10(2):105-108.
- Coulson, R.N., and K.D. Klepzig. 2011. Southern Pine Beetle II. General Technical Report SRS-140. USDA Forest Service Southern Research Station, Asheville, NC. 512 pp.
- Grano, C. X. 1969. Precommercial thinning of loblolly pine. *Journal of Forestry*, 67(11):825-827.
- Hedden, R. L., and R. F. Billings. 1979. Southern pine beetle: factors influencing the growth and decline of summer infestations in east Texas. *Forest Science*, 25:547-566.
- Lohrey, R. E. 1977. Growth responses of loblolly pine to precommercial thinning. *Southern Journal of Applied Forestry*, 1(3):19-22.
- Mann, W. F. and R.E. Lohrey. 1974. Precommercial thinning of southern pines. *Journal of Forestry*, 72(9):557-560.
- Mitchell, D. and T. Gallagher. 2007. Chipping whole trees for fuel chips: A production study. *Southern journal of applied forestry*, 31(4):176-180.

- Miyata, E.S. 1980. Determining fixed and variable costs of logging equipment. General Technical Report NC-55. USDA Forest Service North Central Forest Experimental Station, St. Paul, Minnesota. 20 pp.
- Nowak, J., Asaro, C., Klepzig, K., and R. Billings. 2008. The southern pine beetle prevention initiative: working for healthier forests. *Journal of forestry*, 106(5):261-267.
- Pan, F., Han, H. S., Johnson, L. R., and W. J. Elliot. 2008. Production and cost of harvesting, processing, and transporting small-diameter ( $\leq 5$  inches) trees for energy. *Forest products journal*, 58(5):47-53.
- Perlack, R. D., Stokes, B.J., Lead Authors. 2011. US billion-ton update: biomass supply for a bioenergy and bioproducts industry. United States Department of Energy, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 235 pp.
- Staudhammer, C., Hermansen, L. A., Carter, D., and E. A. Macie. 2011. Wood to energy: using southern interface fuels for bioenergy. USDA Forest Service Southern Research Station, Asheville, North Carolina. 100 pp.
- Timber Mart South. 2014. Norris Foundation, University of Georgia, Athens, Georgia. 3rd quarter.
- Tufts, R. A., Lanford, B.L., Greene, W.D., and J.A. Burrows. Auburn harvesting analyzer. *Compiler* 3(2):14-15
- Virginia Department of Forestry. 2015. Available at:  
<http://www.dof.virginia.gov/locations/chesterfield.htm> (last accessed Apr. 24, 2015)
- Watson, A. C., Sullivan, J., Amacher, G. S. and C. Asaro. 2013. Cost sharing for pre-commercial thinning in southern pine plantations: Willingness to participate in Virginia's pine bark beetle prevention program. *Forest Policy and Economics*, 34:65-72.

## Optimization of in-field drying of wood logging residues for energy products

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Dry wood has higher net energy content than green wood and transporting water in wood is expensive, however current forest harvest procurement procedures pay by delivered weight thus rewarding the transport of moisture content and not the delivery of energy. A feedstock producer gets paid the same for a ton of dry wood as for a ton of green wood, but (air) dry wood has 75% more usable energy than green wood (per unit weight). North Carolina State University is developing efficient woody biomass logistics that take advantage of natural drying processes at the harvest site to increase net energy content per ton and decrease the delivered cost per unit of energy. Using wood dried on trailers, we have previously demonstrated that chipping dried wood is both more energy efficient and productive and that dried wood can be dynamically measured for moisture content as it is delivered. This current study details the drying behavior of hardwood tops field dried in windrows on a harvested site. Windrows were made with grapple skidders in two sizes, single grip wide and double grip wide. Approximately 400 green tons of windrowed wood was piled for this study. Skidder time and fuel use to establish and disassemble these windrows was measured. On a monthly basis, transverse cuts were made into each size of pile. Each stem diameter greater than .5" was measured and its vertical and horizontal location noted. Samples of stems were taken on 10-15% of measured stems to assess moisture content. This information was used to predict overall pile drying rates as well as optimal pile sizing to maximize drying rate or minimize variability in drying. Overall energy input (diesel) to energy gain (wood) estimates were made for both green wood and field dried wood.

# Techniques to Reduce Moisture Content of Forest Residues at the Harvest Site

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The moisture content (MC) of biomass derived from forest residues can pose a challenge to biomass recovery operations. It plays a significant role in determining the cost of transportation and subsequent market price. Additionally, emerging biomass conversion technologies, such as biochar, torrefaction, and briquetting, have very narrow specifications for the MC of their feedstocks. The goal of this study was to evaluate different arrangement patterns of forest residues and its effect on MC reduction at the harvest site. The study compared criss-cross, teepee, traditional piling (processor piled), and scattered residues in three different timber harvest units in northern California. Periodically, wood disc samples were collected from each treatment using a transect method to measure MC. The MC for each treatment was recorded for one year, starting July 2014. Other weather parameters such as average temperature, relative humidity and amounts of precipitation were collected on a daily basis from a nearby weather station. Initial results showed little variation in MC among the treatments and that relative humidity seemed to be directly related to MC. Expected results include a weather based model to predict the drying rates of forest residues for each type of stack pile and the cost of constructing the different arrangement patterns.

**Keyword:** forest residue piles, scattered trees, transect sampling

## 1. Introduction

The market price and transportation costs of woody biomass are highly dependent on the moisture content (MC) present in them (Kofman and Kent 2007; Ochoa 2012). Woody biomass feedstock with less MC is higher priced and letting wood dry for up to a year is economically beneficial for the biomass producer as long as the feedstock is priced in terms of MC at delivery (Roise et al. 2013). Studies in Europe have shown that an 8 month storage of forest residues can reduce the MC up to 25% and increase the heating value up to 4 KWh/kg, thereby having an economic gain of \$9 -15/oven dry ton (Erber 2013). Reduction in MC of woody biomass increases the net energy content and further reduces the harvest and transportation cost of biomass (Roise et al. 2013).



Emerging biomass conversion technologies, such as biochar, torrefaction, and briquetting, can potentially further enhance the economic value of the forest residues; however, these technologies require very narrow specifications for the MC of their feedstocks.

### **1.1 Factors affecting moisture reduction in forest residue piles**

The factors affecting the MC of forest residues have been widely researched (Gigler et al. 2000; Filbakk et al. 2011; Nurmi and Lehtimäki 2011; Gautam et al. 2012; Ochoa 2012).

Generally, favorable storing conditions are sunny, elevated, open, and wind-accessible locations (Erber et al. 2014). Walker (1993) identified seven key factors that affect the rate of MC reduction:

- Relative Humidity: Lower relative humidity promotes increased drying rate.
- Temperature: High temperature has a positive effect on the moisture removal
- Air Flow: Sufficient air flow circulation on the wood surface helps to remove the humid air which can then be replaced by drier air.
- Moisture Gradient: as the steepness of the moisture gradient increases, MC decreases, diffusion rate increases, therefore increasing the rate of flow of water through the wood.
- Species: Certain species dry faster than others; typically softwoods dry faster than hardwoods.
- Initial MC
- Diameter: wood with larger diameter requires more time to dry to a given MC, given the same atmospheric conditions in comparison to wood with smaller diameters.

This study investigates the effect of arrangement patterns (different types of pile structures) on moisture content (MC) reduction during storage of forest residues. The primary objective of this study was to assess the variation in MC related to the different arrangement patterns, and storage period.

## **2. Methodology**

### **2.1 Study site**

The study was conducted on three similar timber harvest units in Humboldt County, California (Figure 1). The Little River weather station (Lat. 48° 45.667' N, Long. 91° 37.683'W) located about one mile away recorded the mean annual temperature and precipitation

accumulation as 51° F and 47 inches, respectively. According to the Köppen classification, the climate is characterized as being Csb (Coastal Mediterranean climate), mild with a cool and dry summer. The sites were about 1,720 to 2,400 ft above mean sea-level and the terrain had ground slopes up to 111 percent (48°).

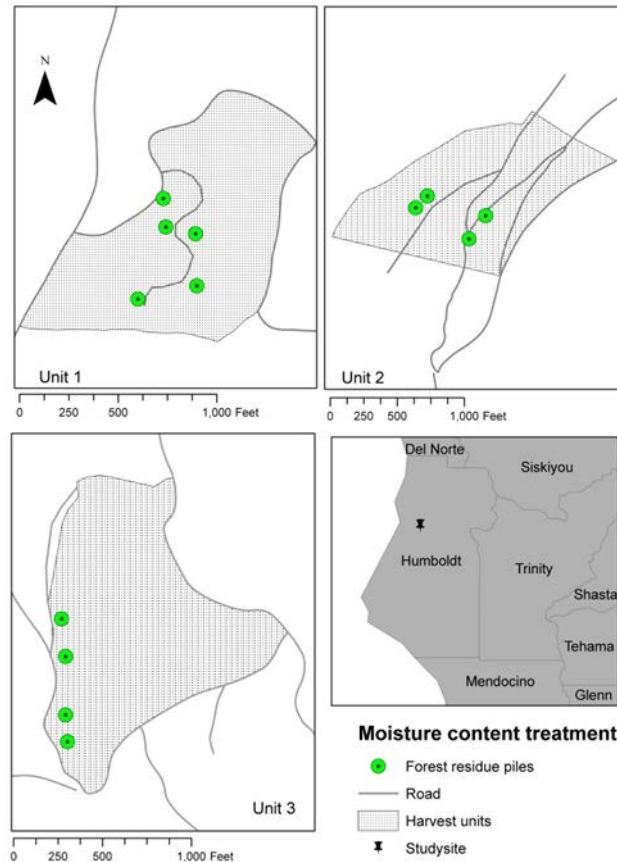


Figure 1. Study units for moisture content reduction in forest residues piles in Humboldt County, California

## 2.2. Outline of the experiment: Pile building and sampling

The materials used to construct the forest residue piles were composed of processed (delimbed) tree tops, broken logs and non-merchantable whole tree of coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and tanoak (*Notholithocarpus densiflorus*).



Figure 2. The forest residue arrangement patterns. 1. Teepees; 2. Processor piles; 3. Criss-cross piles; and 4. Scattered

The trees were harvested during July of 2014, the piles were created in August, then stored for 10 months until June 2015. Sampling was conducted every month after the installation of the experiment. Machinery used to construct the piles varied; however, most piles were constructed with a loader and some with a processor. The locations of the piles were designed as to ensure they were on the road side and received minimal shade throughout the day.

The four different arrangement patterns were (Figure 2):

1. Criss-cross: This pile type was designed exclusively for the study purpose. A loader constructed the pile with the intention of maximizing airflow. The platforms were raised from the ground to minimize water stagnation beneath them during a rainstorm event. The materials were predominantly processed (delimbed) tree tops, broken logs and stems of non-merchantable species.
2. Processor pile (stacked pile): Uniformly arranged piles created by the processor with the butt-ends placed together. They were composed of delimbed tree-tops generated from processing. Occasionally, broken logs and small diameter trees were also included.
3. Teepees: The conventional way of piling forest residues in the region. These piles were composed of all forest residues including tree-t ops, chunks, branches, broken logs, and small-diameter trees.
4. Scattered: These were forest residues left at the harvest units and not brought to the landing during the primary transportation (stump to landing).

### 2.3. Estimation of moisture content and weather conditions

Transect sampling was used for sample collection (Figure 3). The sampling points of the piles were designed such that they represented the geometric shape of the pile and allowed access to the point of sampling, without affecting the conditions of storage. Transects were created by markings or laying ribbons in specific orientation at equal intervals during the construction of the stack pile. Materials that fell on the transect were then systematically selected based on the required number of samples for each class (eg. diameter class, tree species, etc.) (Filbakk et al. 2011). For the rest of the study the samples were collected from the same section of the pile. Selected wood pieces



were cut with a chainsaw at the point of the intersection to expose the complete diameter to extract the wood discs (Gautam et al. 2012). The remaining materials that were not sampled were left undisturbed for future sampling. This approach ensured that continuous sampling was possible in natural in-field conditions and also took into consideration various geometries of the sample piles (Figure 3). Since it was not possible to collect a sample from the middle of the pile, sampling was carried out by cutting access points into the pile arrangement. Safety of the personnel operating the chainsaw was given utmost priority during sample collection.

Samples were taken every month between 15th to 20th at 12:00 pm to 2:30 pm. Sampling was not done on rainy days and days following rain fall events. Wood discs were cut from branches of the selected wood piece with a thickness ranging from 1 -2 inches by using a gasoline-powered chain saw (Stihl MS 290). The samples were cut at least one foot away from the end of the branch because wood picks up and loses moisture very rapidly through the end grain; a phenomenon referred to as edge effect (Reeb and Milota 1999; Erber et al. 2014). Once a sample was taken from a particular wood piece, it was then excluded from sampling during the remainder of the study. Samples collected were classified into the following categories: two diameter classes (less than and greater than three inches), species (hardwood and conifer), and forest residue pile type.

#### **2.4. Oven drying**

The discs collected were initially weighed in the field right after extraction. Later at the laboratory, the diameter was measured and MC assessment procedures were carried out by the oven dry method according to current standards. The samples were then dried at 103° C for 3 days and then re-weighed. The difference in weight was the amount of water within the sample. Depending on the tree species, extractives can represent a small share of this weight. Needles and twigs hold more extractives than stem wood (Erber et al. 2014).

All weight measurements were based on oven dry basis. Weather data such as ambient temperature, relative moisture, wind speed and precipitation were collected from a nearby meteorological station throughout the storage period.

#### **2.5. Analysis of the data**

Analysis of variance tests were carried out using the General Linear Model in IBM SPSS Statistical Software 2. The datasets were initially screened for outliers followed by which the

null hypotheses of no significant difference in MC was tested for different storage periods (months) and pile arrangements. Difference within the diameter class (1-3 inch and greater than 3 inches) and species (hardwood and conifers) were tested using t-tests. Paired t-tests were used to test significance between MC values taken from moisture meters and oven drying methods. The experimental designs for all the models were full factorial design, with MC as the dependent variables for each. The data for each model was tested for normality and homogeneity of variance before conducting the analysis of variance. Any significant differences in the analysis were analyzed using post-hoc tests. Scheffe’s test was preferred because most of the sample populations were not of similar size.

### 3. Results and discussion

More than 2600 discs were collected from 11 piles over 10 months of sampling. The diameter of the discs sampled ranged between 1.0 to 15.4 inches with an average of 4.6 inches. The length of the wood piece averaged 24 ft and the large-end diameter 6 inches. The average dimensions (height x width x length) for the criss-cross and processor piles were 8 x 27 x 37 and 7 x 22 x 32 feet, respectively. The teepees were generally larger in size with some having heights up to 35 feet. The average dimensions (height x diameter) were 21 x 56 feet.

Table 1. Dimensions of the forest residue piles in feet.

Pile type	Unit	Height	Width	Length
Criss-cross	1	8	29	36
	2	6	26	33
	3	11	27	41
Processor pile	1	7	20	31
	2	6	17	27
	3	8	30	39
Teepees	1	20	Diameter 60	

1	35	61
2	12	60
3	22	58
3	16	41

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### 3.1 Setting the experiment

T-test results on the MC data obtained from the oven drying method and moisture meter (for the first three months) showed that the values were significantly different ( $p < 0.001$ ). Therefore, the oven drying method was adopted for the rest of the sampling. MC measurements using moisture meters were not as reliable as the disc extraction techniques because moisture can vary greatly depending on where the measurement was taken. Even if the chainsaw resulted in minor reduction in MC due to the heat generated during sawing, it is still regarded as an efficient method for MC measurements. Initial MC for the forest residues prior to pile construction ranged from 12 to 76% with an average of 35%.

Wood discs were collected from different parts of the branch /stem (top, middle and base) in order to see if the MC varied across the length of the branch. ANOVA indicated that there was no significant difference between the various parts of the wood piece ( $p=0.902$ ) suggesting that the wood disc taken from any part of a particular stem would represent the whole stem. It should be noted for this study that the base and top discs were cut one foot from the exposed ends. However, it is known that the MC tends to be higher in the middle of the wood piece compared to the exposed ends.

### 3.2 Moisture reduction

The results are divided in several sections with the intention of examining the relationship between MC and other variables such as diameter of the wood piece, month/time since harvest, species, and forest residue pile structures.

### 3.2 Storage period

The MC losses due to storage were highest in the beginning of the storage period (July and August 2014), this was due to the high temperature during these initial months (Figure 3).

Once the tree is felled, green wood loses moisture quickly during the period as it loses free water. Gradually, equilibrium of the MC reduction is attained with the temperature and relative humidity. Thereafter the rate of drying is reduced (Gautam 2012).

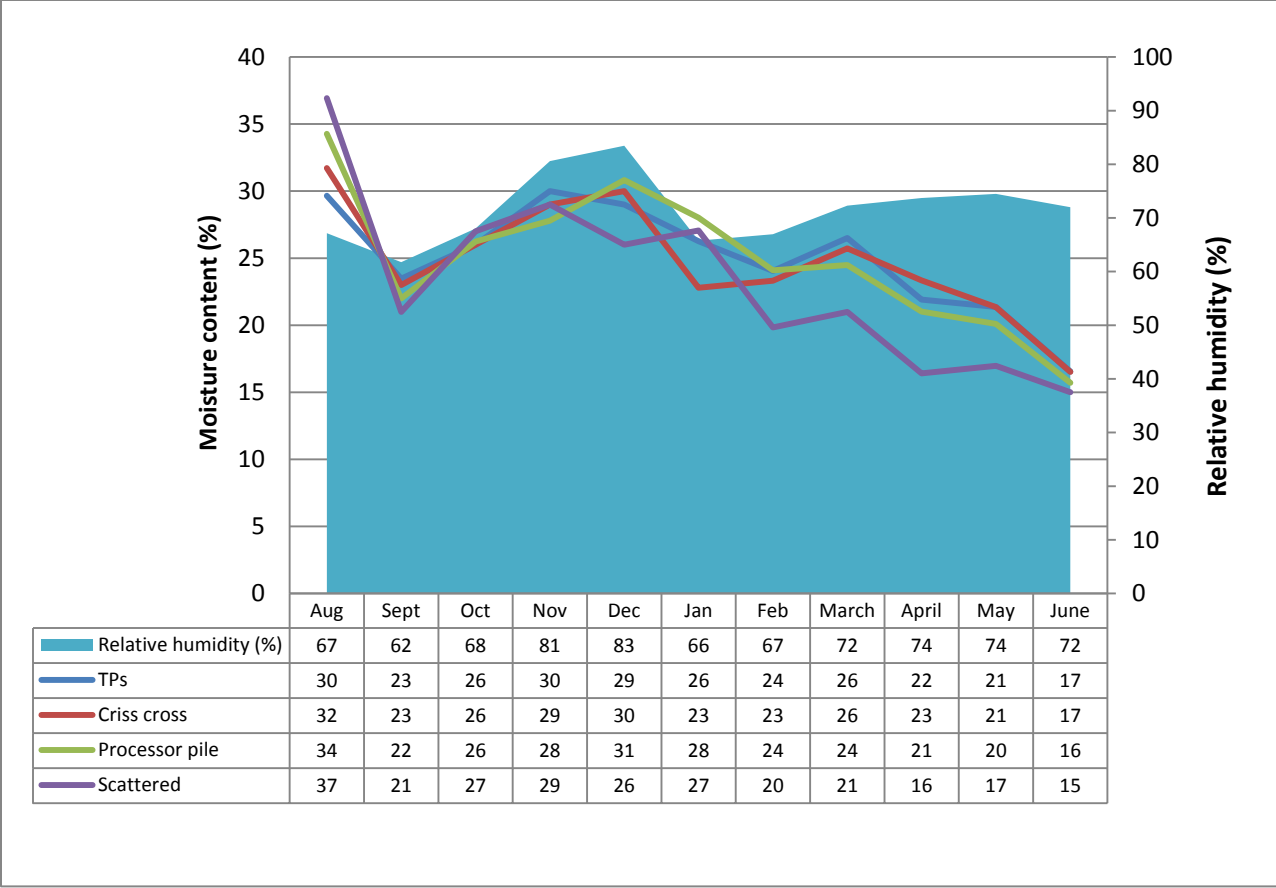
ANOVA showed that there was a significant difference in the MC between the months ( $p < 0.001$ ). Post-hoc tests revealed that the differences were basically between various seasons and no significant difference existed within the seasons, which suggests that the average MC of the forest residues dropped during the period of storage (Figure 3). July and August, 2014 (Month 1 and 2) could be placed under one season having the highest loss in MC. Free water from the freshly felled trees was likely lost in this season. October through March would be another subset with no significant difference in moisture loss. During this season the wood materials might have attained equilibrium with the surrounding environment. May to June, 2015 showed the next drop in MC, which could be attributed to the high temperature during the period. These three sub-groups were significantly different from the others ( $p < 0.001$ ).

### **3.3 Species and diameter**

There was significant difference between the species ( $p < 0.001$ ). Guatam et al. (2012) explained this as the difference between the chemical composition and anatomical structure for hardwood and softwood species. Hardwood species having 25 -40% hemicellulose, as opposed to 20- 30% in softwoods, tends to bond more with water because hemicellulose is the most hygroscopic component of cell wall. The other reasons included were that the cell walls of hardwoods generally have more potential bonding sites for water than softwoods.

T-tests done to determine the effects of the diameter class showed that there was a significant difference between the two groups ( $p = 0.028$ ). Four inch diameter was taken as the cut-off limit because the materials with a minimum four inch diameter could be potentially chipped for higher quality feedstock. All materials less than 4 inches (minimal diameter materials) will have to be sent to a grinder as a part of comminution because they could clog at the mouth of the chipper. Larger sized wood (average of 28%) tends to hold more water when compared to smaller wood pieces (average of 24%).





### 3.4 Pile arrangements and its impact on forest management

Storage of the forest residue for up to a year prior to utilization has been proven to be economical (Erber 2013). This is due to an increase in value due to the MC reduction in the forest residues. In this study on average there was a reduction in MC from 51% (fresh cut) to 16% (June, 2015). As the secondary transportation component of the biomass feedstock accounts for almost half of the total production costs (McDonald et al. 2001; Kizha et al. 2015), this practice ensures maximum amount of material being transported per load (Ronnqvist et al. 1998; McDonald et al., 1995). However, storage of the material will tie up capital costs and demand use of piled land area for replanting (Filbakk et al. 2011).

The Criss-cross and processor piles had minimal amounts of inorganic contamination. Therefore, they could be potentially chipped, rather than ground, to produce even sized

feedstock which is higher quality and can be utilized in a Biomass Conversion Technology. The teepees on the other hand, had a large variation of material sizes, ranging from foliage to larger branches and chunks and could only be grinded because separating the tops and stem wood from them would make the operation economically infeasible. The soil contaminations were also very high for these pile structures. These piles were comparatively easier to burn when compared to scattered forest residues and also reduced the risk of forest fire spill outs during burning sessions. Furthermore, piled forest residues can be more efficiently burned under adverse weather conditions, thereby reducing the quantity of smoke emitted. It also can be done with reduced staffing levels (Wright et al. 2010).

A loader constructed the criss-cross piles and teepees. The processor piles, as the name indicates, were created by the processor with a low cost of constructing (Kizha. and Han 2015). Even though the least cost incurred with the scattered treatment during the operation, collection of these forest residues will require machine re-entry, which can significantly increase the cost of storage. From an environmental point of view, these forest residues can be unsafe to the forest eco-system because it increases fire risk for the area. The downed woody debris could further attract pest and parasites. Forest residue accumulation it also minimizes the area available for re-planting (Alcorn 2015).

#### **4. Future analysis**

This is an on-going study; the data collection is expected to end by August 2015. The weather parameters such as, ambient temperature, relative moisture, wind speed, and precipitation, will be collected from the nearest weather station for the entire storage period. These will be used to develop a model to predict the rate of drying for the four forest residue pile structures. Other parameters which will be used to model will include storage months, species, and diameter. The cost of constructing the different types of piles will also be evaluated.

#### **5. Conclusions**

The effect of storage on the MC of forest residue stored under natural climatic conditions prevalent in the pacific north coast for 10 months showed that the MC of forest residues decreased with storage time. The highest drying rate was observed for the initial months of storing and as time passed the drying rate was in equilibrium with the atmospheric conditions. There was no significant difference in MC reduction between three of the four

arrangement patterns (criss-cross, processor pile, and teepees). However, these three were different from scattered treatment.

## 6. Acknowledgement

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## 7. References

- Alcorn M. 2014. Personal Communication.
- Erber, G., J. Routa, L. Wilhelmsson, J. Raitila, M. Toiviainen, J. Riekkinen, and L. Sikanen. 2014. A prediction model prototype for estimating optimal storage and sorting. Finnish Forest Research Institute, Vantaa, Finland.
- Filbakk, T., O. Høibø, and J. Nurmi. 2011. Modelling natural drying efficiency in covered and uncovered piles of whole broadleaf trees for energy use. *Biomass Bioenergy*. 35(1):454–463.
- Gautam, S., R. Pulkki, C. Shahi, and M. Leitch. 2012. Fuel quality changes in full tree logging residue during storage in roadside slash piles in Northwestern Ontario. *Biomass Bioenergy*. 42:43–50.
- Gigler, J. K., W. K. P. Van Loon, J. V. Van Den Berg, C. Sonneveld, and G. Meerdink. 2000. Natural wind drying of willow stems. *Biomass Bioenergy*. 19(3):153–163.
- Kizha. A.R. and H-S Han. 2015. Cost and productivity for processing and sorting forest residues. 38th Council on Forest Engineering. Annual Meeting. July 19 -22, 2015. Lexington, Kentucky.
- Kizha. AR, H-S Han, T. Montgomery and A. Hohl. 2015. Determining cost zones and hot spots for procuring feedstock for woody biomass-based power plants in northern California. *California Agriculture Journal*, Special issue of on Forests and Bioenergy.
- Kofman, P.D and T. Kent. 2007. Harvesting and processing forest biomass for energy production in Ireland. The Forest Energy 2006 preprogramme. COFORD, Dublin.

- McDonald, T., Stokes, B. and McNeel, J. 1995. Effect of product for, compaction, vibration and communication on energywood bulk density. In Proceedings of a Workshop on Preparation and Supply of High Quality Wood Fuels; 1994 June 13-16; Garpenberg, Sweden: IEA/BA Task IX; 6-23.
- McDonald, T., Rummer, B., Taylor, S. and Valenzuela, J. 2001. Potential for shared log transport services. P. 115-120. In Proceedings of the 24th Annual Council on Forest Engineering Meeting. Snowshoe Mountain, West Virginia. Wang, J. et al. (eds). Council of Forest Engineering, Corvallis Oregon.
- Nurmi, J., and J. Lehtimäki. 2011. Debarking and drying of downy birch (*Betula pubescens*) and Scots pine (*Pinus sylvestris*) fuelwood in conjunction with multi-tree harvesting. *Biomass Bioenergy*. 35(8):3376–3382.
- Nurmi, J. 1993. Heating values of the above ground biomass of small-sized trees. *Acta Forestalia Fennica* Vol. 236. 19 p.
- Ochoa, F. A. B. 2012. Evaluation of six tools for estimating woody biomass moisture content. Thesis submitted to Oregon State University
- Reeb, J. E., and M. R. Milota. 1999. Moisture content by the oven-dry method for industrial testing.
- Roise, J. P., G. Catts, D. Hazel, A. Hobbs, and C. Hopkins. 2013. Balancing biomass harvesting and drying tactics with delivered payment practice. Technical Report US Endowment for Forestry. Greenville, SC:
- Ronnqvist M., Sahlin, H. and Carlsson, D. 1998. Operative planning and dispatching of forestry transportation. Linköping Institute of Technology, Sweden. Report LiTH-MAT-R-1998-18. 31pp.
- Röser, D., B. Mola-Yudego, L. Sikanen, R. Prinz, D. Gritten, B. Emer, K. Väätäinen, and A. Erkkilä. 2011. Natural drying treatments during seasonal storage of wood for bioenergy in different European locations. *Biomass Bioenergy*. 35(10):4238–4247.
- Walker, C. F. 1993. Primary wood processing principles and practice. London, BR: Chapman & Hall.
- Wihersaari, M. 2005. Evaluation of greenhouse gas emission risks from storage of wood residue. *Biomass Bioenergy*. 28(5):444–453.
- Wright, C. S., C. S. Balog, and J. W. Kelly. 2010. Estimating volume, biomass, and potential emissions of hand-piled fuels. General Technical Report, US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

# Monitoring Moisture Content, Temperature, and Humidity in Whole-tree Pine Chip Piles

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Two whole-tree chip piles were monitored for moisture content, temperature, and relative humidity from October 8th, 2010 to March 16th, 2011 at a location in south Alabama. Initial moisture content samples were collected immediately after chips were delivered to the study location on October 8th for Pile 1 and October 22nd for Pile 2. During pile construction, Lascar EL-USB-2+ sensors were placed at strategic locations within each pile to monitor temperature and humidity. Samples were collected from within each pile over time through a plastic pipe that was placed near the pile center during construction. Initial moisture content for Pile 1 was 51.4%. Samples collected from the middle of Pile 1 over the drying period averaged 48.3%. Pile 2 had an initial moisture content of 46.3% and samples collected from the middle during the drying period averaged 42.2%. The maximum temperature recorded in both piles occurred at the upper location and was 146°F for Pile 1 and 137°F for Pile 2. Both piles had lower moisture contents near the center as compared to moisture contents observed 18-inches below the surface.

**Keywords:** Pine chips, drying, storage.

## 1. Introduction

Storage of wood chips is a common practice of mills for maintaining inventory when deliveries are slow. Clean chips are the most common type of wood that is stored in piles, although storing whole-tree chips is also practiced to keep a fuel source on hand. While storing chips in piles is a responsible practice and helps ensure a continuous feedstock supply, if not properly managed, it can result in degraded chip quality, loss of by-products, nematode infestations, and in extreme cases, spontaneous combustion.

Living cells in wood after it is piled consume oxygen and release heat, which provides an environment conducive for bacterial growth within the first 5 to 7 days (Fuller 1985). Chips stored in piles are at a greater risk of fungus and degradation, resulting in a lower heating value (APA 1981). APA (1981) concluded that hardwood chips and whole-tree chips produce the greatest amount of fungus. The formation of acetic acid can occur after the development of

bacteria in the pile and is influenced by factors such as pile height, the degree of compaction, and the amount of chip fines and sawdust present (Springer and Hajny, 1970). The formation of acetic acid occurs when temperature reaches 140 to 160°F and results in wood deterioration by attacking the cellulose molecule (Fuller 1985). This is most common for large pile heights with a high degree of compaction. For piles with lower heights that are not compacted, wood-rotting fungi are more likely to develop when temperatures drop below 120°F (Fuller 1985).

The most prevalent species of chips used in the Southern U.S. is pine, which is high in resin content. This makes it excellent for producing by-products such as tall-oil and turpentine (Landry and Stillwell, 1984). McDonald and Twaddle (2000) surveyed mills in the U.S. and found that concerns over pile losses varied by region of the country. Size and fungal degradation were important for mills in the Northeast and North Central regions, while chip size and by-product losses were major concerns in the South. Mills in the West were most concerned with brightness loss. Piled pine chips lose turpentine more rapidly than tall-oil. Turpentine losses can reach 70 to 80% after a two-month period for piles 9 to 20 feet in height, while tall-oil losses range from 60 to 70% after two months (Fuller 1985).

Chip piles are also subject to damage caused by micro-organisms such as the pinewood nematode. The development of micro-organisms in chip piles is mainly governed by temperature, although wood moisture also has an impact on the population density of the nematode in chips (Dwinell 1986). The temperature in a chip pile depends on the ambient temperature, the size and compaction of the pile, and the fines and bark content of the chips (Bergman 1985). Dwinell (1986) determined the optimum temperature range for the reproduction of the pinewood nematode in southern pine chips was 95 to 104°F. In addition, nematode densities in chips declined as the percentage of moisture in the chips declined from 40 to 26 nematodes per gram after moisture loss reached 22% after a five-day incubation period (Dwinell 1986).

The heating value of whole-tree chips can be compromised when stored outside. Whole-tree chips stored outside, uncovered, can lose up to 25% of their potential heating value after approximately 120 days (APA 1981). Moisture content of piled chips has an effect on heating value and can vary significantly within a pile. White and Curtis found that outside layers of chip piles tend to increase in moisture content while core zones tend to lose water (APA 1981).

The objective of this study was to monitor moisture content, temperature, and relative humidity over time at various locations inside two piles of uncovered, green whole-tree pine chips. After the monitoring period, moisture content and bulk density at various locations within each pile was also of interest.

## 2. Methods

The project began October 8th, 2010 and was completed on March 16th, 2011. Piles were constructed on an existing concrete slab at an abandoned woodyard in Georgiana, Alabama. Two whole-tree chip piles were constructed using a John Deere 120C tracked excavator (Figure 1). During pile construction, EL-USB-2+ sensors by Lascar Electronics were placed near the center of each pile at approximately 3 feet (bottom), 6 feet (middle), and 8 feet (top) from the ground. Sensors were also placed on the north and south face 18 inches deep. Each sensor was programmed to record temperature and relative humidity once every hour. Prior to the study, new batteries were installed in each sensor. Specifications for temperature and relative humidity of the sensors were 31 to 176°F and 0 to 100%, respectively.



Figure 2. Chip pile construction using an excavator.

Also during pile construction, samples were collected and placed in 5 gallon buckets and sealed with lids for later determination of moisture content, ash content, and particle size. Five samples were collected from each pile. To monitor moisture content over time a 5 foot PVC

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<sup>1</sup> The use of trade or firm names in this publication is for reader information and does not imply endorsement of any product or service by the U.S. Department of Agriculture or other organizations represented here.

pipe was placed in each pile about 4 feet above ground ending near the center. A soil auger was inserted into the PVC pipe to collect samples at designated time frames. Moisture content was assessed as prescribed in European Standard EN 14774-2 (2009). Samples were weighed wet and placed in a drying oven at  $105 \pm 2^\circ\text{C}$  until total mass loss differed by less than 0.2% between measurements taken one hour apart. After piles were constructed, measurements were taken on each pile and included vertical height, base circumference, and slope length. Heights were measured using a clinometer, while circumference and slope length were measured using a cloth tape. From these measurements, total volume for each pile was calculated. Bulk density was determined using procedures outlined in European Standard EN 15103 (2009).

Piles were deconstructed on March 16th, 2011. Prior to deconstruction, total height, base circumference, and slope length were measured. During deconstruction, each pile was split vertically and half removed. This was done so that an internal profile could be revealed and samples collected at strategic locations (Figure 2). Two samples were collected at each location for moisture content determination. Samples collected from locations A, B, and C were also analyzed for bulk density. In addition, three samples were collected from the surface on the north and south face of each pile. Once samples were collected, deconstruction was completed and sensors were recovered.

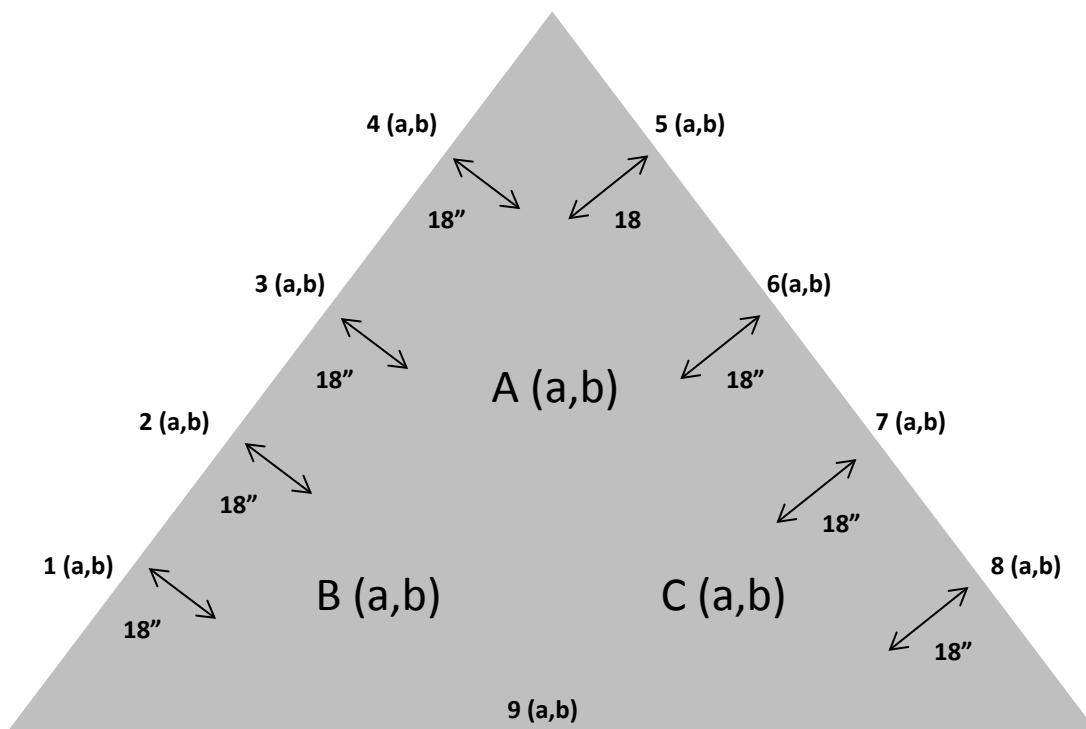


Figure 3. Sample locations during pile deconstruction.



### 3. Results

Climatological data are summarized in Table 1. High and low values for temperature and humidity are averages over the course of the drying period. Mean values for temperature and humidity were calculated by summing all high and low values and dividing by two times the number of drying days. For precipitation, high and low values reflect the maximum and minimum rainfall recorded on a particular day. Values for high wind speed and gust reflect averages over the drying period. A total of 18.78 inches of rainfall was recorded at the Greenville, Alabama weather station during the drying period. During the last three days of the drying period 0.47 inches of rainfall was recorded. A total of 2.71 inches of rainfall was recorded during the last week of the drying period.

Table 1. Climatological data for the drying period from October 8th, 2010 to March 16th, 2011.

Variable	High	Mean	Low	Gust	Total
Temperature (°F)	61.8	50.7	40.1	-	-
Humidity (%)	90.7	67.7	45.6	-	-
Precipitation (in)	3.2	0.12	0.0	-	18.78
Wind Speed (mph)	11.5	5.0	-	23.2	-

Dimensions of each pile are summarized in Table 2. After piles were constructed, a total of eight auger-collected samples were made prior to the end of the study period from Pile 1 and seven collections from Pile 2 for moisture content analysis over time (Figure 3). Initial moisture contents (wet-basis) from Oct. 8th for Pile 1 and Oct. 22nd for Pile 2 are also included in Figure 3. Pile 1 had an initial moisture content of 51.4%, compared to 48.3% for Pile 2. The last sample collection made through the PVC pipe occurred on March 2nd and was 51.4% for Pile 1 compared to 40.0% for Pile 2.

Table 2. Measured parameters for both piles.

Whole-Tree Chip Piles				
Pile	Vertical Height (ft)	Base Circumference (ft)	Slope Length (ft)	Volume (ft <sup>3</sup> )
1	10	78.4	15.4	1303
2	9.5	80.0	17.0	1412

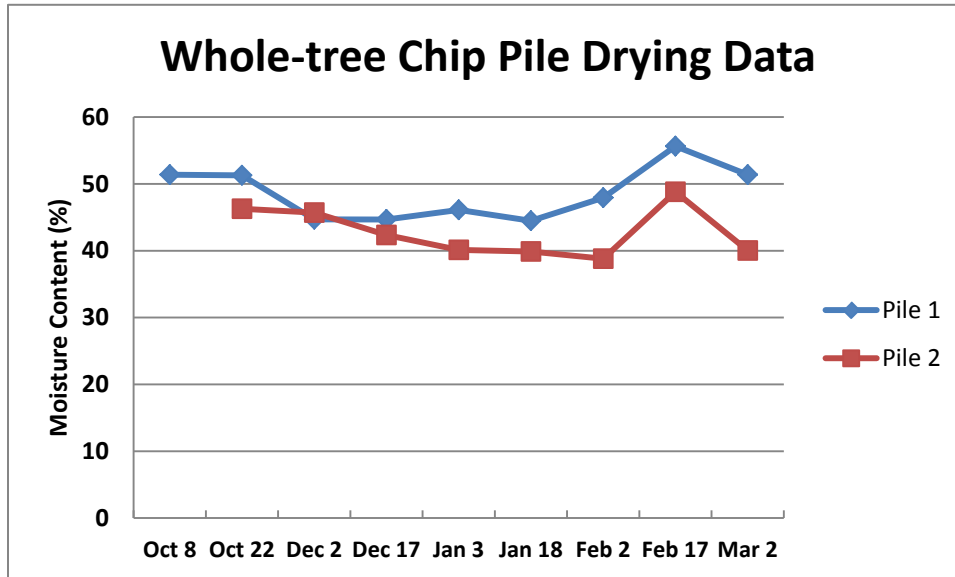


Figure 4. Moisture content trends over time for each pile.

Each sensor recorded one observation per hour; therefore, the number of observations listed in Table 3 also reflects the number of hours data were recorded. For Pile 1, the maximum data recording time possible was 3815 hours, which was achieved only by the sensor placed in the north face of the pile. All other sensors did not achieve 100% data recording during the study period. For temperature, the bottom sensor recorded 65% of the time, followed by the south sensor (53%) and the middle sensor (31%). The top sensor only recorded for 270 hours, or 7% of the time. Pile 2 had a maximum possible recording time of 3500 hours, which was achieved by both the north and south sensors. The top sensor recorded temperature 95% of the time, followed by the bottom sensor (63%) and the middle sensor (23%).

The minimum temperature recorded for both piles occurred on the north face during the month of December (36°F for Pile 1 and 32°F for Pile 2). Pile 1 also had a 36°F reading during the month of February. For both piles the maximum temperature recorded was by the top sensor during the month of October (146°F for Pile 1 and 137°F for Pile 2).

Duncan's Multiple Range Test (SAS 1988) was used to detect for significant differences ( $\alpha=0.05$ ) in temperature between piles at each sensor location. Results showed that mean temperatures were significantly different between piles at each location.

Table 3. Descriptive statistics of temperature for both Piles.

Whole-Tree Chip Piles – Temperature (°F)										
Sensor Location	Pile 1					Pile 2				
	n	Mean	SD	Min	Max	n	Mean	SD	Min	Max
Bottom	2484	94.5a <sup>1</sup>	15.57	63	126	2205	83.2b	14.83	61	118
Middle	1201	118.9a	17.13	73	139	771	100.9b	12.39	86	135
Top	270	127.1a	22.32	72	146	3330	79.4b	15.90	48	137
North	3815	62.7a	25.40	36	118	3500	49.7b	15.00	32	99
South	2040	71.1a	1.84	66	74	3500	67.2b	9.52	52	105

<sup>1</sup>Means with the same letter between piles are not significantly different using Duncan’s Multiple Range Test.

Mean relative humidity was consistent for Pile 1 for the bottom, middle, top, and north locations and ranged from 98.2 to 99.9%, while the south location averaged 66.6%. Relative humidity in Pile 2 ranged from 81.6 to 99.8%.

Figures 4 and 5 display mean monthly temperatures recorded by each sensor for both piles. Overall, mean temperatures reached a minimum during the month of January and gradually increased afterwards. For Pile 1, the highest mean monthly temperatures occurred in October and were 129.5°F for the middle sensor, followed by 127.1°F for the top sensor. The bottom of Pile 1 reached a maximum temperature of 126.0°F on day nine. The middle location reached a maximum temperature of 139.0°F on day ten and remained above 100°F until day 42. The maximum temperature at the top location was 146.0°F on day nine and 144.0°F on day twelve when the sensor stopped recording. The maximum temperature was 117.8°F on day eleven for the north location and 74.0°F at day eleven for the south location.

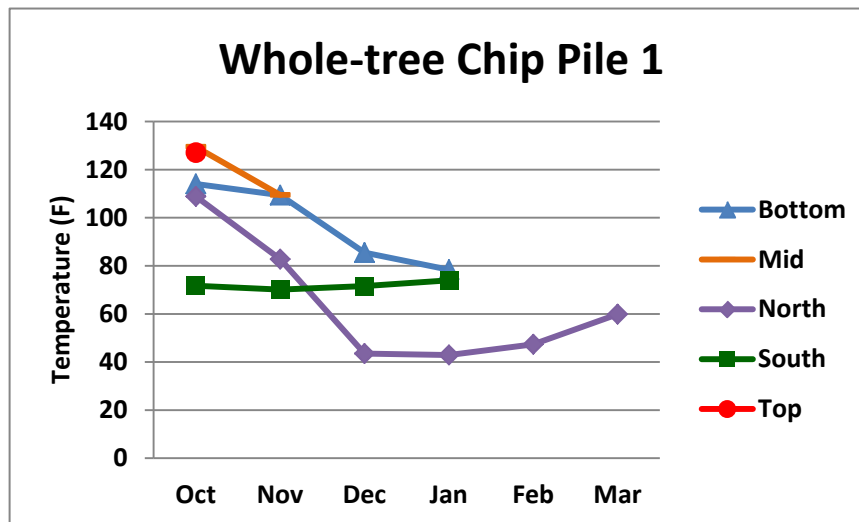
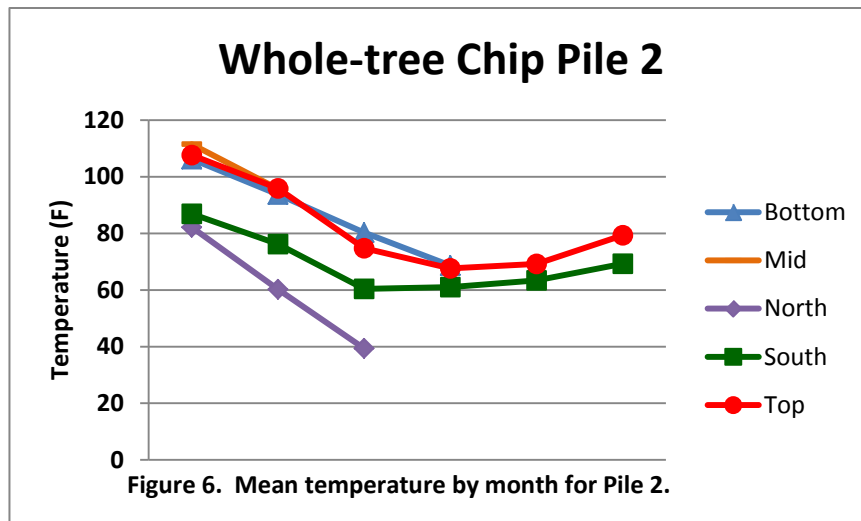


Figure 5. Mean temperature by month for Pile 1.

Temperature recorded by the south sensor in Pile 1 had a lower standard deviation as compared to the other sensors. This raised some concern about the sensor’s accuracy. Testing of the sensor in a lab drying oven for five different temperatures revealed the sensor recorded temperatures with acceptable accuracy. Percent differences between the sensor and oven readings ranged from 2.4 to 5.6%.

For Pile 2 the highest mean monthly temperature was also recorded by the middle sensor during October at 111.5°F. The three highest mean monthly temperatures were recorded by the top, middle, and bottom sensors during October and differed by no more than 5.3°F (107.7°F for the top, 111.5°F for the middle and 106.2 °F for the bottom sensor). The bottom of Pile 2 reached a maximum temperature of 117.6°F on day two. Both the middle and top locations for Pile 2 reached their maximum temperature on day three (139.0°F for the middle and 135.0°F for the top). The maximum temperature for the north (96.3°F) and south (101.0°F) locations occurred on day two of the drying period.



Moisture contents from each sample location within each pile are summarized in Figure 6. These samples were collected during deconstruction of the piles. Both piles were much wetter around the surface and top as compared to other areas. For locations 1-8 (surface) moisture contents ranged from 60.1 to 68.1% for Pile 1 and 65.5 to 69.5% for Pile 2. At the center of the piles at locations A, B, and C moisture contents ranged from 44.2 to 48.7% for Pile 1 and 31.3 to 44.0% for Pile 2. For sample location 9 (bottom) Pile 1 had a moisture content of 45.5%, compared to 26.8% for Pile 2. Comparing moisture contents between the surface and center locations resulted in a 33% difference for Pile 1, compared to a 52% difference for Pile 2.

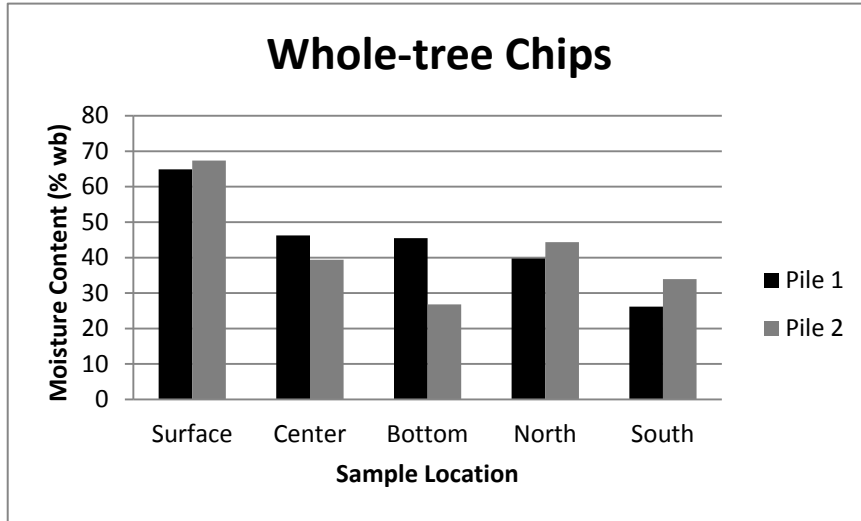


Figure 6. Moisture content by location for each pile.

Bulk density was measured from samples collected at points A, B, and C during pile deconstruction and are summarized in Figure 7. Values were consistent and ranged from 10.34 to 10.62 lb/ft<sup>3</sup> for Pile 1 and 10.17 to 10.67 lb/ft<sup>3</sup> for Pile 2.

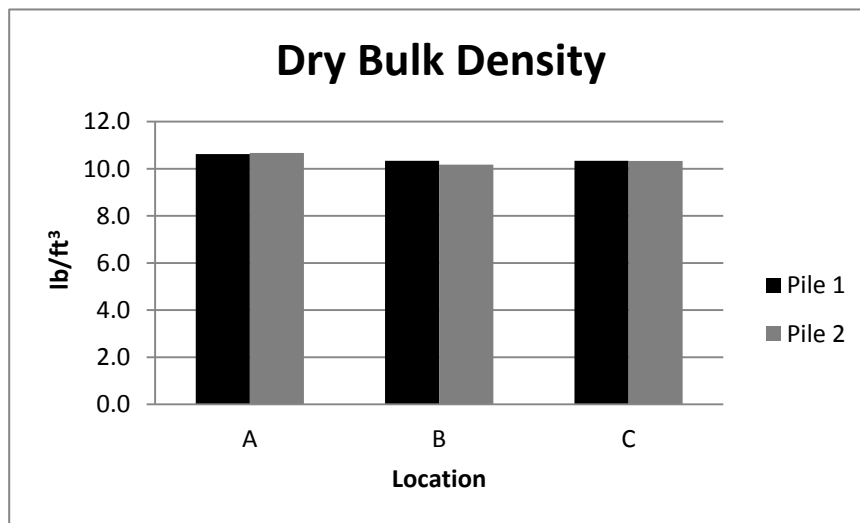


Figure 7. Dry bulk density at center locations for each pile.

#### 4. Discussion

Both temperature and relative humidity data were recorded in both piles, however, temperature was the major focus in this paper since it is a more crucial and important variable

of interest to the forest industry. Temperatures within piles were never high enough where spontaneous combustion would be likely to occur (180°F+), although they were in the range conducive for the development of wood-rotting fungi and the pinewood nematode.

The highest temperature observed of 146°F occurred at the top location in Pile 1 and only remained at that level for thirteen consecutive hours on the ninth day of the study period. The top location temperature in Pile 1 decreased slightly to 144°F by the twelfth day, at which point the sensor stopped. The maximum temperature recorded in Pile 2 was 137°F at the top location during day two of the study period.

For smaller, non-compacted piles wood-rotting fungi is more probable when temperatures drop below 120°F. For Pile 1, three of the sensors (bottom, north, and south) recorded more than 50% of the time for the total study period. Both the north and south sensors recorded temperatures of less than 120°F for 100% of their recording time. The bottom sensor recorded temperatures of less than 120°F for 90% of its recording time. Pile 2 had four sensors (bottom, north, south, and top) that recorded more than 50% of the time for the total study period. The bottom, north, and south sensors all recorded temperatures less than 120°F 100% of the time, while the top sensor recorded temperatures in this range 98% of the time.

The pinewood nematode has been found to thrive when temperatures are between 95 to 104°F. Of the three sensors in Pile 1 that recorded more than 50% of the time, the bottom sensor had the highest percentage (29%) of time with temperatures within this range. The north sensor only recorded temperatures within this range 3% of the time, while the south sensor recorded no temperatures within this range. Of the four sensors in Pile 2 that recorded more than 50% of the time, the bottom sensor also had the highest percentage (22%) of time with temperatures within this range. The top sensor recorded within this range approximately 15% of the time.

Statistical analysis showed that mean temperatures between piles at each location were significantly different. This implies that temperature within piled chips can be highly variable, even with the same type of material.

## 5. Conclusions

It appears that storing whole-tree pine chips in small piles 10 feet in height are not susceptible of reaching internal temperatures high enough to cause spontaneous combustion. At the end of the drying period piles were higher in moisture content along the surface as compared to the center. Pile 1 had a 33% difference in moisture content between the surface

and center compared to a 52% difference for Pile 2. Duncan's Multiple Range Test indicated there were significant differences in recorded temperatures between piles for each sensor location. Temperature data revealed that chip piles of this type are more susceptible to wood-rotting fungi than they are to the pinewood nematode under these conditions.

## 6. References

- APA. 1981. Report on chip storage. American Pulpwood Association, Southwide Energy Committee, Atlanta, Georgia. Sept. 9-10, 1981. 6 pp.
- Bergman, Osten. 1985. Deterioration and protection of pulpwood chips in outdoor storage. Rep. 170. Uppsala, Sweden: Swedish University of Agricultural Science, Department of forest Products; 1985. 95 pp.
- Dwinell, L. David. 1986. Ecology of the pinewood nematode in southern pine chip piles. Res. Pap. SE-258. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 1986. 14 pp.
- EN 14774-2:2009. European Committee for Standardization. 2009. Solid biofuels-Determination of moisture content-Oven dry method-Part 2: Total moisture-Simplified method. Austrian Standards Institute, Wein, Austria. 7 p
- EN 15103:2009. European Committee for Standardization. 2009. Solid biofuels-Determination of bulk density. Austrian Standards Institute, Wein, Austria. 12 p.
- Fuller, W.S. 1985. Chip pile storage – a review of practices to avoid deterioration and economic losses. TAPPI Journal, The Journal of the Technical Association of the Pulp and Paper Industry. 68(8): 48-52. August 1985.
- Landry, G.C. and Stillwell, C.D. 1984. Pulp Paper 11: 144(1984).
- McDonald, T. and A. Twaddle. 2000. Industry trends in chip storage and handling. TAPPI 2000 Pulping/Process & Products Quality Conference, November 5-9, 2000, Boston, MA. 7 pp.
- SAS Institute Inc., SAS/STAT User's Guide, Release 6.03 Edition, Cary, NC: SAS Institute Inc., 1988. 1028 pp.
- Springer, E.L. and G.J. Hajny. 1970. Spontaneous heating in piled wood chips. U.S.Tappi 53(1): 85-86. Department of Agriculture, Forest Service, Madison, WI.

## X. Concurrent Session 4A – Economic Analysis of Timber Valuation

### **An Assessment of Stumpage Payment Methods Used by Non-Federal Public Timber Sale Programs**

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A mail survey was used to evaluate how non-federal public forest land management agencies use stumpage payment methods in their timber sale programs. The survey population included 53 state agencies across the United States and 44 county agencies within the Lake States (Michigan, Minnesota and Wisconsin) that manage and administer timber sales on state or county titled forest land. Of particular importance was gathering the perceptions of timber sale program administrators regarding the advantages and disadvantages the two most common stumpage payment methods: consumer scale (also commonly called pay-as-cut) and lump sum (also commonly called sold-on-appraised-volume). Agencies with relatively little timber sale activity have a tendency to use only one stumpage payment method, whereas agencies with robust timber sale programs were more likely to use both methods. Program administrators perceive greater differences in the administrative and financial aspects of the two stumpage payment methods and few differences with respect to their ecological effects. The study provides suggestions for improving the cost-effectiveness of timber sale programs.

**Keywords:** consumer scale, lump sum, timber sale program, cost-effectiveness, stumpage

#### **1. Introduction**

While the policies and procedures used in timber sale programs will vary by public land management agencies, they all share the common goals to control administrative costs and to collect fair market value for the timber products that are sold. One contractual element of selling timber that has been thought to influence the economic efficiency of a timber sale program is the choice of stumpage payment method used to collect the revenue for the timber harvested. The two common stumpage payment methods used by public agencies are consumer scale and lump sum. The consumer scale method (also commonly called pay-as-cut) charges the stumpage purchaser only for the volume of timber that is harvested and scaled.



The lump sum method (also commonly called sold-on-appraised-volume) charges the stumpage purchaser a fixed price that is based on the stand's estimated merchantable volume, not the timber volume harvested and removed from a timber sale.

The main administrative tasks of public timber sale programs using the consumer scale stumpage payment method are those associated with collecting and processing scale tickets. Scale ticket processing refers to the administrative effort required to monitor and account for the volume of timber harvested and scaled, and to collect payment from the stumpage purchaser for the harvested timber. The consumer scale timber payment method typically requires frequent harvest inspections to monitor the harvesting activity and collect scaling tickets from the purchaser (Leffler and Rucker 1991, Paarsch 1993). The lump sum method requires a single up-front payment for the estimated merchantable volume, thereby avoiding the administrative tasks associated with a scale ticketing system which can produce possible cost-savings to an agency (Maroaka and Watson 1983, Paarsch 1993, Brown et al. 2010).

With the lump sum stumpage payment method, the timber sale's estimated merchantable timber volume may be different than the timber volume that is harvested. Consequently, the stumpage purchaser bears the financial risk of a volume under-run while the public agency bears the risk of a volume over-run. Public agencies may attempt to mitigate this financial risk by increasing the accuracy of their merchantable timber volume estimates (Deckard et al. 2011). Purchasers may also attempt to mitigate their financial risk by discounting their bids prices for the stumpage (Maroaka and Watson 1983, Deckard et al. 2011). Previous studies have found that the lump sum stumpage payment method will result in increased utilization of the timber sale's merchantable timber (Nautiyal and Love 1971, Flick 1985) because of the sunk cost to the purchaser (Maroaka and Watson 1983), especially on low value timber sales (Sendak 1991).

In terms of how public agencies use stumpage payment methods, Leffler and Rucker (1991) suggested that resource managers need to select the method that maximizes revenue with the least transactional costs to administer. In a study that assessed how timber sale program policies and procedures impact the stumpage prices received, Brown et al. (2010) found that sixty-three percent of state timber sale programs used the lump sum method and thirty-seven percent used the consumer scale method. They noted that many states use a mixture of the two methods in their timber sales.

In summary, the choice of stumpage payment method has strong potential to result in certain financial tradeoffs as differences in administrative costs during pre-sale, active-sale or post-sale activities or as revenue leakages from the timber products that are sold. Our objective was to evaluate the advantages and disadvantages of the consumer scale and lump sum

stumpage payment methods with respect to their financial and administrative effects. Furthermore, since previous research has found that the choice of stumpage payment method can result in utilization differences, we also wanted to obtain the perspectives of timber sale program administrators with respect to the ecological effects associated with each stumpage payment method. We also wanted to understand how the consumer scale and lump sum methods were used on timber sales that were sold by public agencies.

## **2. Methods**

To accomplish our study objectives, we sent a mail survey to state and county agencies that manage timber sale programs. The 58 states agencies included in the survey were identified by searching the internet for each “[state] state forestry program.” The search revealed seven states with multiple agencies (e.g. state “Department of Forestry” and state “Department of Wildlife and Fisheries”) that manage separate state titled forest lands with timber sales. Counties in the Lake States (Michigan, Minnesota and Wisconsin) also have active timber sale programs and were also included in our survey. The list of 15 Minnesota county forest management agencies was generated from a membership list for the Minnesota Association of County Land Commissioners ([mncountyland.org](http://mncountyland.org)). The list of 29 Wisconsin county forestry management agencies was generated from a membership list for the Wisconsin County Forest Association ([wisconsincountyforests.com](http://wisconsincountyforests.com)). The two Michigan county forest management agencies were identified by contacting an Extension Forester with Michigan State University and requesting expert information about which counties in Michigan have timber sale programs.

The contact person for each of the 104 agencies included in the survey was identified as the individual responsible for leading or supervising the timber sale program. We felt those individuals would have expert knowledge on the policies and procedures used by their respective agency regarding stumpage payment methods. We anticipated that if those individuals did not have the information requested in the survey, they would likely seek out other individuals within their agency who could provide the requested information.

We pilot tested a draft questionnaire with five professional foresters from four agencies (two county, one state, one federal agency). The four agencies were selected because of our prior knowledge about their use of timber payment methods. The pilot test provided feedback on the draft questionnaire’s format, content, and individual question design that was used to finalize the questionnaire.

The survey was administered in the fall of 2014 following a modification of the methods developed by Dillman (2007). Our survey process utilized a five-wave contact procedure starting with a pre-notice postcard, followed one week later with a survey questionnaire and a cover letter describing the purpose of the study, followed one week later with a reminder notice postcard, followed two weeks later with a second survey questionnaire and second cover letter to the non-respondents and followed three weeks later with phone calls to the remaining non-respondents.

The questionnaire included a series of questions that asked timber sale program supervisors about their perceptions of the administrative, financial and ecological advantages and disadvantages of using the consumer scale and lump sum methods. The scaled questions were designed using a 5-point Likert-scale with 1 indicating “Strongly Disagree”, 3 indicating “Neutral” and 5 indicating “Strongly Agree.” Respondents also had the option of selecting a “Don’t Know” response for each statement. Paired t-tests were conducted on the Likert-scaled question to determine whether there were significant differences between the two timber payment methods for each statement ( $\alpha=0.05$ ).

The agencies that responded to the survey were grouped into three size classes based on the total number of timber sales offered in fiscal year 2013. The breakpoint for each size class category was determined from the quartiles of the aggregate data of the total number of timber sales sold in fiscal year 2013 with “small” sized agencies being less than the 25% quartile, “medium” sized agencies being between the 25% and 75% quartiles, and “large” sized agencies being larger than the 75% quartile.

### 3. Results

Seven program supervisors reported not having an active timber sale program; thus, reducing the population size to 97 agencies. Ninety program supervisors returned the survey questionnaire and one program supervisor verbally declined to participate in the study, resulting in a 94% response rate. However, the usable response rate was 93% (Table 1). The nonresponse included four county agencies from Wisconsin, one state agency from the North region<sup>2</sup> and one state agency from the South region (an overall 89% response rate for county agencies and 96% response rate for state agencies). Given the high response rate, we felt the data was representative of our survey population.

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<sup>2</sup> Agencies were categorized based on the USDA-Forest Service’s Resource Planning Act regions.

The average number of timber sales sold in fiscal year 2013 for counties and states was 37.5 and 73.3, respectively (Table 2). The maximum number of reported timber sales sold in 2013 by county and state agencies were 160 and 982, respectively.

We observed that small sized agencies (n=20) had a tendency to use only the lump sum method (45%) or only the consumer scale method (40%) and less use of both methods (10%; meaning that both methods were used on separate and mutually exclusive timber sales) or blended methods (5%; meaning that both methods were used on single timber sales). For example, sawtimber sold with the consumer scale method and pulpwood sold with the lump sum method (Figure 1). Medium sized agencies (n=42) maintained a high use of only the consumer scale method (45%) but also increased the use of both stumpage payment methods (38%) on separate timber sales in their timber sale programs. Large sized agencies (n=20) had a greater tendency to use both methods on separate timber sales (40%) or blended methods (40%) and less use of only the lump sum method (15%) or only the consumer scale method (5%).

Table 1. Survey response by agency type and regiona.

<b>Agency type and region</b>	<b>Number of respondents</b>
<b>Counties</b>	
North (Lake States)	39
<b>States</b>	
North	22
Pacific Coast	6
Rocky Mountains	9
South	14

<sup>a</sup>Agency's region categorized based on the USDA-Forest Service's Resource Planning Act regions.

Table 2. Statistics for number of timber sales sold during fiscal year 2013 for counties and states.

<b>Statistic</b>	<b>Counties</b>	<b>States</b>
Minimum	2	0
Maximum	160	982
Average	37.5	73.3
Standard deviation	37.0	178.2

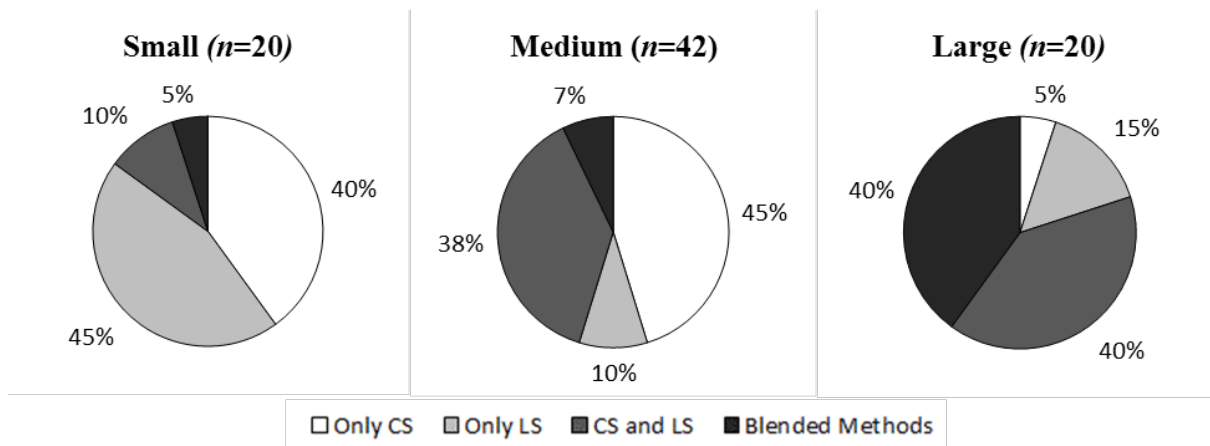


Figure 1. Use of stumpage payment methods by size category for responding agencies. "Small" = 1 - 7 timber sales sold in fiscal year 2013, "medium" = 8 - 53 timber sales sold in fiscal year 2013, "large" = 54 to 982 timber sales sold in fiscal year 2013; "CS" refers to consumer scale, "LS" refers to lump sum and "Blended Methods" refers to both methods used on single timber sales (e.g., pulpwood sold with the lump sum method and sawtimber sold with the consumer scale method).

Table 3 reports the perceptions of timber sale program administrators regarding potential administrative differences of using the consumer scale and lump sum stumpage payment methods. These perceptions varied for all of the statements and all were statistically significant ( $p < 0.0001$ ). The widest range of values reported (consumer scale mean value = 4.02 and lump sum mean value = 2.29) was for the statement regarding the administrative time required to process paperwork and other timber sale documents. Administrators felt consumer scale sales require more administrative time than lump sum timber sales. The narrowest range of values reported (consumer scale mean value = 3.62 and lump sum mean value = 4.17) was for the statement pertaining to a forester's ability to simultaneously manage or administer several timber sales of each method.

Respondents had strongly contrasting perceptions ( $p < 0.023$ ) for all but two of the seven statements designed to address the potential financial differences of using the consumer scale and lump sum stumpage payment methods (Table 4). The widest range of values reported (consumer scale mean value = 3.65 and lump sum mean value = 2.55) was for the statement asking respondents to evaluate each method's administrative costs to administer. The narrowest range of values reported (consumer scale mean value = 3.73 and lump sum mean value = 3.63) was for the statement inquiring if each method encourages competition from potential purchasers.

Respondents also had strongly contrasting perceptions ( $p < 0.001$ ) for only two statements designed to address the potential ecological differences of using the consumer scale

and lump sum stumpage payment methods (Table 5). The widest range of values reported (consumer scale mean value = 2.74 and lump sum mean value = 3.38) was for the statement asking if each method encourages high utilization of standing dead and on-the-ground dead material. The narrowest range of values reported (consumer scale mean value = 3.54 and lump sum mean value = 3.57) was for the statement inquiring if each method affects which leave trees are retained post-harvest (if not marked by the forester).

Table 3. Comparison of the administrative differences between the consumer scale and lump sum stumpage payment methods. Values are mean scores based on a 5-point Likert scale; where 1 = strongly disagree, 3 = neutral, 5 = strongly agree. Standard deviations are shown in parentheses.

Statement	Stumpage Payment Method		<i>p-value</i>
	Consumer Scale	Lump Sum	
Requires more administrative time than average to cruise and determine a volume estimate. ( <i>n</i> =83)	2.58 (1.05)	3.72 (1.07)	0.000
Requires more administrative time than average during harvest operations (e.g., inspections). ( <i>n</i> =84)	3.71 (0.94)	2.63 (0.88)	0.000
Requires more administrative time than average to process paperwork and other documents from the sale. ( <i>n</i> =82)	4.02 (0.85)	2.29 (0.79)	0.000
A forester could manage or administer several sales with this payment method at one time. ( <i>n</i> =82)	3.62 (1.11)	4.17 (0.93)	0.000
Requires more administrative personnel involved with the timber sale from start to finish. ( <i>n</i> =82)	3.27 (1.04)	2.51 (0.84)	0.000

Table 4. Comparison of the financial differences between the consumer scale and lump sum stumpage payment methods. Values are mean scores based on a 5-point Likert scale; where 1 = strongly disagree, 3 = neutral, 5 = strongly agree. Standard deviations are shown in parentheses.

Statement	Stumpage Payment Method		<i>p-value</i>
	Consumer Scale	Lump Sum	
Will generate higher stumpage bids than normal. ( <i>n</i> =77)	3.51 (0.79)	3.18 (0.88)	0.023
Is attractive to bidders when the sale has a high percentage of low value timber. ( <i>n</i> =76)	3.59 (0.90)	2.92 (0.98)	0.001
Is attractive to bidders when their operating costs are high. ( <i>n</i> =75)	3.63 (0.80)	3.01 (0.88)	0.000
Encourages competition for sales. ( <i>n</i> =79)	3.73 (0.80)	3.63 (0.89)	0.380
Is a financial risk to your agency. ( <i>n</i> =82)	2.73 (1.12)	3.09 (1.24)	0.111
Is costly for your agency to administer. ( <i>n</i> =83)	3.65 (0.98)	2.55 (0.99)	0.000
Will maximize timber revenue for your agency. ( <i>n</i> =79)	3.72 (0.88)	3.10 (0.99)	0.001

Table 5. Comparison of the ecological differences between the consumer scale and lump sum stumpage payment methods. Values are mean scores based on a 5-point Likert scale; where 1 = strongly disagree, 3 = neutral, 5 = strongly agree. Standard deviations are shown in parentheses.

Statement	Stumpage Payment Method		<i>p-value</i>
	Consumer Scale	Lump Sum	
Allows land managers to meet regeneration objectives. ( <i>n</i> =79)	3.65 (0.97)	3.67 (1.06)	0.798
Has a positive influence on post-harvest wildlife habitat. ( <i>n</i> =81)	3.54 (1.01)	3.49 (1.03)	0.620
Encourages the logger to utilize timber in riparian areas. ( <i>n</i> =77)	2.95 (0.96)	3.43 (1.08)	0.001
Encourages high utilization of standing dead and on-the-ground dead material. ( <i>n</i> =81)	2.74 (0.93)	3.38 (1.11)	0.000
Affects which leave trees the logger will choose (If required and not marked by the forester). ( <i>n</i> =79)	3.54 (1.05)	3.57 (1.15)	0.818
Has a positive influence on post-harvest visual and aesthetic qualities. ( <i>n</i> =79)	3.41 (0.91)	3.30 (1.04)	0.445

#### 4. Discussion and Conclusions

The administrators of state and county timber sale programs have wide-ranging opinions about the consumer scale and lump sum timber payment methods. We expected such differences would be a function of the administrative tasks required for each method, as has been cited in the literature. Additionally, we explored the possibility that ecological differences could exist post-harvest between the two methods. The survey results allowed us to better understand the perceptions of those differences by timber sale program supervisors and how the two methods are currently being used in state and county agency timber sale programs.

We found that agency use of the two timber payment methods varies according to the number of timber sales sold. Those state and county timber sale programs that offered few timber sales each year tend to use a single timber payment method, with the number using consumer scale and lump sum methods nearly equal. In contrast, large sized agencies had a greater tendency to use both stumpage payment methods (on separate and mutually exclusive timber sales) or blended payment methods (on single timber sales; for example, sawtimber sold with the consumer scale method and pulpwood sold with the lump sum method). For the large sized agencies, we attribute the increased use of both methods to the likelihood that the



variability of individual timber sale characteristics (e.g., variability in species, product types, size diameters, occurrence of salvage timber sales) increases with timber sale activity. Therefore, the program supervisors will choose the “the right tool for the job” depending on the timber sale characteristics; for example, several respondents indicated with comments in the survey margins that the consumer scale method is preferred on partial cuts or high value species-product timber sales.

The responding timber sale program supervisors stated there are administrative and financial differences between the consumer scale and lump sum timber payment methods. They characterized three perceived advantages of the lump sum stumpage payment method over the consumer scale method: less administration time is required during harvest operations and post-sale activities, less administration personnel are involved with a timber sale and the overall result is that the lump sum stumpage payment method is less costly to an agency. The perceived disadvantages of the lump sum timber payment method as compared to the consumer scale method are additional administrative time during pre-sale activities (e.g. estimating the timber sale’s merchantable volume) and a potential loss in the number of bidders if the sale contains low-valued timber and/or high operating costs. The perceived advantage of the consumer scale timber payment method over the lump sum method is higher stumpage bid prices that will increase timber sale revenue. Survey respondents also generally agreed that the consumer scale timber payment method lessens the financial risk to their agency. Program supervisors indicated the two timber payment methods produce fewer differences between each other in ecological outcomes; for example, meeting post-harvest regeneration goals or influencing wildlife habitat.

Non-federal timber sale program supervisors thought the lump sum timber sale method could result in higher utilization in riparian areas and could encourage higher utilization of dead material (e.g., snags and on-the-ground retention logs), compared to the consumer scale timber payment method. If ecological goals or silviculture prescriptions are designed to achieve high utilization of material (e.g., salvage timber sales or clearcut regeneration harvest) the lump sum timber payment method was perceived to be the more appropriate stumpage payment method.

In summary, this study will be of interest to timber sale program supervisors and other decision makers who may be curious about the general perceptions of the consumer scale and lump sum stumpage payment methods with regards to administrative, financial and ecological advantages and disadvantages of their use.

## 5. Acknowledgments

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## 6. References

- Brown, R., M. Kilgore, C. Blinn, J. Coggins and C. Pfender. 2010. Assessing state timber sale policies, programs and stumpage price drivers. Staff Paper #209. St. Paul, MN: University of Minnesota, Department of Forest Resources. 152 p.
- Deckard, D.D., G.P. Paulson and G.W. Deegan. 2011. Optimal state timber sales scaling methods. Report to the House and Senate Natural Resources Policy and Finance Committees and Divisions. 20 p.
- Dillman, D.A. 2007. Mail and internet surveys: The Tailored Design Method. Hoboken, New Jersey: John Wiley and Sons Inc. 447 p.
- Flick, W.A. 1985. Economics of timber sale decisions. *Southern Journal of Applied Forestry* 9(3):146-150.
- Leffler, K.B., Rucker R.R. 1991. Transactions costs and the efficient organization of production: a study of timber-harvesting contracts. *Journal of Political Economy* 99:1060-1087.
- Maroaka, D.D., and R.B. Watson. 1983. Improving the efficiency of federal timber sale procedures. *Natural Resources Journal* 23:815-825.
- Nautiyal, J. C., and D. V. Love. 1971. Some economic implications of methods of charging stumpage. *The Forestry Chronicle* 47(1): 25-28.
- Paarsch, H.J. 1993. The effect of stumpage rates on timber recovery. *Can. J. Econ.* 26:107-120.
- Sendak, P.E. 1991. Timber sale value as a function of sale characteristics and number of bidders. Research Paper NE-657. Radnor, PA: USDA Forest Service, Northeastern Forest Experiment Station. 11 p.
- Smith, W.B., P.D. Miles, C.H. Perry, and S.A Pugh. 2009. Forest resources of the United States, 2007. Gen. Tech. Rep. WO-78. Washington, DC: USDA, Forest Service. 349 p.

## Does Timber Payment Method Affect Stumpage Price?

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Two complementary techniques were employed to explore the financial impact of two methods (sold on appraised estimate and consumer scale) used by the St. Louis County Land Department in northern Minnesota to collect payment for timber sold at public auction. The first technique was a hedonic price analysis model, which identified important drivers of a stumpage purchaser's bid price for stumpage on 473 timber sales sold from 2006-2012. The model investigated the relative influence that payment method had on the winning bid value. The second analytical technique explored the influence of payment method on stumpage bids through a field experiment called paired bidding, which assessed the impact of different timber sale attributes on a bidder's willingness to pay for stumpage. It did so by requiring a given tract of timber be advertised for sale and bid on (via a sealed bid auction) in two ways, with the only difference between the two sale versions being the method by which the purchased timber would be paid for. Both the hedonic model and the paired bid experiment found that willingness to pay for stumpage was not influenced by the timber payment method used to pay for the timber.

**Key words:** Hedonic price analysis, willingness to pay, St. Louis County Land Department, paired bidding experiment

### 1. Introduction

An important aspect of public timber sales that can have a substantial impact on stumpage price is the method used to collect payment from the timber buyer (i.e., timber payment method) (Brown et al., 2010). Public agencies generally collect payment for timber sold in one of two ways: consumer scale or sold on appraised volume (SOAV). For timber sales using the consumer scale timber payment method, the volume of wood harvested by the buyer and transported to a consuming mill from a tract is measured (scaled) by the seller (or a third party), with the buyer paying a specified amount (i.e., its sale price) for each unit of volume harvested (Brown et al., 2010). In contrast, buyers using the SOAV timber payment method pay a specified amount for the entire tract of timber offered for sale, regardless of the amount of timber actually harvested from the tract and brought to a consuming mill (Brown et al., 2010).

Public timber sale programs select the timber payment method based on the administrative requirements as well as a variety of economic, social, and ecological factors.

This study investigates how the timber payment method impacts the timber sale revenue of the St. Louis County Land Department's (SLCLD) timber sale program. St. Louis County is the largest county in Minnesota and the SLCLD manages approximately 872,100 acres of forest land of which 639,400 acres are considered commercial forest land (St. Louis County Minnesota, 2015). The primary reasons behind selecting the SLCLD for this study are the relatively high number of annual timber sales, the physical characteristics of SLCLD timber sales (i.e., species, volume, and location), its use of both timber payment methods, and its willingness to collaborate on the study. By exploring timber payment method's influence on stumpage bids, this study provides public agencies and policymakers with information that can help identify the financial tradeoffs associated with these two timber payment methods—an area of research for which little information and analysis exists.

## **2. Willingness to Pay for Stumpage**

A study by Kueper et al. (2014) reported that 59% of Minnesota DNR timber purchasers prefer consumer scale sales and 41% prefer SOAV sales. This preference might influence a bidder's willingness to pay (WTP) for a timber tract and thus impact the gross timber sale revenue generated by the seller. Kilgore and Blinn (2005) reported that a buyer's knowledge of the forester who set up the timber sale might influence its WTP. If the tract was sold under the SOAV method, bidders may base their bidding behavior on the specific forester who appraised the timber tract. Over time, buyers can become familiar with a forester's timber appraisal practices (e.g., tends to underestimate merchantable volume) and use that information to adjust their WTP accordingly (e.g., increase their WTP if the appraiser consistently underestimates the volume of merchantable timber in a timber sale) (Brown, et al., 2010).

Several studies have analyzed timber payment methods and their expected impact on bid price and wood utilization. Flick (1985) highlighted some of the potential tradeoffs between each timber payment method and hypothesized that SOAV sales promote "better timber utilization and tend to elicit higher prices" from buyers (p. 149). Similarly, Maroaka and Watson (1983) found that use of the SOAV timber payment method by the USDA Forest Service reduced administrative costs, produced higher stumpage bids, and encouraged timely harvests. The findings from these two studies contradict the results in the Minnesota DNR report (Deckard et al., 2011), which stated that SOAV stumpage bids were discounted by 5-15% compared to bids submitted for consumer scale sales to account for the increased financial risk of SOAV sales

(i.e., increased risk to the buyer due to the potential of a seller underestimating a tract’s total volume).

### 3. Hedonic Price Analysis

Hedonic price analyses are a common method for analyzing timber sale data and are often employed by forest economists to better understand the factors that influence stumpage price. Griliches (1991) noted that the hedonic method “relates the prices of different versions of a commodity to differences in their characteristics, ‘qualities’, and discovers thereby the relative valuation of such qualities (p. 185).” In other words, the model used in a hedonic price analysis estimates the relationship between the price of a good, input, or service and the characteristics embodied within that good, input, or service (Brown et al., 2012).

This study utilized hedonic price analysis to assess the significant predictors of WTP from timber sales offered by the SLCLD. The model used 473 timber sales from the SLCLD that were sold from 2006-2012. Table 1 describes the independent variables included in the hedonic price analysis model, which includes the timber payment method (SOAV) and several other timber sale characteristics thought to influence a bidder’s WTP for timber. Note the SLCLD uses the same timber appraisal standards for all timber sales, regardless of the payment method, meaning a timber sale’s estimated merchantable timber volume is not related to the timber payment method. The dependent variable is the winning bid value (\$) per acre, which is the estimated (appraised) volume for each species, multiplied by the unit winning bid price for each species-product combination. The hedonic price analysis model tested the null hypothesis that there are no differences in winning bid value attributed to the timber payment method. The model was run in SAS 9.3 (SAS Institute, 2011).

Table 1. Description of timber tract characteristics from the SLCLD database used in the hedonic price analysis model and their expected impact on winning bid value (\$) per acre.

<b>Timber tract characteristic</b>	<b>Description</b>	<b>Expected impact on winning bid value<sup>1</sup></b>
<b>SOAV</b>	The percent (0 to 100) of the total appraised volume sold under the SOAV timber payment method. The remainder was the portion sold under the Consumer Scale (CS) method.	(+) higher utilization on SOAV sales
<b>Species</b>	The percent (0 to 100) of total appraised volume that was comprised of hardwood, softwood, or aspen species. Calculated by dividing total hardwood, softwood, or aspen cords appraised by total cords appraised within the tract.	(+/-) species have different market value

<b>Appraised cords per acre</b>	The total estimated (appraised) volume in cords per acre. Calculated by dividing total estimated cords appraised by total acres.	(+) higher density of harvestable volume per unit area
<b>Location</b>	Binary variable that equals one if the tract was administered through the southern area office (Pike Lake) in St. Louis County; variable equals zero if the tract was administered through the northern area office (Virginia) in St. Louis County.	(+) southern area is closer to more consuming mills
<b>Sealed bid</b>	Binary variable that equals one if the tract was offered for sale through a sealed bid auction; equals zero if the tract was offered for sale through an oral auction.	(+) sealed bid known to increase WTP
<b>Blocks</b>	Number of sale parcels (i.e., blocks) per tract. Includes sales with up to 9 blocks (87.1% of sales had fewer than 4 blocks).	(-) higher move costs for each additional harvesting block
<b>Winter</b>	Binary variable that indicates that the buyer may only harvest the sale during frozen ground conditions, as identified on the timber sale auction listing. The variable equals zero if the tract was only accessible during the summer or if there were no seasonal restrictions placed on when the tract could be harvested. 1 =winter only and 0 = summer or year-round.	(-) winter only harvesting restriction reduces bidders' WTP because more tracts are offered for sale with this restriction
<b>Quarter [1-4]</b>	Four dummy variables that indicate the quarter during which the sale sold (i.e., auction date). Q1=January-March; Q2=April-June; Q3=July-September; Q4=October-December. Q4 was omitted as the base comparison.	(+) higher seasonal need for timber sales in beginning of calendar year
<b>Year [2006-2012]</b>	Six dummy variables used to indicate the calendar year in which the sale was offered (Year06-Year12). Year06 was omitted as the base comparison.	(-) lower timber prices in years 2006-2012

1Positive and negative expected influence on winning bid value (\$) per acre are noted by (+) and (-), respectively.

The following equation represents the hedonic price winning bid value model for the SLCLD timber sales:

$$\text{Winning bid value (\$/acre)} = \alpha_i + \sum \beta_j x_i + \epsilon_i$$

The  $x_i$ 's in the winning bid value model equation are the tract characteristics that could influence the winning bid value per acre received by the SLCLD (Table 1). The  $\beta_j$ 's are the parameter estimates which indicate the direction and relative strength of the relationship with respect to winning bid value per acre. The term  $\alpha_i$  is the intercept parameter, and  $\epsilon_i$  is the error term.

## Results

The winning bid value model's F-statistic indicates that the included variables are jointly significant at the 1% level, and the R<sup>2</sup> highlights the model's explanatory power with approximately 75% of the variation in winning bid value explained. Several variables have a statistically significant ( $\alpha = 0.05$ ) influence on winning bid value (\$) per acre, including hardwood, appraised cords, location, winter, and year (Table 2).

Table 2. Results from winning bid value model (dependent variable = winning bid value (\$) per acre) for timber sales sold by the SLCLD from 2006-2012 (n = 473).

Independent variables	Coefficient <sup>1</sup>	S.E.	95% C.I.	
Intercept	74.65*	47.61	-18.90	168.21
SOAV	28.47	22.16	-15.07	72.01
Hardwood	-345.84***	40.38	-425.19	-266.49
Aspen	-38.20	30.90	-98.92	22.52
Appraised cords	30.73***	1.00	28.76	32.70
Blocks	-2.07	5.90	-13.66	9.53
Location	33.50**	15.29	3.45	63.55
Sealed bid	19.40	13.62	-7.37	46.17
Winter	-65.82***	14.03	-93.39	-38.25
Q1	50.62**	21.11	9.14	92.09
Q2	34.40*	19.35	-3.63	72.43
Q3	35.33*	19.79	-3.56	74.22
Year07	-141.63***	35.07	-210.55	-72.71
Year08	-179.89***	35.38	-249.43	-110.36
Year09	-230.14***	36.95	-302.75	-157.53
Year10	-171.88***	38.62	-247.78	-95.98
Year11	-156.29***	39.12	-233.17	-79.41
Year12	-167.85***	44.54	-255.38	-80.32
<b>Model Fit:</b>				
R <sup>2</sup> = 0.7535				
Adj. R <sup>2</sup> = 0.7438				
F-statistic = 77.11 (Pr < 0.0001)				

<sup>1</sup>\*\*\* = significant at 1% level, \*\* = significant at the 5% level, and \* = significant at 10% level.

Importantly, the SOAV variable (i.e., timber payment method variable) is not significant at the 10% level. Therefore, the model fails to reject the null hypothesis that there are no differences in winning bid value attributed to the timber payment method. In other words, the

model indicates that a bidder's WTP is not significantly influenced by timber payment method used.

#### **4. Paired Bidding Experiment**

Regression methods such as those used in the hedonic price analysis only control for the variation in those variables that are included in the model. The winning bid value model attempts to control for all of the observable characteristics<sup>3</sup> included in the model to estimate the relative influence of timber payment method on bid price. However, it does not control for any observable characteristics for which data was not available and unobservable characteristics<sup>4</sup> influencing WTP.

Since regression methods do not completely control for all sources of variability (i.e., observable and unobservable characteristics), a paired bidding experiment was conducted to provide another perspective on timber payment method's influence on WTP. The paired bidding method complements the regression methods used in the bid price model because it controls for all timber sale factors (both observed and unobserved) that are known to the seller and buyer, except the variable of interest (Kilgore and Blinn, 2003). The variable of interest in the paired bidding experiment was the timber payment method. Similar to the bid price model, the paired bid experiment analyzed the relative influence of timber payment method on a bidder's WTP (i.e., bid price).

The paired bidding method requires a timber tract to be offered through a sealed bid process to potential buyers under two treatment scenarios, and for the buyer to submit a sealed bid for each scenario. Except for the variable of interest (timber payment method in our study), all other attributes of the sale (e.g., location, tract size, volume per acre) remain unchanged. Each buyer interested in the paired bid sale must submit two bids for the timber tract—one for the tract with treatment A (e.g., SOAV timber payment method) and one for the tract with treatment B (e.g., consumer scale timber payment method), with the sale awarded to the highest bidder for the treatment selected. The selected treatment for each tract (i.e., pair) is randomly determined (e.g., through the flip of a coin) after all bids have been submitted. Because the paired bidding method efficiently controls for all variation in timber sale attributes, except for the selected variable of interest (i.e., timber payment method), one can isolate the

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<sup>3</sup> Observable characteristics are the features of a timber sale that are known by the seller and buyer and for which data are available. Examples include the size of the sale, estimated volume, and location of the tract.

<sup>4</sup> Unobservable characteristics are the features of a timber sale that are not known to the seller but are known to the buyer, which include the buyer's logging experience, the current inventory and location of stumpage held by potential buyers, information about the contracts that buyers have with consuming mills, etc.



effect of the variable of interest on stumpage bids. Since the method resulted in the actual sale of timber, the potential for strategic behavior on the part of bidders (i.e., bids not reflective of their true WTP) is minimized, if not eliminated altogether (Kilgore and Blinn, 2003). The paired bidding technique in this analysis evaluated how each timber payment method impacted a bidder's WTP.

On February 20, 2014, the SLCLD paired bidding experiment was implemented to evaluate how the two timber payment methods impact stumpage bid prices. The experiment was administered by the SLCLD staff through their sealed bid auction process. The paired bidding experiment required bidders to submit two bids for each timber tract they were interested in bidding on: one bid for the tract with a SOAV treatment and one bid for the same tract with a consumer scale treatment. All buyers were notified of the special bidding procedures and instructed that any bid without both Version A (SOAV) and Version B (consumer scale) would not be considered valid. The treatment (i.e., Version A and Version B) for each paired bidding tract was selected through the flip of a coin after all bids had been submitted, and the winning paired bid tract was the highest bid for the treatment selected for each tract.

## **Results**

There were no bidders that submitted the paired bids incorrectly (e.g., all submitted bids contained pairs of bids). A total of 16 tracts were offered for sale and 15 timber tracts were sold through the paired bidding auction, generating 84 paired bids. One paired bidding tract did not receive any bids and was not sold at the February 2014 auction.

For each pair of bids for a given timber tract, the value difference between timber payment method treatments (i.e., SOAV bid value minus consumer scale bid value) was calculated (Figure 1). Any negative values (i.e., below the baseline) had higher bids for the consumer scale treatment and positive values (i.e., above the baseline) contained higher bids for the SOAV treatment.

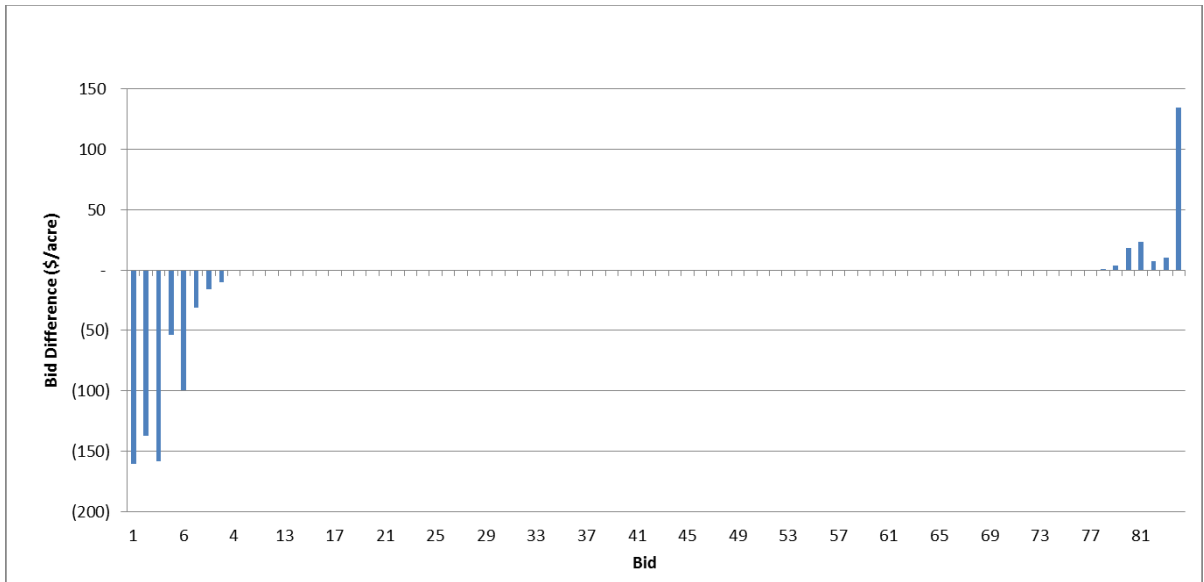


Figure 1. Paired bidding timber payment method experiment results from the SLCLD's auction on February 20, 2014. The bid difference (y-axis) is shown in dollars per acre for the SOAV bid minus the consumer scale bid (n = 84 paired bids).

The vast majority of paired bids (69 of the 84 bids) did not differentiate their WTP as a function of the timber payment method. All 15 tracts had at least one bidder that did not differentiate their paired bids (i.e., SOAV = consumer scale). However, the results show that bid premiums are both unidirectional (e.g., bid premium for one timber payment method on a given tract) and bidirectional (e.g., bid premium for both timber payment methods on a given tract). The unidirectional bids include the sales that had only SOAV premiums (one tract) or only consumer scale premiums (three tracts) on the paired bids. The bidirectional bids (four tracts) had at least one bid premium for SOAV and at least one bid premium for consumer scale. As the instances of bid premiums for either timber payment method are few (i.e., only 15 of the 84 paired bids) it appears that bidders seldom differentiate their bids based solely on timber payment method, and when they do, it is not necessarily unidirectional.

A paired t-test was used to test the significance of the mean difference in total bid values between the 84 consumer scale and SOAV samples (Wooldridge, 2013). The paired t-test for sample means tests the null hypothesis that there are no differences in a bidder's WTP between the SOAV and consumer scale timber payment methods. The mean values of timber sales for the SOAV and consumer scale paired bids are \$52,174 and \$53,057, respectively. The paired t-test found that the difference in sample means was not statistically different from zero at  $\alpha = 0.05$ . Therefore, the paired bid experiment fails to reject the null hypothesis that there

are no differences between WTP for timber under the two payment methods. This finding is consistent with the results in the winning bid value model, which found that timber payment method did not influence the WTP for timber.

## **5. Summary and Conclusions**

This study examined the impact that timber payment method has on a bidder's WTP for timber auctioned for sale by the SLCLD. It tested the hypothesis that the timber payment method might generate different bids for timber under the assumption stumpage buyers could merchandize more timber volume on SOAV sales. This hypothesis was based on the notion that the stumpage cost of a SOAV timber sale is fixed, regardless of the volume of timber removed. Therefore, buyers of SOAV timber sales might be incentivized to utilize as much merchantable volume as possible because they don't incur any stumpage costs once all of the appraised volume has been harvested. In contrast, consumer scale sale buyers might not utilize some material if the marginal cost of harvesting the tree (or sections thereof) exceeds the marginal revenue it will generate.

Timber payment method's influence on stumpage price was analyzed using a hedonic price analysis and a paired bidding experiment. The hedonic price analysis found that several timber sale features significantly influenced the winning bid value per acre, including the composition of hardwood species within the timber sale, volume density (i.e., appraised cords per acre), location, whether the tract could only be harvested during the winter due to season restrictions, and the year in which the tract was sold. However, the primary variable of interest, timber payment method, was not found to influence WTP for timber in the winning bid value model. Similarly, the paired bidding experiment demonstrated that a prospective stumpage purchaser's bid price is not significantly influenced by timber payment method. Collectively, these two analyses confirm that the timber payment method did not influence a bidder's WTP for timber on SLCLD timber sales.

This study was the first empirical assessment of timber payment method's influence on a buyer's WTP for stumpage sold by a public land management organization. Its findings stand in contrast to previous studies, which found that the timber payment method produced both a premium (Flick, 1985; Maroaka and Watson, 1983) and a discount (Deckard et al. 2011) on WTP for timber. Additional research is recommended to further explore this relationship.

## 6. Acknowledgments

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## 7. Literature Cited

- Brown, R.N., M.A. Kilgore, C.R. Blinn, J.S. Coggins and C. Pfender. (2010). Assessing state timber sale policies, Programs and stumpage price drivers. Staff Paper 209. St. Paul, MN: University of Minnesota, Department of Forest Resources. 209: 152 p.
- Brown, R. N., M. A. Kilgore, C. R. Blinn, and J. S. Coggins. (2012). The impact of timber-sale tract, policy, and administrative characteristics on stumpage prices: An econometric analysis. *Forest Policy and Economics* 21:71-80.
- Deckard, D.D., G.P. Paulson and G.W. Deegan. (2011). Optimal state timber sales scaling methods. Report to the House and Senate Natural Resources Policy and Finance Committees and Divisions.
- Flick, W.A. (1985). Economics of timber sale decisions. *Southern Journal of Applied Forestry* 9(3):146-150.
- Griliches, Z. (1991). Hedonic price indexes and the measurement of capital and productivity: some historical reflections. University of Chicago Press: 185-206.
- Kilgore, M.A. and C. R. Blinn. (2003). The financial cost to forest landowners who implement forest management guidelines: An empirical assessment. *Journal of Forestry*. Volume 101(8):37-41.
- Kilgore, M.A. and C. R. Blinn. (2005). The impact of timber harvesting guidelines and timber sale attributes on stumpage bidding behavior. *Northern Journal of Applied Forestry* 22(4):275-280.
- Kueper, A.M., M. A. Kilgore, and C. R. Blinn. (2014). A comparison of lake states logger and forester perceptions of ideal state timber tract characteristics. *Forest Science* 60(4):804-810.
- Maroaka, D.D., and R.B. Watson. (1983). Improving the efficiency of federal timber sale procedures. *Natural Resources Journal* 23:815-825.
- SAS Institute Inc. Copyright. (2011). SAS 9.3 software. Cary, NC, USA.
- St. Louis County Minnesota. Timber Sales Program. Retrieved from, <http://www.stlouiscountymn.gov/GOVERNMENT/AuctionsSales/TimberSales.aspx>
- Wooldridge, J. M. (2013). *Introductory econometrics: A modern approach*. Fifth Edition. Mason, OH: South-Western Cengage Learning. 688 p.

# Evaluating Forest Based Land Use Change Trends Using a Cellular Automata-Markov Model: A Case Study of Turkey

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Land use changes greatly impact especially forest ecosystem such as carbon sequestration, water quality, global climate, and soil conditions. Therefore, identification and simulation of land use change that occur in a given period of time is important for decision makers. Precise estimates for future land use change giving a possible change can be determined with the help of simulation models. Simulation model can help the decision makers and land use planner to sustain forest ecosystem development. A Markov chain and cellular automata (CA) models are generally used to determine transition possibilities of land use categories. In this study, we investigated the capability of Markov chain analysis and CA model to better comprehend the dynamics of forest ecosystem for case study area in south east of Turkey. Temporal land use maps derived from stand type map from 1991, 2002, and 2012 and Markov cellular automata methods (CA–Markov) were used for characterizing trends and patterns 1991–2002 and 2002–2012, and to develop predictive scenarios through 2022. With Markov chain analysis, transition matrix was calculated based on 1991 and 2002 land use map and then predicted 2012 land use map using transition matrices. Predicted and actual land use map for 2012 were validated using accuracy value. Future land use were then projected using a CA–Markov model based on the 2002 and 2012 land use map and transition matrices. Integrated with Geographical Information System (GIS) and Cellular Automata-Markov Chain approach of land use changes has proven to be an effective way to predict future land cover. With the simulation was performed for the 2022 trends identified for possible land use change, change in the expected risk of extinction especially in the area of woodland and arable land is illustrated by numerical value. The results in the coming years land use change also shows the destruction of natural resources, the model demonstrates how to change the estimate of the spatial and land use change numerical form for the year 2022.

**Keywords:** Cellular automata-markov chain, Kahramanmaras, Land use, Simulation model

## 1. Introduction

Land use change has become a fundamental component in monitoring environmental changes and managing natural resources sustainably and it is one of the most important driving factors of global environmental change and affecting ecological systems (Vitousek 1994; Mondal and Southworth 2010). Land use changes have impacts on forest ecosystem values and attributes including soil erosion (Sidle et al. 2006), carbon sequestration (Sivrikaya et al. 2013) greenhouse effect (Houghton 1994), water quality (Rimal 2011), biodiversity (Laurance 1999, Sivrikaya et al. 2007) and releasing atmospheric carbon dioxide contributing to the greenhouse effect (Yang et al. 2014).

Defining of land use change both quantitatively and qualitatively, understanding land use change process within the cause and effect relation and prediction of future land uses have great importance for supporting decision making process (Verburg et al. 2006; Erdoğan et al. 2011). Qualitative explanation is frequently used to provide description of how land use will change in the future and how it has been changing. Quantitative curves, tables and charts can also be used to current the percentage and trend of land use change. However, quantitative information can not characterize the spatial distribution of land use and the change process (Xin et al. 2012).

The simulation of land use change is a commonly essential for land manager and decision makers but difficult process due to constraint mechanisms and driving factors of land use change processes (Lambin et al. 2001; Xin et al. 2012). There are various methods for land use change modeling such as logistic regression modeling (Puertas et al. 2014), hybrid models (Falahatkar et al. 2011) and dynamic modeling approaches, like Markov chains and cellular automata (Mitsova et al. 2011; Xin et al. 2012). Markov chain and cellular automata are most convenient and popular models used by decision makers and researchers due to its easy combination with both the GIS and remotely sensed data, in addition to its interactive quantified and visualization outcomes. They provide information about the rates and patterns of change, and help recognizing the implications of forest ecosystem dynamics (Peterson et al., 2009; Mondal and Southworth 2010; Mitsova et al. 2011; Xin et al. 2012; Yang et al. 2014).

Markov chains model is capable of predicting land use changes from earlier period to later period and use this information for simulating land use change for future periods (Estmen 1995). A cellular automaton has been commonly preferred to simulate nonlinear forest ecosystems (Wolfram, 1984). CA-based models have a strong skill to characterize stochastic and non-linear spatial processes (Batty et al. 1997). Nowadays, CA-based cellular automata models have been used in land use change estimation (Yang et al. 2008).

The goal of our research was to investigate the potential use of an integrated Markov chain analysis and cellular automata model to better understand the dynamics of forest ecosystem for case study area in south east of Turkey and to develop simulated land use map to examine possible differences between actual and simulated land use map for 2022.

## **2. Methods**

### **2.1 Study area**

Andırın Forest District Enterprise (FDE), located in the Mediterranean city of Kahramanmaraş in Turkey was selected as a case study area (Figure 1). The study area lies between 253000 and 289000 East longitude and 4136000-4193000 North latitudes with respect to Universal Transverse Mercator (UTM) European 50 datum 37 zone. Andırın FDE consists of Akifiye, Andırın, Kaleboynu and Yeşilova planning units. The total area of Andırın FDE is 119,804.9 ha, whereas 81,578.6 ha of these lands are covered by forests. The dominant tree species are *Pinus brutia* Ten, *Pinus nigra* Arn., *Cedrus libani* A.Rich., *Quercus* sp., and Mediterranean maquis.

### **2.2 GIS data and Land use map**

In this study, the last three forest stand type maps (1991, 2002 and 2012) obtained from forest management plans were used as a main source of this study. The stand type maps of 2002 and 2012 were obtained from Kahramanmaraş regional directorate of forestry as ArcGIS digital format. Stand type maps for 1991 were scanned with 600 dpi, and saved in TIFF format. They were registered as digital topographic maps with 1:25000 scale. Then, forest management maps were rectified to UTM European 50 datum 37 zone by using nearest neighbor resampling methods based on 30 well distributed ground control points.

Spatial database was developed to establish spatial forest database for monitoring and simulating land use change. The attribute data (i.e. land use class, development stage, and crown closure) associated with forest management maps were generated by digitizing rectified maps with a 1/2000 to 1/5000 screen view scale. The maximum root mean square (RMS) errors were computed as less than 5 m. Finally, the spatial database was developed by generating digital maps for each attribute data. The land use categories were identified: Forest Land (FL), Built-up Land (BL), Agricultural Land (AL) and Others (O). The description of each of the land use classes is given in Table 1.

### 2.3 Markov-CA model

Markov-CA model combines the theories of the Cellular Automata (CA) and Markov chain, and is generally used in estimating land use change (Sang et al., 2011; Yang et al., 2014). CA is a spatially dynamic and explicit modeling approach and having powerful experiences in simulating the spatio-temporal patterns of forest ecosystem which cannot be characterized by specific equations. Integration of Markov and cellular automata approaches has been presented to improve models describing dynamic and complex forest ecosystem patterns (Peterson et al. 2009; Mondal and Southworth, 2010).

In this study, the predicted land use map was produced using the IDRISI Selva software. The Markov module investigates two land use maps and outputs a transition areas matrix, transition potential map and simulation land use map. At first, the transition probability matrices for 2012 were estimated using Markov module based on the transitions between two former land use maps for 1991 and 2002. The CA Markov module used these transition probability matrices to forecast spatial patterns for 2012 using the 1991 land use map as the base land use map. Then we estimated predicted land use areas from the transition probability matrices generated for 1991 and 2002. Transition potential map for 2012 was generated from transition probability matrix, which is calculated using Markov Chain. Simulated and actual land use maps were compared and accuracy and validity of method were tested. Finally, simulated land use maps for 2022 were estimated based on the transitions between two former land use maps for 2002 and 2012 using the 2002 land use map as the base map. A 5x5 contiguity filter was used to define the neighborhood of each cell.

### 3. Results and Discussion

Using the Markov module, transition probability matrix of land use classes during 1991-2002 was listed in Table 2 and Markov probability matrix was used for simulating the transitions. Table 2 indicated that there was 4.0 percent chance that forest land class would conversion to agricultural land class and 3.0 percent chance that forest land class would transition to other during 1991–2002. In the same period, other important transition was from build-up land class to agricultural land class (43.1 percent), other class to forest land class (22.5 percent) and agricultural land class to forest land class (14.2 percent).

Land use maps were generated for the year of 1991 and 2002 (Figure 2) using transition probability matrix and areal distribution of each land use class was presented in Table 3. The results indicated that main land use class was FL class which account for 67.9% and 68.7% of the planning unit for 1991 and 2002, respectively and other main type was agricultural land



class as 25.6% and 25.5% of the planning unit. Forested land class increased from 81329.2 ha to 82373.4 ha between 1991 and 2002, with a net increase of 1044.2 ha.

Transition probability matrices for 1991-2002 was used for forecasting spatial patterns for 2012 using the 1991 land use map as the base land use map and simulated area, actual area and difference (area and rate) were listed by categories in Table 4. At the same time, the simulated land use map in 2012 was created by using CA-Markov (Figure 2). With regard to the quantitative precision, the best forecasting class is BL class, where the actual area is 2149.6 ha, while simulated area is 2196.7 ha. Difference percent rates for BL and FL classes are mainly low at 0 and 0.5, respectively. Differences for O and AL classes are 0.9 and 1.4 respectively, little higher than that of FL and BL classes. According to results, the model is effectively to estimates area change of land use classes in the future. In terms of amount of area difference, BL, FL, O and AL classes are 47.1, 654.7, 1026.6 and 1634.2, respectively, which means that great part of land use classes in simulated map are forecasted correctly. Therefore, the CA Markov module can be used to predicting the spatial land use pattern objectively and accurately for the future.

Using 2002 and 2012 land use maps, the transition probability and area matrix were estimated and the CA Markov module then used these transition probability matrices to forecast spatial patterns for 2022 using the 2012 land use map as the base land use map (Table 5 and Figure 3). Our projections indicated that main land use class was FL class which account for 68.0% of the planning unit for 2022 and other main type was agricultural land class as 24.5% of the planning unit. The results showed that major changing happened in Other classes with a net decrease of 625.9 ha. Agricultural and forest land increased approximately 615 ha and 180 ha, respectively by the year 2022 while bare land decreased 170 ha.

#### **4. Conclusions**

The spatio-temporal dynamics of forest ecosystem in Mediterranean region of Turkey were analysed and the potential use of an integrated cellular automata model and Markov chain analysis to better understand the dynamics of forest ecosystem for case study area in south east of Turkey was tested. With Markov chain analysis, transition matrix was calculated based on 1991 and 2002 land use map and then predicted 2012 land use map using transition matrices. Predicted and actual land use map for 2012 were validated using accuracy value. Future land use were then projected using a CA-Markov model based on the 2002 or 2012 land use map and transition matrices.

The simulated land use map in 2012 was generated by using CA-Markov and compared actual land use map for 2012.e 2). According to quantitative accuracy, the best forecasting class

is BL class, where the actual area is 2149.6 ha, while simulated area is 2196.7 ha. Difference percent rates for BL and FL classes are mainly low at 0 and 0.5, respectively. According to results, the model is effectively to estimates area change of land use classes in the future. Therefore, the CA Markov module can be used to predicting the spatial land use pattern objectively and accurately for the future.

Our projections for land use map in 2022 indicated that main land use class was FL class which account for 68.0% of the planning unit for 2022 and other main type was agricultural land class as 24.5% of the planning unit.

## 5. References

- BATTY, M., COUCLELIS, H., and EICHEN M. 1997. Urban system as cellular automata. *Environ Plann.* 24:159-164.
- ERDOĞAN, N., NURLU, E., ERDEM, Ü. 2011. Modelling land use changes in Karaburun by using CLUE-s. *ITU AZ*, 2 : 91-102 .
- ESTMEN, J.R. 1995. Idrisi for windows user guide version 1/0. Clark University.
- FALAHATKAR, S., SOFFIANIAN, A.R., KHAJEDDIN, S.J., ZIAEE, H.R., NADOUSHAN, M.A. 2011. Integration of Remote Sensing data and GIS for prediction of land cover map. *Int. J Geomat. Geosci.* 1:4. 75-88.
- HOUGHTON, R.A. 1994. The worldwide extent of land-use change. *Bioscience* 44:305–313.
- LAMBIN, E.F., TURNER, B.L., GEIST, H.J., AGBOLA, S.B., ANGELSEN, A., BRUCE, J.W., COOMES, O.T., DIRZO, R., FISCHER, G., FOLKE, C., GEORGE, P.S., HOMEWOOD, K., IMBERNON, J., LEEMANS, R., LI, X.B., MORAN, E.F., MORTIMORE, M., RAMAKRISHNAN, P.S., RICHARDS, J.F., SKANES, H., STEFFEN, W., STONE, G.D., SVEDIN, U., VELDKAMP, T.A., VOGEL, C., XU, J.C. 2001. The causes of land use and land cover change: moving beyond the myths. *Global Environ. Chang.* 11:261–269.
- LAURANCE, W.F. 1999. Reflections on the tropical deforestation crisis. *Biol. Conserv.* 91:109–117.
- MITSOVA, D., SHUSTER, W., WANG, X. 2011. A Cellular automata model of land cover change to integrate urban growth with open space conservation, *Landscape Urban Plan.* 99:141–153.
- MONDAL, P., SOUTHWORTH, J. 2010. Evaluation of conservation interventions using a cellular automata-markov model, *Forest Ecol Manag.* 260:1716–1725

- PETERSON, L.K., BERGEN, K.M., BROWN, D.G., VASHCHUK, L., BLAM, Y. 2009. Forested land-cover patterns and trends over changing forest management eras in the siberian baikal region, *Forest Ecol Manag.* 257:911–922
- PUERTAS, O.L., HENRIQUEZ, C., MEZA, F.J. 2014. Assessing spatial dynamics of urban growth using an integrated land use model. Application in Santiago Metropolitan Area, 2010–2045. *Land Use Policy* 38:415–425.
- RIMAL, B., 2011. Application of remote sensing and gis, land use/land cover change in Kathmandu metropolitan city, Nepal, *Journal of Theoretical and Applied Information Technology*.
- SANG, L.L., ZHANG, C., YANG, J.Y., ZHU, D.H., YUN, W.J. 2011. Simulation of land use spatial pattern of towns and villages based on CA-Markov Model. *Math. Comput. Model.* 54:938–943.
- SIDLE, R.C., ZIEGLER, A.D., NEGISHI, J.N., NIK, A.R., SIEW, R., TURKELBOOM, F. 2006. Erosion processes in steep terrain—truths, myths, and uncertainties related to forest management in Southeast Asia. *Forest Ecol Manag* 224:199–225.
- SIVRIKAYA, F., ÇAKIR, G., KADIOĞULLARI, A.İ., KELEŞ, S., BAŞKENT, E.Z., TERZIOĞLU, S. 2007. Evaluating land use/land cover changes and fragmentation in the camili forest planning unit of northeastern turkey from 1972 to 2005. *Land Degrad Dev.* 18: 383-396.
- SIVRIKAYA, F., BAŞKENT, E.Z., BOZALI, N. 2013. Spatial dynamics of carbon storage: a case study from Turkey, *Environ Monit Assess.* 185:9403–9412, DOI 10.1007/s10661-013-3260-x
- VERBURG, P.H., KOK, K., PONTIUS Jr., R.G., VELDKAMP, A. 2006. Modelling land use and land cover changes, 117-135, *Land use and land cover changes: local process and global impacts*, Lambin, E.F. and Geist, H. (Eds.), *Global Change—The IGBP Series*, Springer-verlag, Berlin, Germany, 222p.
- VITOUSEK, P.M. 1994. Beyond global warming: ecology and global change. *Ecology* 75:1861–1876.
- WOLFRAM, S. 1984. Cellular automata as models of complexity, *Nature.* 31:419-424.
- XIN, Y., XIN- Qj, Z., LI-NA, L. 2012. A spatiotemporal model of land use change based on ant colony optimization, Markov chain and cellular automata, *Ecol. Modell.* 233:11– 19.
- YANGQ, Li X., SHI X. 2008. Cellular automata for simulating land use changes based on support vector machines, *Computers & Geosciences*, 34, pp 592-602.
- YANG, X., ZHENG, X.Q., CHEN, R. 2014. A land use change model: integrating landscape pattern indexes and Markov-CA, *Ecol Modell.* 283:1-7.

**TABLES**

Table 1. Land use classes descriptions.

Table 2. Transition probability matrix of land use classes, 1991 and 2002.

Table 3. Transition area matrix of land use classes (ha), 1991 and 2002.

Table 4. Comparison of accuracy for simulated land use and actual land use for 2012.

Table 5. Comparison of accuracy for actual land use for 2012 and simulated land use for 2022.

Table 1. Land use classes descriptions.

Land use classes	Description
Forest Land	Deciduous (Broadleaf) forest, needled forest, degrade high forest, degrade coppice forest, productive coppice forest, mixed forest lands
Built-up Land	Residential, urban and rural areas
Agricultural Land	Agricultural area, crop fields, fallow lands and vegetable lands
Others	Bare soil, forest openings, waters (rivers, ponds, lakes), reservoirs, rocks

Table 2. Transition probability matrix of land use classes, 1991 and 2002.

1991	2002			
	FL	BL	AL	O
FL	0.9268	0.0026	0.0402	0.0303
BL	0.1161	0.4333	0.4312	0.0193
AL	0.1422	0.0353	0.7900	0.0325
O	0.2245	0.0009	0.0783	0.6962

Table 3. Transition area matrix of land use classes (ha), 1991 and 2002.

1991	2002				Total
	FL	BL	AL	O	
FL	75667.00	135.42	3960.76	1566.02	81329.20
BL	151.00	1183.09	624.85	3.13	1962.07
AL	4046.05	295.27	25528.40	773.52	30643.24
O	2509.38	0.50	440.43	2975.80	5926.11
Total	82373.40	1614.28	30554.4	5318.47	119860.62

Table 4. Comparison of accuracy for simulated land use and actual land use for 2012.

Land use classes	Simulated area (ha)		Actual area (ha)		Difference	
	ha	%	ha	%	ha	%
FL	80600.5	67.3	81255.2	67.8	-654.7	-0.5
BL	2196.7	1.8	2149.6	1.8	+47.1	0.0
AL	30411	25.4	28776.8	24.0	+1634.2	+1.4
O	6596.7	5.5	7623.3	6.4	-1026.6	-0.9
<b>TOTAL</b>	<b>119804.9</b>	<b>100.0</b>	<b>119804.9</b>	<b>100.0</b>		

Table 5. Comparison of accuracy for actual land use for 2012 and simulated land use for 2022.

Land use classes	Actual area (ha)		Simulated Area (ha)		Difference	
	2012		2022			
	ha	%	ha	%	ha	%
FL	81255.2	67.8	81435.8	68.0	180.6	0.2
BL	2149.6	1.8	1979.4	1.7	-170.2	-7.9
AL	28776.8	24.0	29392.3	24.5	615.5	2.1
O	7623.3	6.4	6997.4	5.8	-625.9	-8.2
<b>TOTAL</b>	<b>119804.9</b>	<b>100.0</b>	<b>119804.9</b>	<b>100.0</b>		

## FIGURES

Figure 1. Map of the study area showing the locations of Andırın FDE

Figure 2. Actual land use map a) 1992, b) 2001, c) 2012, d) Simulated land use map in 2012 by CA-Markov

Figure 3. a) Actual land use map in 2012 b) Simulated land use map in 2022 by CA-Markov

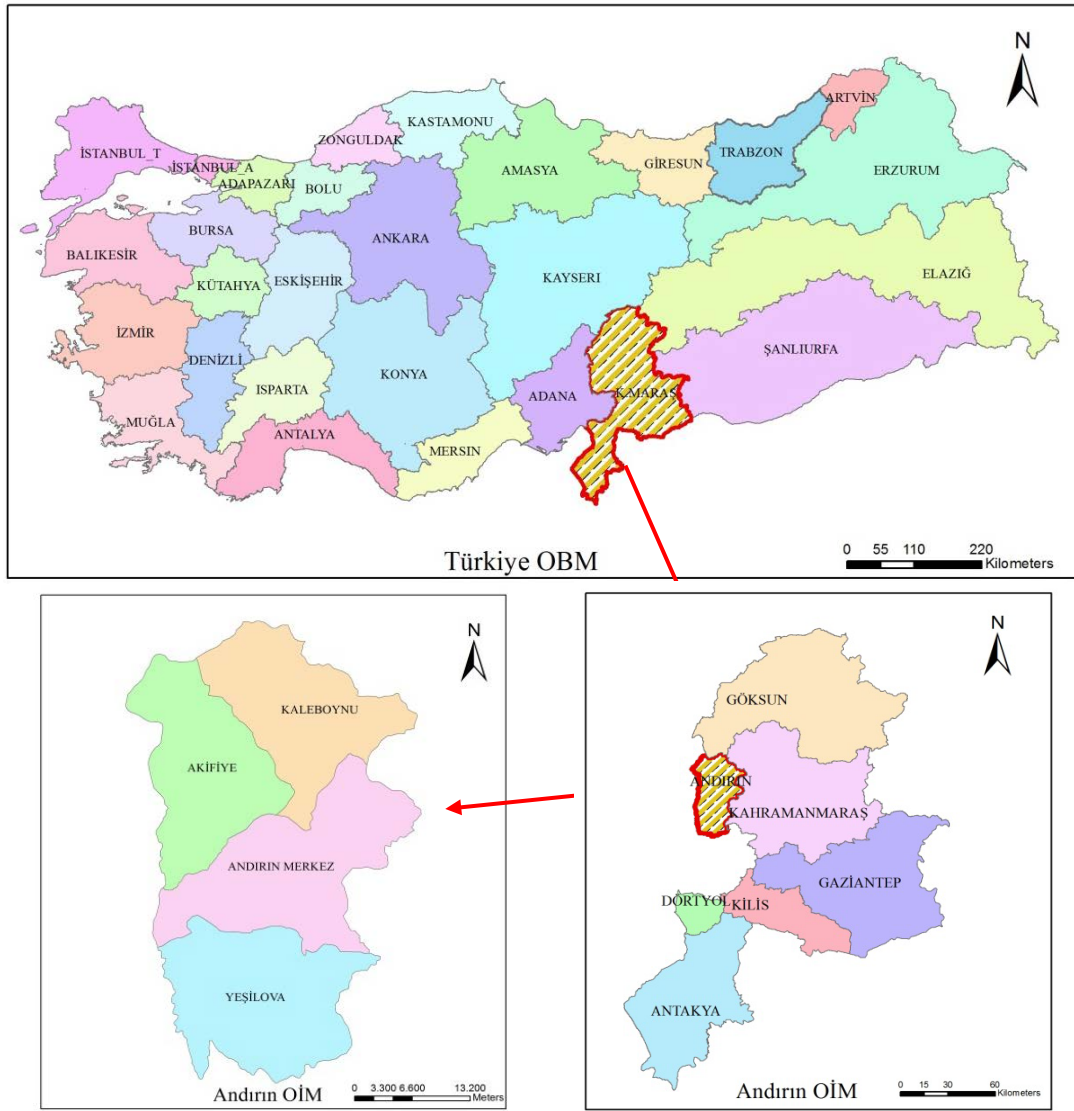


Figure 1. Map of the study area showing the locations of Andırın FDE

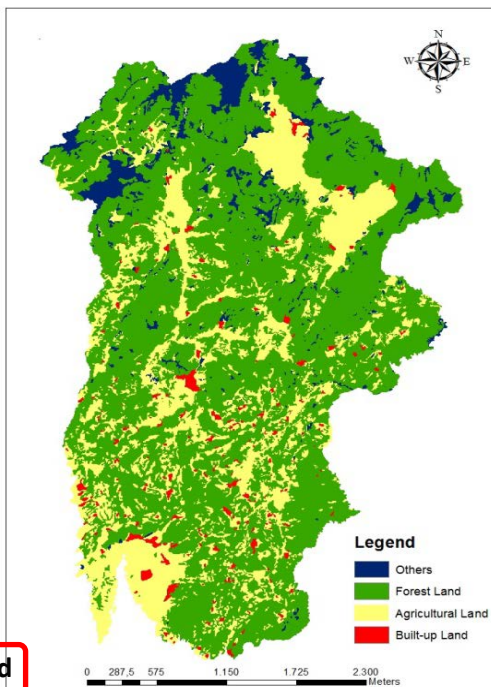
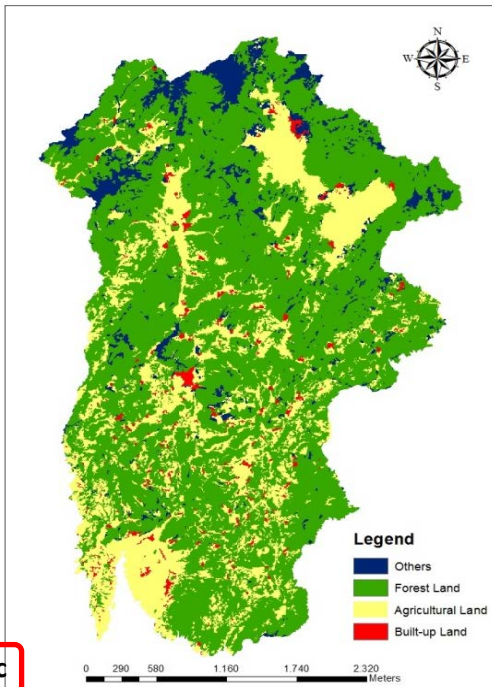
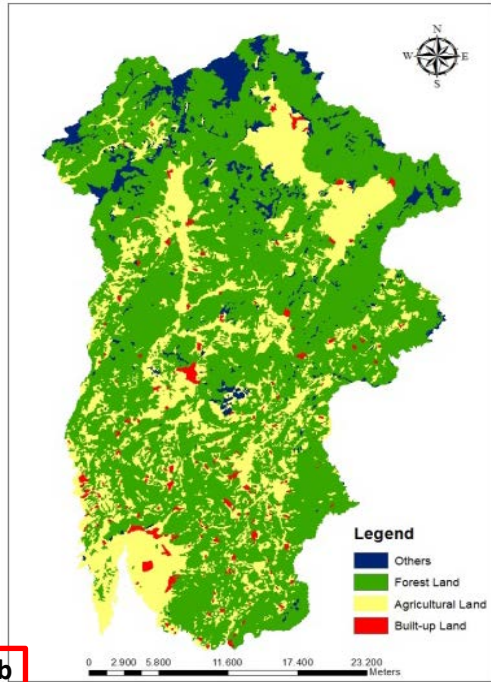
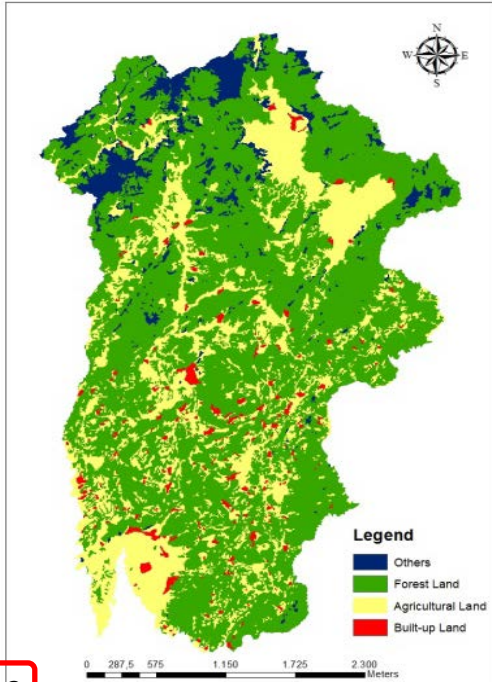


Figure 2. Actual land use map a) 1992, b) 2001, c) 2012, d) Simulated land use map in 2012 by CA-Markov



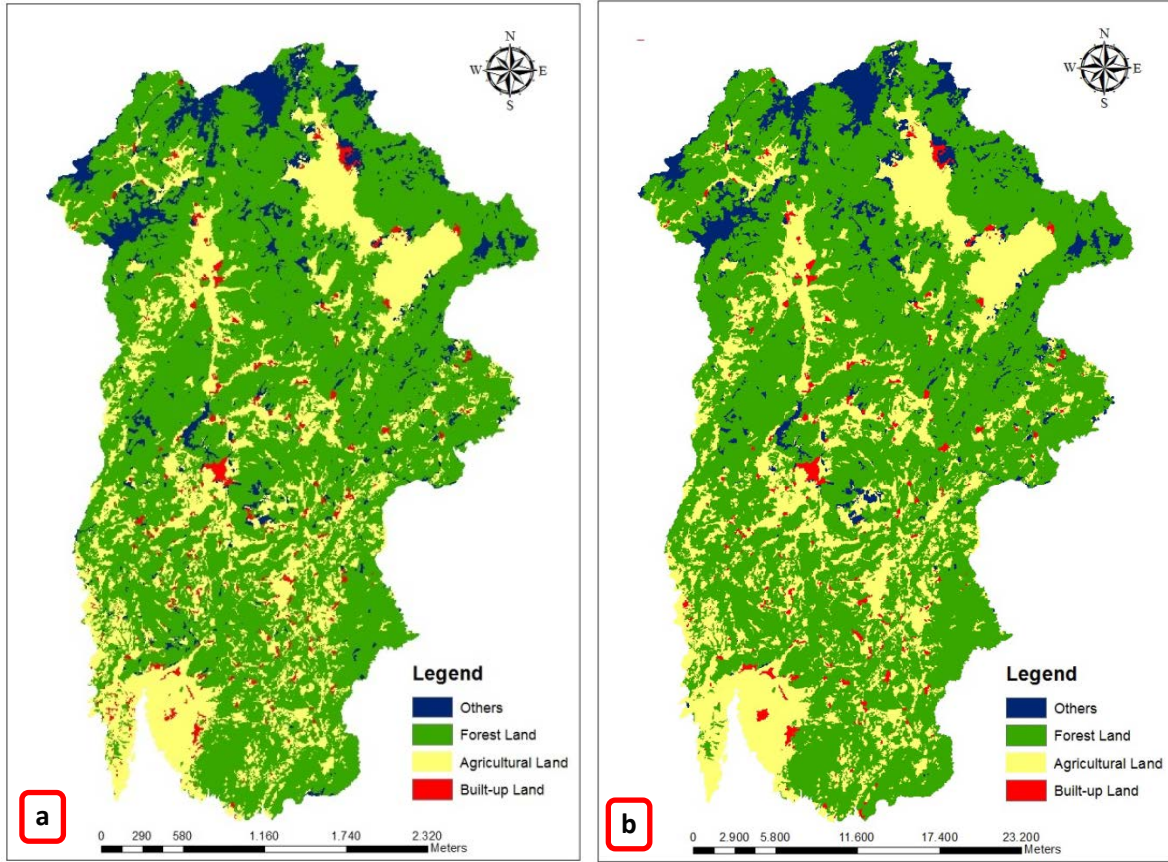


Figure 3. a) Actual land use map in 2012 b) Simulated land use map in 2022 by CA-Markov

## **XI. Concurrent Session 4B – Spatial Analysis in Forest Operations**

### **Assessing Spatial Distribution and Availability of Forest Biomass by Harvesting System in the Pacific Northwest, USA**

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To support the biomass supply model for a regional forest residue to aviation fuel project (NARA), we evaluated the spatial distribution of biomass by harvesting system and estimated distance to road. The NARA project is a USDA funded project with the objective of evaluating a supply chain from forest biomass to aviation fuel production. The base resource data are FIA plots. To improve our understanding of the topography, likely harvest system, and distribution of forest residues we developed a GIS-based model. We present a methodology based on the processing of vector and raster data that can be used at the regional level. Regional data (digital elevation models, road networks, ownership, landcover) was collected from the primary federal and state agencies. Digital elevation models were processed to estimate the amount of forested land that could be suitable for either ground-based or cable equipment. We then combined the harvest system overlay with the road system. In cable terrain, residues were assumed to be at roadside. For ground-based systems we assumed part of the residues is generated at roadside landings and part was generated in the field at different distances from the road. The results from the analysis will be used to characterize the biomass collection and comminution costs for biomass generated in the vicinity of each FIA plot. Validation of the GIS processing is done by comparing model results with the harvest unit layers on the state of Oregon forests.

**Key-words:** Biomass, spatial analysis, harvesting systems.

#### **1. Background | Introduction**

The Northwest Advanced Renewable Alliance’s mission is to provide economically viable and socially acceptable regional solutions to support the creation of forest residuals to bio-jet industry in the Pacific Northwest (NARA 2015). A critical element of this mission is to properly identify and evaluate the forest residuals supply chain which includes the extraction, transportation and comminution of forest residuals along with processing and other auxiliary activities required to sustainably produce bio-jet fuel at scale. A main objective in the NARA project is to accurately estimate supply chain costs by developing economic modeling protocols in an effort to better utilize existing resources and site locations for future infrastructure placement.

### Supply Chain Cost Structure

Feedstock costs (Phase #1) include collection, transportation and grinding of residuals prior to production facility processing. These costs account for roughly 33% of the total supply chain operational expenses (OPEX) while Phase #2 costs (pretreatment, processing at the mill and distribution costs) account for nearly 67% (Wolcott 2013). This paper will limit discussion to the operational feedstock supply chain cost structure within the NARA economic modeling framework. In particular, we will highlight the collection cost structure, its current estimation methodology and importance while suggesting ways to refine model inputs and incorporate spatial data. Figure 1 illustrates the typical regional residual supply chain structure.

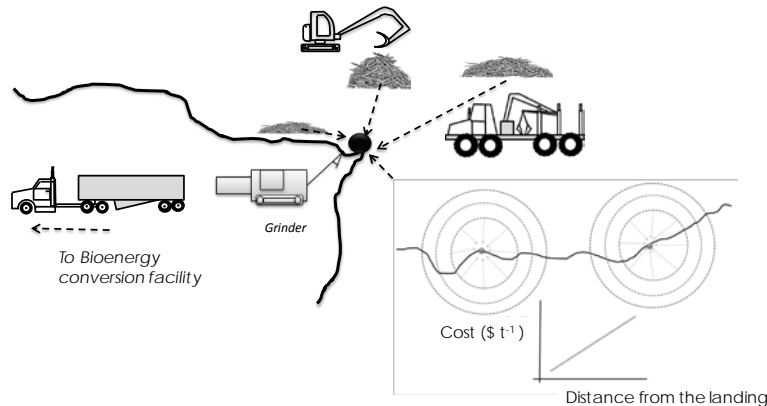


Figure 1. Typical forest harvest residue collection system in western Oregon and Washington (Zamora and Sessions 2014).

### Collection System Utilization

Two main harvesting systems (ground-based and cable-based) are used for most logging operations in Pacific Northwest forests. Ground-based systems (typically shovel logging) are

generally utilized when slopes are less than around 30% for safe productive work (Conway 1976, MacDonald 1999). Cable-based systems are generally employed on steeper slopes. As a general principle, ground-based systems are more cost effective solution if conditions are suitable (Lousier 1990, Jarmer et al. 1992).

When utilizing cable systems, the residuals are primarily located at a landing site adjacent to roadside and thus readily accessible. Alternatively, ground-based logging systems such as shovel logging typically disperse a larger volume of residuals in the field with a smaller fraction located at roadside. Usually residues are not moved directly to roadside, but are moved to discrete landings along the roads for comminution. This is important as the distance to roadside is the primary collection cost driver and subsequent barrier to sustainable utilization. Studies suggest that residuals which are piled and within 150 feet of roadside cost roughly \$5-10/ BDT compared to \$20-30/ BDT for material that is further from roadside (Zamora and Sessions 2015). Subsequently, collection costs can vary by a factor of six, ultimately varying overall feedstock costs by up to 25%; accounting for nearly 10% of the entire operational supply chain cost structure.

For ground-based harvesting systems two distance bands are the most logical for evaluation, the area within 300 feet of a road, and the area outside of 300 feet. If residues are to be transported less than 300 feet, the least expensive method is by excavator. For harvest units with residue collection distances greater than 300 feet adding one or more forwarders loaded by an excavator can be more economical if the equipment is available.

## **2. Problem Description**

The NARA biomass supply model relies on the Forest Inventory and Analysis (FIA) database for the description of forest characteristics. In order to project when and where forest biomass residues will be created the NARA biomass supply model simulates commercial timber harvest to meet regional product demands using a variant of the Timber Assessment Market Model developed by Adam and Haynes (1980). The NARA biomass supply model allocates the volume of commercial timber harvest that will occur at each plot center in each time period considering timber characteristics, logging costs, and transport distances. In the NARA biomass supply model forest harvest residues are a byproduct of the timber harvest, they do not drive it. To develop the supply, the quantity of biomass and cost of delivered biomass must be calculated. Currently the NARA biomass supply model assumes all forest harvest residues at a plot point are available on truck at the same average cost. This method does not incorporate any spatial information of the site which will greatly impact residual accessibility, harvesting

method and thus projected collection costs and volumes. The objective of this paper is to develop a methodology that can be used to refine the average cost of getting forest biomass to roadside.

### **Project Objective and Outputs**

From a modeling perspective we need to answer the following key questions: What harvest method is likely to be used at a specific location? How many acres of forested land within state and private ownership classes are in close proximity to existing roads? How much and where is the area available for near term harvesting on a per FIA plot basis?

The specific goal of this project is to classify state and private forest land that is likely to be harvested within the next 25-35 years (i.e., not recently harvested) and falls into one of the following four categories: cable-based, ground-based within 150 feet of road, ground-based between 150 and 300 ft of a road, and ground-based beyond 300 ft of a road. Our contribution is to develop a methodology for incorporating spatial data to further refine the collection costs input to NARA's supply chain economic model. The information provided will be customized to meet these input requirements. We discuss how the model is applied (via point and sample dataset) in western Oregon and will be extended over the entire NARA region. We also present how the model compares to Oregon Department of Forestry (ODF) historical harvest data while exploring its limitations and overall implications to the NARA cost model.

## **3. Model Description**

### **Methods**

In order to solve this problem, ArcGIS 10 geospatial software and the Python programming language were utilized to manipulate and automate data processing (ESRI 2015). Key input data included: FIA point locations (USFS), Regional Road Networks (State), Digital Elevation Models (USGS DEMs), Protected Areas Data (USGS) and Global Forest Change (2000-2013) mapping data (Hansen et al. 2013a). The process was broken up into distinct phases including 1) pre-filtering the data, 2) spatial processing and discretizing, 3) road data processing and 4) land cover change analysis designed to answer the key questions related to estimating the underlying harvesting method, land type, road offset and land availability questions.

The general methodology is based on sampling a 1250ac area around the FIA point location, subdividing this acreage into 50ac subplots which were then analyzed to estimate a harvesting method and subsequent residual collection criteria related to road offset distance

and area availability (Figure 2). Each subplot was then assigned an estimated harvest unit type which became the basis for the analysis.

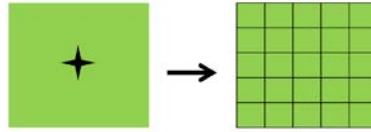


Figure 2. Conceptual model of land area discretizing (rasterizing)

### **Pre-Filtering Data**

In this project, residuals are assumed to be solely a by-product of commercial logging operations. As such, the NARA project is primarily interested in productive sites from state and private land ownership classes rather than federal sites where production is limited. Only forested state and private FIA points were selected for analysis.

### **Spatial Processing**

Once the FIA points were filtered, the point data was then used in conjunction with state specific DEM data to create a square buffer/ DEM raster around the point encompassing 1250 acres. The FIA DEM raster file was used as the input file for the slope function which output the percent slope at each point within the dataset. This raster file was then reclassified into two segments depending on the percent slope (<30%, >30%). This reclassified raster dataset was then split (discretized) into twenty-five 50 acre subplots. The 25 individual raster files were then reclassified again in accordance to their percentage of either likely ground-based systems (<30%) or cable-based systems (>30%) based on area majority. At this point the land is effectively reclassified in accordance with harvesting method with discrete raster and shape files for each of the 50 acre subplots.

### **Road Data Processing**

Once the individualized 50 acre subplot data was generated, road data is imported into the system and manipulated with a similar process being utilized to separate the data into the desired 1250ac units (namely data masking). The plot level shapefiles were then buffered with a 300 ft offset to determine approximate area available adjacent to the roadway. Finally, only the

ground-based system plots were then compared to the road offset shapefiles to determine approximate areas within the 300 ft buffer.

### **Land Cover Change Processing**

In order to get a more accurate assessment of the overall land available for harvest in the near term, land that was recently harvested was removed. The Global Forest Change dataset (Forest Cover Loss Layer) was utilized as a supplemental data layer. Similar to the other processing features, this dataset was sub-sampled and matched at the subplot level and then combined with harvesting system data. This allowed us to determine land area available for future harvests within each harvest class.

## **4. Application and Results**

### **Study Area**

We applied and compared the model results to actual harvest units in Oregon with data provided by the Oregon Department of Forestry (ODF). This was done to modify and compare this method before extrapolation to the entire NARA region. Below, we illustrate the methodology as applied to 1) a single FIA plot and 2) a series of 39 FIA plot locations in the Astoria region of northwest Oregon for comparison. It is important to note that this methodology is to be performed for all the plots in the entire NARA region which includes Oregon, Washington, Montana and Idaho to standardize economic model inputs.

### **State Forest Comparison – Single Plot Example**

For illustrative purposes and to provide an example of the actual output to be delivered to NARA, the analysis was applied to a single FIA plot (Figure 3) located in northwest Oregon (45° 24' 3.19"N, -123° 33' 18.84"W).

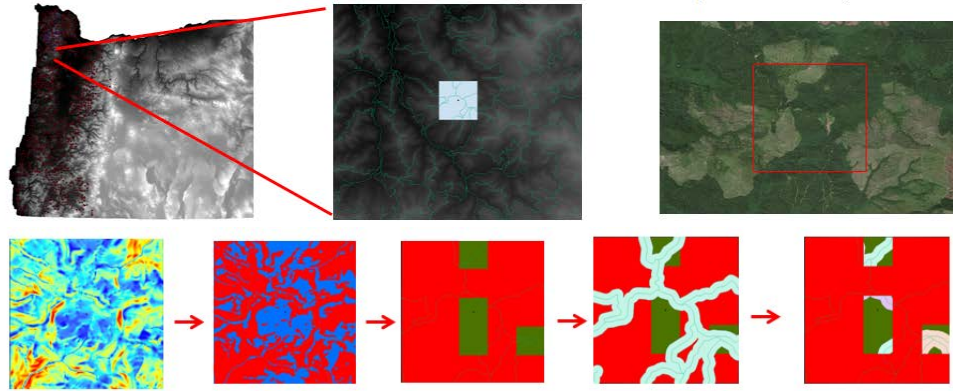


Figure 3. Example of proposed methodology: FIA plot location, point envelope, Google Earth aerial imagery, slope manipulation, reclassification and discretization, road system 300 ft offset buffer overlay.

It is important to note that on a per-plot basis the individual results will vary. ODF harvest units are predefined, irregular and tailored towards the site terrain and local logistics beforehand, while the model is a blanket interpretation of the area cut into pre-defined segments based on slope. While the results on a per-plot-basis are highly variable it is anticipated that from a system-wide view the method provides a realistic representation.

When reviewing a single plot we can also qualitatively see the efficacy of the land available and harvesting unit approximations. When viewing the land from an aerial perspective, we see a clear correlation of land available for harvest from the ground cover change layer when compared to actual aerial imagery (Figure 4). Additionally, we see that (in this case) the model harvest unit does a good job at approximating ground-based systems as the dominant area (middle of the unit, Figure 4). Overall, for this point, the model over-predicted ground-based operations by roughly 8% (Table 1). An over-prediction like this would provide a more conservative approximation of accessible residuals in the sense that a fraction of ground-based residues are not at roadside and must be collected as opposed to residues from cable-based harvesting systems at roadside. The NARA input is the percent of the private or state forested land within the 1250 acre sample that has not recently been harvested and falls into one of the following four categories: 1) cable-based, 2) ground-based within 150 ft of road, 3) ground-based between 150 and 300 ft of a road, and 4) ground-based beyond 300 ft of a road (Table 1). NARA would apply those land area percentages as part of the biomass cost estimation process.



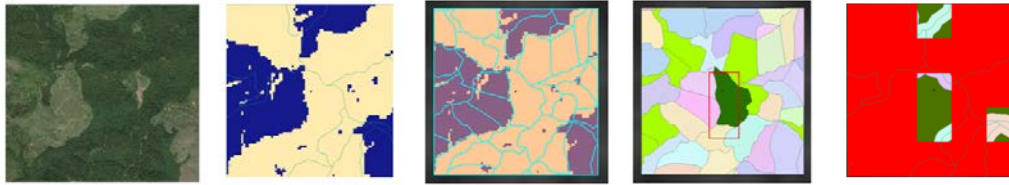


Figure 4. Comparison of ODF harvesting systems with model projections. Google Earth Overlay, Global Forest Change Layer, ODF Harvest Unit separation, ODF Harvest Unit (Dark Green is 70% ground, light green is less than 40%, all others are cable system).

Table 1. Example Comparison of ODF vs. Model projections for a single 1250ac Plot (45° 24' 3.19"N, - 123° 33' 18.84"W). Model NARA Input File generated based on available land area only.

		<b>ODF Total</b>	<b>Model Total</b>	<b>NARA Input (Of Available)</b>
<b>Systems Availability</b>	<b>System</b>			
	Ground-Based Systems	8%	16.00%	
	Cable-Based Systems	92%	84.00%	
<b>Availability</b>	Ground-Based Available		50.99%	
	Cable-Based Available		65.87%	87.15%
	% Available Overall		63.49%	
<b>Systems Area</b>	Ground-Based 150 ft Offset		20.72%	2.66%
	Ground-Based 300 ft Offset		41.43%	2.66%
	Ground-Based Other		100.00%	7.53%

### State Forest Comparison

The methodology was compared to 39 FIA plot locations which represented approximately 48,750 acres (Figure 5). With this data, we compared and analyzed the overall harvesting system allocation by overall area as well as review information from a per-plot-basis. We can see that, similar to the single plot example, the composite data compares favorably with the ODF data where cable-based system area was underestimated by 0.59% and ground-based systems area overestimated by 5.86% (Table 2). When reviewing the ODF harvest unit data compared to the model on a per-plot basis we see that the average overestimation towards ground-based system is roughly 6% with a standard deviation of about 25% (Figure 6).

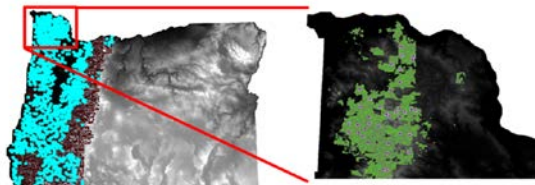


Figure 5. Oregon State Forest Validation Zone, Northwestern Oregon

Table 2. Comparison of ODF vs. Model projections for 39 points where data is available.

	ODF	MODEL	DIFFERENCE
<b>Ground-Based Systems</b>	25.42%	31.28%	5.86%
<b>Cable-Based Systems</b>	69.31%	68.72%	-0.59%
<b>Helicopter</b>	5.27%		

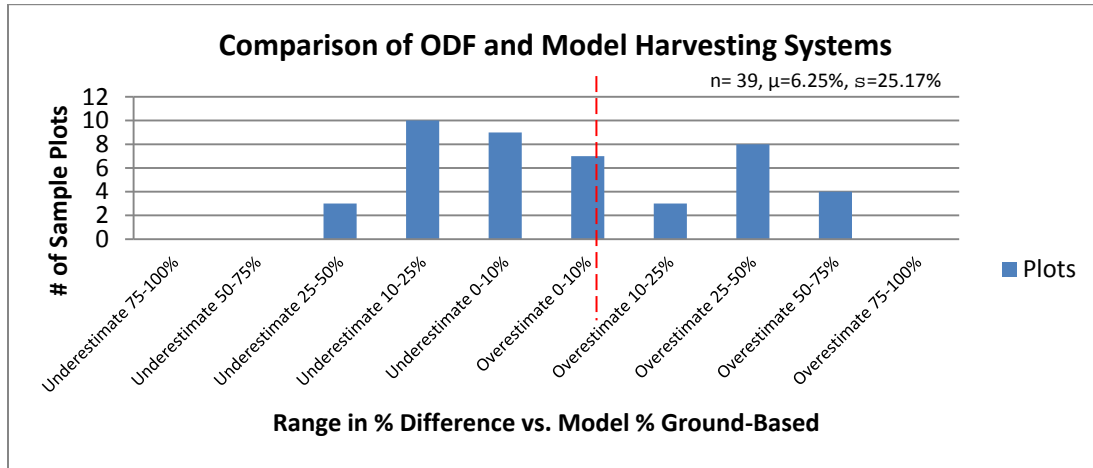


Figure 6. Comparison of ODF and modeled harvesting systems for the 39 FIA plots (1250ac area each) based on % difference of model predicted ground-based area. Data normalized to exclude helicopter and non-harvest areas.

It is likely the model over-predicts ground-based systems due to broader terrain characteristics that favor cable-based operations (i.e. raised road system along a ridge adjacent to milder slopes). Conversely, the model may under-predict due to its inability to capture situations where ground-based systems are used to harvest easily accessible timber near roads to supplement the cable operation.

## 5. Conclusions

This methodology provides a framework for estimating residual accessibility on a landscape scale. Overall, this method provides a simple, logical framework for estimating operating harvest system and associated landscape harvest residue accessibility and distance from roadside characteristics on a spatial scale; an improvement over the current method.

## **Limitations | Sensitivity**

This method employs a simple discretization technique that cannot characterize all the dimensions of an actual harvest unit such as size, placement, method, road logistics or a combination of methods in a specific area. The logic in our simplified method uses assumptions of harvest unit size, harvest system selection, and harvest system homogeneity within the harvest unit. We discuss the sensitivity of these assumptions below.

### **FIA Unit Plot Centroid/ Layout Design**

In this study, the plots were assumed to be simple squares surrounding the projected FIA plot centroid. In reality, FIA plots are not delineated in this fashion, with the point reflecting the centroid of a spherical area. Additionally, since the FIA point placements are ‘fuzzed’ to begin with, the actual area (and thus residual quantities) are only approximate.

### **FIA Unit Plot (1250ac)**

For analysis purposes, we chose a 1250ac plot to be representative of the FIA area. This design was primarily chosen due to overlapping areas (with larger plots), irregular point placement and to standardize the size. In reality, an FIA plot typically represents a 6000ac area (though there are plot variants). We assume this sample to be characteristic of the broader area.

### **Harvest Unit Size (50ac)**

We assume a 50 acre harvest unit subplot throughout the study as this correlates well with the Pacific Northwest practices, industry norms and the data obtained from our ODF sample. In our 39 plot sample we see a harvest unit average of 52 acres. However, a standard deviation of 27 acres with the overall range in excess of 100 acres illustrates the highly variable nature of the data. Additional sensitivity analysis by varying harvest unit size showed best results when using a 50 acre model harvest unit size (Table 3).

Table 3. Comparison of ODF vs. Model projections for 39 points. Percent difference of ground-based systems compared to observed (normalized for no helicopter or other system utilization) when varying individual harvest unit size (25ac, 50ac, 140ac).

	<b>25ac Model</b>	<b>50ac Model</b>	<b>140ac Model</b>
AVG % Difference	7.41%	6.25%	7.16%
Standard Deviation	23.60%	25.17%	27.83%

### **Harvest Method Slope Indicator (30%)**

In order to identify the harvesting system, we used a 30% cutoff to differentiate ground-based systems (<30%) and cable-based systems (>30%) based following classifications used by Conway (1976), Dykstra (1997), and MacDonald (1999). While this is the often used, there has been a trend toward using ground-based equipment on steeper slopes. Additional sensitivity analysis showed that this variable (as expected) was particularly sensitive to estimated system choice with 30% being a fairly accurate representation.

Table 4. Comparison of ODF vs. Model projections for 39 points (normalized for no helicopter or other system utilization) when varying the harvest slope indicator (20%, 30%, 40%).

	<b>ODF Values</b>	<b>20% Model</b>	<b>30% Model</b>	<b>40% Model</b>
Ground-Based Systems	25%	16%	31%	51%
Cable-Based Systems	69%	84%	69%	49%
Helicopter / Other	5%			

### **Harvest Unit System Cutoff (50%)**

In conjunction with the slope indicator, we used a simple slope majority rule to denote likely harvesting method. While this will likely explain many logging practices employed, it will not account for combinations of harvest systems used within any given harvest unit. From the 39 ODF plots, we saw that nearly 48% of all actual harvest units used a combination of harvest systems with an average of 30% difference between ground and cable-based logging systems.

### **Temporary Roads**

We used regional road network data. Temporary dry season spur roads, not on the regional road network data, would shorten collection distances on ground-based units. To the extent that these occur, the method here would underestimate the area close to roadside.

## 6. Future Work

This paper presents a simple, logical technique to estimate the spatial area that can contribute to harvest residual extraction. The model is designed to provide input percent areas to the NARA economic model in an effort to further refine the estimated collection costs portion of this model. This study shows that this technique can be employed (with clear limitations) in order to further refine this model and clarify harvest residual accessibility within the region. Future work to enhance this model could focus on three areas. First, it is thought that the largest source of error is related to harvest unit configuration. In order to improve the process, more sophisticated rules could be developed to reconfigure the harvest units to follow watershed boundaries, topographic contours and roadways. Second, additional data such as soil stability, vegetation type, riparian areas and other sensitive areas could be added to better approximate land available, systems constraints and subsequent residual locations. Third, it would be beneficial to have a greater number of comparison zones (points) in a variety of conditions and States to further refine and test key assumptions regarding slope delineation, harvest unit system cutoff and harvest unit size.

## 7. LITERATURE CITED

- Adams, D.M. and Haynes, R.W. 1980. The 1980 softwood timber assessment market model: structure, projections, and policy simulations. *Forest Science Monographs*. 26(3): 22.
- Conway, S. 1976. *Logging Practices, Principles of Timber Harvesting Systems*. San Francisco: Miller Freeman, 419p.
- Dykstra, D.P. 1996. Chapter 5: Extraction. *FAO model code of forest harvesting practice*. Available online at <http://www.fao.org/docrep/v6530e/v6530e08.htm>; last accessed May 28, 2015.
- ESRI. 2015. *ArcGIS 10. ArcGIS for Desktop*. Available online at [www.esri.com/software/arcgis/](http://www.esri.com/software/arcgis/); last accessed May 28, 2015.
- Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.A. Turubanova, A. Tyukavina, D. Thau, S.V. Stehman, S.J. Goetz, T.R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C.O. Justice,

- and J. R. G. Townshend. 2013a. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* 342 (6160), 850-853.
- Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.A. Turubanova, A. Tyukavina, D. Thau, S.V. Stehman, S.J. Goetz, T.R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C.O. Justice, and J. R. G. Townshend. 2013b. Global Forest Change Imagery. Available online at: [earthenginepartners.appspot.com/science-2013-global-forest/download\\_v1.1.html](http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.1.html): last accessed May 28, 2015.
- Jarmer, C.B., J.W. Mann, and W.A. Atkinson. 1992. Harvesting timber to achieve reforestation objectives. In: S.D. Hobbs, S.D. Tesch, P.W. Owston, R.E. Stewart, J.C. Tappeiner and G.E. Wells (Eds). *Reforestation Practices in Southwestern Oregon and Northern California*. Forest Research Laboratory (FRL), Oregon State University. USA. Pp 202-23 0.
- Lousier, J. D., comp. 1990. Impacts of forest harvesting and regeneration on forest sites. Land Management Report 67. Victoria: British Columbia Ministry of Forests. 90 p.
- MacDonald, A. J. 1999. Harvesting systems and equipment in British Columbia. [Victoria]: British Columbia, Ministry of Forests, Forest Practices Branch.
- Northwest Advanced Renewables Alliance (NARA) 2015. Wood to Wing. Available online at [www.nararenewables.org/](http://www.nararenewables.org/); last accessed May 28, 2015.
- Wilcott, M. 2013. Wood to Wing: Envisioning an Aviation Biofuels Industry Based on Forest Residuals in the Pacific Northwest. NARA. Oregon State University. Richardson Hall, Corvallis. 11 April 2013. Starker Lecture Series.
- Zamora-Cristales, R. and J. Sessions. 2015. Modeling harvest forest residue collection for bioenergy production. *Croatian Journal of Forest Engineering*. In Review.
- Zamora-Cristales, R., J. Sessions, K. Boston and G. Murphy 2014. Economic Optimization of Forest Biomass Processing and Transport in the Pacific Northwest USA. *Forest Science*. <http://dx.doi.org/10.5849/forsci.13-158>

# Photogrammetric-based Volume Models for Piled Slash Using Small Unmanned Aircraft Systems

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Advancements in conversion technologies for woody biomass coupled with the need for large scale restoration treatments in forests prone to wildfire, insect and disease outbreaks have resulted in a global interest to use forest treatment residues for bioenergy production and other bio-based products. A forest biomass supply chain relies heavily on the capacity to accurately and efficiently estimate residue volumes. Allometric equations are commonly used to predict residue volumes available for use in bioenergy enterprises, however estimates can vary drastically from the observed quantities depending on operational configuration, terrain, silviculture, and pre and post-treatment stand characteristics. An alternative method is to measure residue piles directly by surveying pile dimensions and assuming a geometric shape and bulk density to infer volume and weight. However, this becomes increasingly difficult when residue piles are large and contain both tops and limbs and large cull components. We propose a method to efficiently estimate piled residue volumes by using a low-cost camera mounted on an unmanned aerial system. Residue piles are surveyed by capturing a series of photographs from multiple perspectives then reconstructing the images to produce a high density 3D point cloud. The point cloud is used to create 3D surface models of the residue piles. This method can be used to efficiently estimate the volume of residue piles that are large, small, clustered and/or dispersed across a treatment unit.

**Keywords:** forest biomass, treatment residue, volume estimation, structure from motion

## 1. Introduction

Broad areas of damaged and dead forests from insect infestations and wildfire in the western U.S. have increased the availability of forest biomass for use in bioenergy and other bio-based markets. Generally, available feedstock for biomass markets consists of tops and limbs and other components of harvested trees that do not compete with the sawlog or pulp

industry. These residues are operationally prohibitive due to low bulk density and, in some cases, their dispersion across the treatment unit. However, the onset of broad-scale natural disturbances in recent years, namely mountain pine beetle, and active management in these areas to restore healthy ecosystems has dramatically changed the physical characteristics and economic potential of forest residues in biomass markets. Residue piles produced from harvesting operations in beetle-killed forest often contain large cull components and piles are commonly large in size because less merchantable material is available for use in conventional timber markets. These characteristics warrant alternative methods to estimate pile volume since traditional approaches become inferior as piles increase in size and variability of piece size.

Accurate measurement of residue piles is an important step in a forest biomass supply chain to establish a contract between the buyer and seller, estimate handling and processing costs, and ensure that appropriate and efficient extraction methods are used. For the purpose of feedstock in bioenergy production, piled residues are generally expressed in units of mass to account for the density, or packing ratio (PR), and the moisture content of the material in the pile. Mass estimates of piled residues are subject to multiple sources of uncertainty since mass calculations hinge on volume, PR, and moisture content estimates. A common method for estimating the weight of residue piles is presented by Hardy (1996). This ground-based approach requires the selection of a geometric function that best describes the shape of the pile to estimate volume. Guidelines are also provided for determining the PR and moisture content. Few studies have been successful in identifying alternative methods to reduce sources of uncertainty in pile mass estimation. Trofymow et al. (2013) used aerial LIDAR to provide realistic, irregular volume models for piled slash. Although PR and moisture content measurements were still performed manually, the authors found significant improvements over conventional methods for estimating pile volume. One caveat of this approach is the use of expensive equipment to acquire the volume models. LIDAR applications currently may not be an appropriate means of estimating forest residue due to narrow profit margins in forest biomass markets. To circumvent the high cost of LIDAR instrumentation and flight, Long and Boston (2013) propose an alternative ground-based method for estimating pile volume using a laser range finder to construct irregular volume models. Although this approach is more time consuming than other ground-based methods, volume estimates showed superiority over geometric models and demonstrated strong correlations with volume estimates via terrestrial LIDAR scans.

This study presents an alternative method to estimate pile volume that we feel is superior over previously presented methods when considering accuracy and costs. A low-cost



camera mounted on an unmanned aerial system (UAS) is used to capture a series of digital photographs of residue piles from multiple perspectives. The photographs are re-constructed using the structure from motion algorithm to create three dimensional surface models that accurately represent the complex shapes of the piles. Multiple techniques are used to estimate the volume of the surface models and values are compared to ground-based geometric volume estimates previously conducted on the study site. The purpose of this study is to explore techniques to improve the accuracy of volume estimates. Other sources of uncertainty, such as PR and moisture content were not considered in this study. Values from the previously conducted survey are simply used to test for significant difference between the surveying techniques, not to validate the presented methodology.

## 2. Methods

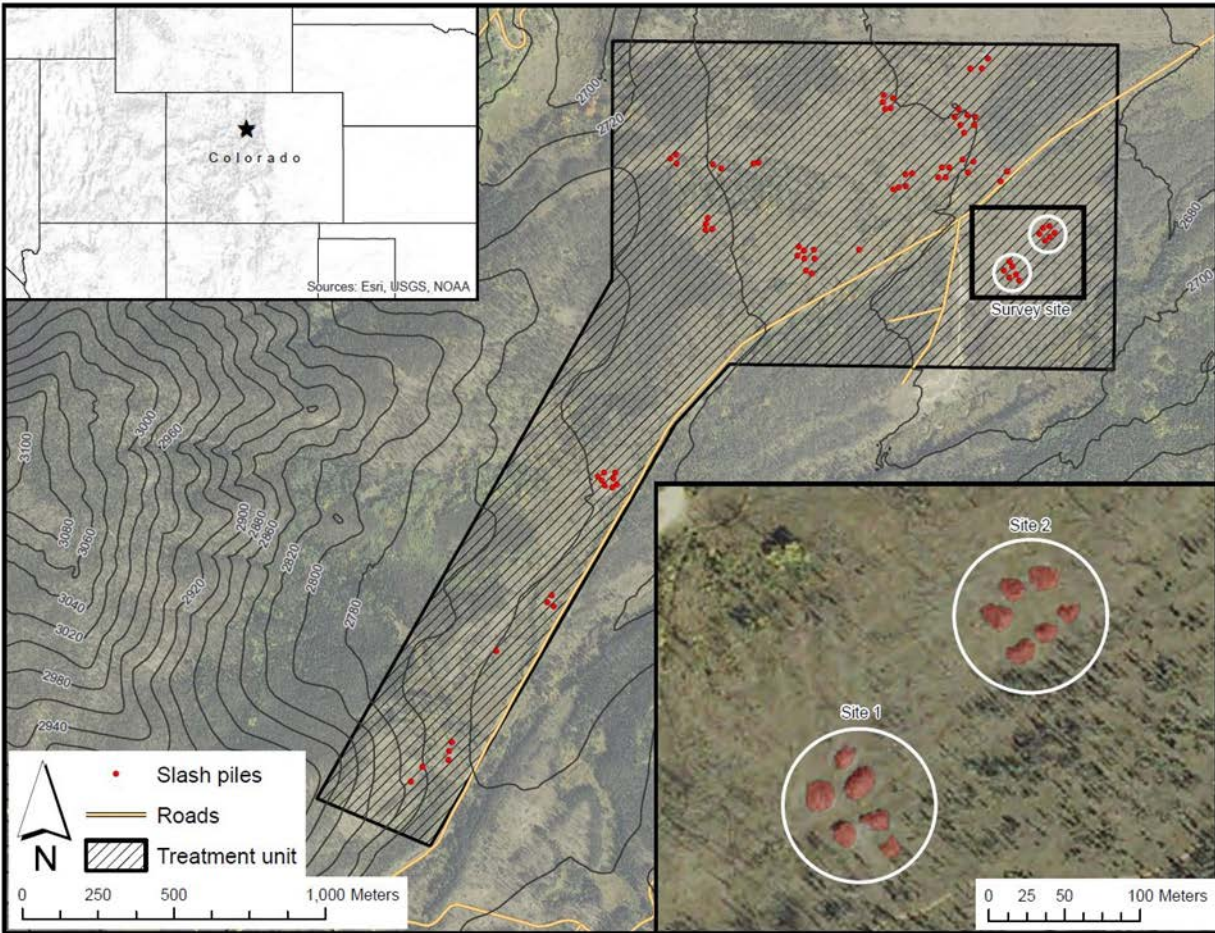
### Study Site

The study site included a subset of a recent harvest in the central Rocky Mountains near Fraser, Colorado (Figure 1). The area had previously experienced a mountain pine beetle infestation and the majority of the growing stock had died since the attack. The harvest prescription targeted beetle-killed trees that still had merchantable volume and non-merchantable material was piled on small landings scattered throughout the unit. The entire harvest unit included 78 piles scattered across the area. Many piles were clustered around the landings and few were isolated between clusters. The surveyed area included 2 clusters of slash piles each with 6 residue piles in the western region of the harvest unit.

2700  
2720

2600

Figure 1: Survey site near Fraser, Colorado. The surveyed residue piles are shown in the inset on the bottom right.



### Flight characteristics and instrumentation

Aerial imagery was taken at each site for the purpose of conducting photogrammetry. Flights were carried out with a tethered UAS equipped with a gimbal stabilized color digital camera. The UAS selected was the Matrix which is an electric powered quad rotor developed by TurboAce. The Matrix weighs 6.8 kg when equipped with a 16 amp battery and the camera. The UAS configuration has an operational endurance of 20 - 30 minutes depending on temperature and air density. The Aerial Information Systems Lab at Oregon State University College of Forestry outfitted the Matrix with a 3D Robotics Pixhawk for autonomous flight control and waypoint navigation. We equipped the Matrix with a Sony NEX 5T mirrorless 16 megapixel

camera and a 20 mm lens. The NEX was chosen because it has a relatively large sensor (23.4 x 15.6 mm) for its 10.1 oz camera body. The Sony SEL20F28 20 mm is a lightweight (69g) lens that provides a wide footprint with minor barrel distortion. Image footprint at 62m above ground level (AGL) is 72.5m x 48.4m.

Camera focus was manually established by focusing on a tree > 40 m away to ensure proper focus at operating altitude. White balance calibration to a 15% gray card was used to ensure proper color balancing for visual interpretation. The camera was set to shutter priority mode with a 1 ms shutter speed. Automatic triggering of the shutter was facilitated by a one second intervalometer that is part of Sony’s Time Lapse application.

Ground control was established with five 1.2 x 1.2 m iron cross aerial targets. Targets were placed at four arbitrarily defined corners on the site extent with the fifth target placed in the center. Targets were georeferenced with a Trimble GeoExplorer 6000 XH GPS. Code and carrier corrections were performed in Trimble Pathfinder Office using the nearest continuously operating reference station (CORS). Resulting georeferencing uncertainty was reported as < 10 cm.

Table 1: Flight characteristics

Site	1	2
Linear distance flown (m)	522	648
Velocity (m/s)	3	5
Sidelap (%)	80	80
Imaging interval (s)	1	1
Site elevation (m ASL)	2691	2691
Fight altitude (m AGL)	62	62
Flight direction	NW to SE	ENE to WSW
Easting registration error (m)	0.0434	0.114
Northing registration error (m)	0.179	0.2216
Height registration error (m)	0.15	0.06

## Image processing

Images from each site were aggregated and processed independently in Agisoft Photoscan ver. 1.15 to produce a 2 dimensional orthomosaic and a 3 dimensional photogrammetric surface model. Take off and landing photos were filtered out manually to reduce processing time. A lens distortion correction model was created in Agisoft Lens ver. 0.4.0 by taking 100 photos of a white and black checkerboard grid using the same camera and settings established for the flight. Images from the flight were loaded into Photoscan and the lens distortion model

applied. An initial alignment was produced using “high accuracy and “generic” settings. Aligned images were examined for high projection errors and roll and pitch values > 10 degrees. No images required realignment or removal. Ground control points (GCPs) were identified and the coarse surface was aligned to the GCPs. The surface was then reprojected from GCP WGS84 latitudes and longitudes to WGS84 UTM 13 N projected eastings and northings. Lastly, a dense point cloud constructed from the surface.



Figure 2: Site 1 Orthomosaic - Orthorectified, georeferenced image of six piles at Site 1.

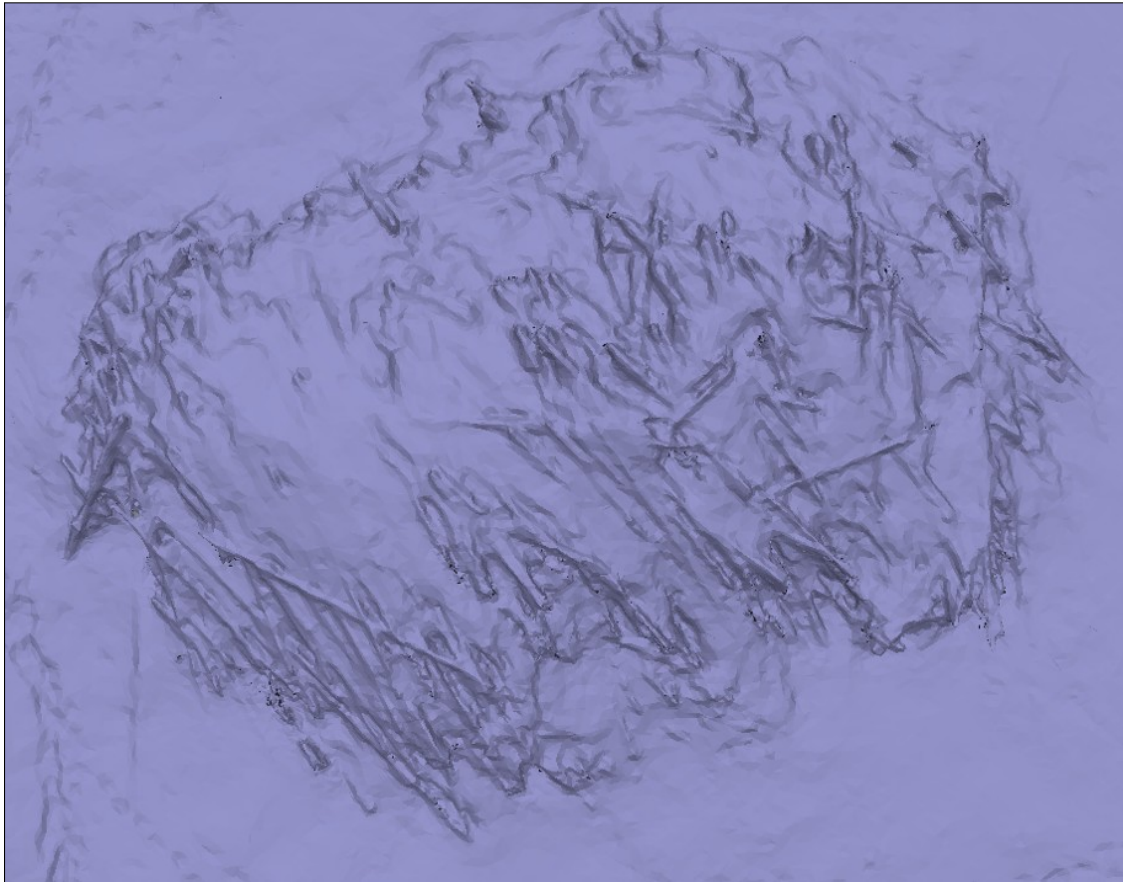


Figure 3: Surface Mesh - Volumetric mesh resulting from the triangulation of the photogrammetric point cloud.

### **Volume measurement**

3D surface meshes were created from the dense clouds of each site. We isolated the sites and generated two triangulated surface models with 1 million (1000k) and 200,000 (200k) faces, respectively. Comparison of volume estimates between two mesh sizes examines the influence of mesh density on volume. Mesh surfaces underwent a gap filling routine to ensure surfaces were unbroken to preventing infinite volume calculations. Piles were individually selected and volumes measured in Photoscan and in MeshMixer ver. 2.0 at both mesh sizes. This process was repeated five times and the results averaged to minimize the influence of operator induced measurement error caused by manual pile delineation. Volume estimation in two software packages was intended to examine the presence of software influence on estimates.

## Statistical analysis

Paired t-test was selected for objective comparison of significant difference between estimated volume and geometrically calculated volume (GCV) by site. Significance was established at the 0.05 level. Additional paired t-test tested for significant difference between Agisoft and MeshMixer volume estimates as well as comparison of volume estimates between 1000k and 200k mesh densities. Pile volume comparisons are within site only because sites experience differences in sun angle, flight properties and snow depth. As such the data set is split into two sets of  $n = 6$  rather than a single group of  $n = 12$  observations.

## 3. Results

Estimated pile volumes derived from the Photoscan 1000k face surface model at Site 1 ranged between 54 m<sup>3</sup> and 573 m<sup>3</sup>. GCV measured volumes range between 96 m<sup>3</sup> and 1288 m<sup>3</sup>. The estimates for Site 2 piles more closely matched the GCV calculated volumes with ranges from 218 - 510 m<sup>3</sup> and 238 - 364 m<sup>3</sup>, respectively (Table 2).

Table 2: Pile volume photo estimates vs GCV measured volumes by site and pile. Photo volume is the average individual pile volume calculated in Photoscan based on the 1000k face triangulated mesh.

Pile	GCV volume (m <sup>3</sup> )	Photo volume (m <sup>3</sup> )
1-1	96.3	54.4
1-2	326.2	224.0
1-3	424.1	429.3
1-4	448.5	337.5
1-5	502.5	397.9
1-6	1288.4	573.2
2-1	217.5	238.0
2-2	231.9	288.9
2-3	295.6	284.0
2-4	299.0	225.1
2-5	447.3	420.9
2-6	509.7	364.2

The results of the paired t-test comparing photo volume estimates to GCV measurements, volume estimates between 1000k and 200k meshes and estimates between Photoscan and Meshmixer appear in Table 3. P-values are the result of a paired t-test at

0.05 significance with 5 degrees of freedom. Comparisons are by site and subject. The first four compare different mesh sizes and volume measuring software to GCV measurements of volume. The last four test for differences between software and between mesh sizes. R2 values are Pearson correlation coefficients testing the linearity between the two datasets. Several comparisons (bold) show moderate to strong evidence of between significantly different from one another with p-values < 0.073. However, with such low degrees of freedom the sensitivity of the test is low.

All comparisons show strong linear correlations to one another with the lowest correlations occurring in the comparison between model estimates and the validation set with R2 of 0.602 - 0.797. Unsurprisingly, between model comparisons all have correlations greater than 0.9.

Table 3: Abbreviations are as follows: GCV = geometrically calculated volume estimates, pscan = Photoscan software, meshmix = MeshMixer software, 1000k is the 1 million face triangulated mesh and the 200k is the 200,000 face triangulated mesh.

Dataset	Site 1		Site 2	
	P-value	R <sup>2</sup>	P-value	R <sup>2</sup>
pscan1000k vs GCV	0.163	0.777	0.353	0.718
pscan200k vs GCV	0.148	0.648	0.193	0.656
meshmix1000k vs GCV	0.125	0.743	<b>0.054</b>	0.667
meshmix200k vs GCV	0.132	0.797	<b>0.073</b>	0.602
pscan1000k vs meshmix1000k	<b>0.003</b>	0.998	<b>0.024</b>	0.9204
pscan200k vs meshmix200k	<b>0.066</b>	0.972	<b>0.001</b>	0.9946
pscan1000k vs pscan 200k	0.777	0.996	0.120	0.9427
meshmix1000k vs meshmix200k	0.223	0.978	0.918	0.9928

#### 4. Discussion

Volumetric estimate accuracy is dependent, at least, partially upon software and the complexity of the surface model. Triangulated surface models suffer from a significant caveat, which is, it must be mathematically correct. This prevents the model from being true 3D in the same manner of a point cloud. Multiple Z or height values are not possible for a single x,y or



horizontal position. This increases the likelihood of volume over estimation in places where logs ends are suspended beyond the edge of the primary mass of the pile. Another factor that may have prevented accurate photogrammetric reconstructed piles was the presence of snow on and around the piles. The varied height and homogeneous texture of the snow on site reduced the certainty at which the structure from motion algorithm can identify matching key features.

There is enough evidence of similarity to the GCV data to warrant further investigation. Future studies should expand to include a statistically significant number of piles (20+) and use an established validation method (Long and Boston 2014). Furthermore, the effects of model detail and the processing software should not be underestimated. Despite the engineering and regulatory complexities, the operational efficiency gains from using an UAS for volumetric analysis are impossible to ignore. A properly equipped UAS carrying a camera similar to the one used in this study could fly 640 acres of piles from an altitude of 122 m above ground level in just 2.5 hours at a velocity of 10 m/s. The efficiency advantage of employing a UAS is retained by only requiring four ground control points (GCPs) if the flight is properly planned.

## **5. Conclusion**

The methods presented in this study provide a fast and efficient approach to estimating slash pile volume. We expect the volume models created by the structure from motion algorithm will demonstrate strong agreement with LIDAR produced volume models without the added costs of expensive LIDAR sensors. However, these models will need to be validated against LIDAR derived models in future studies. This approach also has many advantages over ground-based methods via reduced survey time and the creation of complex shapes to accurately describe residue piles.

The objective of this study was to reduce sources of uncertainty in residue estimation by improving volume estimation. Other sources of uncertainty remain and are not addressed in this study. PR and moisture content estimates still need to be obtained by visiting and manually evaluating each residue pile. Nonetheless, the presented methodology can be integrated with the forest biomass supply chain to improve residue estimation and ensure appropriate processing and handling configurations at relatively low costs.

## **6. Acknowledgments**

We would like to acknowledge the Sulphur Ranger District staff of the Arapaho and Roosevelt National Forests in Colorado for their support in site selection and providing data

from previous pile surveys. This project was supported by the Agriculture and Food Research Initiative Competitive Grant no. 2013-68005-21298 from the USDA National Institute of Food and Agriculture.

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<sup>5</sup>A properly equipped UAS would have an on board dual frequency differential global navigation satellite system (GNSS) aided inertial navigation system(INS).

<sup>6</sup>A properly planned mission ensures at least 70% image overlap and sidelap. Only four corner GCPs are necessary if the area is rectangular and cross tracks are flown on the ends of the flight lines (Boguslaw, 2006).

## 7. References

- Lembicz W. Boguslaw. Minimizing ground control when GPS photogrammetry isn't practical. In ASPRS Annual Conference, 2006, Reno, NV, 2006.
- C. Hardy. Guidelines for estimating volume, biomass, and smoke production for piled slash. Gen. Tech. Rep. PNW-GTR-364. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 1996.
- J Long and K Boston. An evaluation of alternative measurement techniques for estimating the volume of logging residues. Forest Science, 2013.
- J.A. Trofymow, N.C. Coops, and D. Hayhurst. Comparison of remote sensing and ground-based methods for determining residue burn pile wood volumes and biomass. Canadian Journal of Forest Research, 2013.

# GIS-Based Forest Road Network Model for Forest Protection Purposes

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Arrival of the fire truck and ground team into the forest fire area in the shortest time period possible is very crucial in order to effectively fight with forest fires in time. In this study, GIS (Geographical Information System) based system has been developed to decide the route which minimizes the arrival time to the forest fire areas. The study area was city of Erbil, located in the north of Iraq. In the study area, there are nine fire stations for firefighting teams. In this study, firstly, the road network, locations of the headquarters, and possible fire locations were digitized by using ArcGIS 10.0 software. Then, network database were generated based on the digitized data by using Arc Catalog module. Finally, the optimum route, providing the fastest transportation from fire stations to possible fire areas, was determined by using Network Analyst working under Arc Map module. Also, the areas that can be reached by firefighting teams in critical response time were determined. It was found that six of these fires were not accessible by the teams within the critical response time. Thus, only four of the potential fire areas were reached within the critical response time. These results indicated that new fire stations should be established in the study area to provide sufficient firefighting response to all forested lands. Besides, new fire access roads and increasing the design speed on current roads should be considered to increase firefighting response capabilities.

**Keyword:** forest road network, network analysis, shortest path, GIS, fire protection

## 1. Introduction

Forest resources are subject to many risk factors such as illegal land use changes, illegal harvesting of trees and wild forest fires (Ertugrul, 2005). Wildfires seriously damage forest resources, threaten sustainability of forest resources, which leads to biological and ecological impacts on forest ecosystem (Bilici, 2009). Besides, forest fires are important sources of greenhouse gasses (CO<sub>2</sub>, CH<sub>4</sub>, etc.) emitted to the atmosphere (Guido et al., 2004). After forest fires, the volume and value of forest trees, fire-killed or fire-damaged trees can be affected by deterioration agents such as insects and fungus, which reduce the volume and value of forest trees (Akay et al., 2006).

Forest fires are considered to be one of the most detrimental factors affecting forest resources throughout the world and, in particular, Mediterranean countries (i.e. France, Greece, Italy, Portugal, Spain, and Turkey) due to their climate and other factors (Demir et al., 2009). A typical firefighting crew is divided into 5 groups: initial response team, reserved fighting team, mobile team, fire truck team, and aerial support team (Akay et al., 2010). In order to fight forest fires effectively, the arrival time of the initial response team at a fire area should not exceed the critical response time in which the probability of controlling the forest fires rises markedly (GDF, 2008). Therefore, it is crucial to determine the optimum route that minimizes the travel time of the initial response team from fire headquarters to the fire areas using firefighting trucks.

To develop an adequate transportation planning, many alternative routes should be evaluated so that an optimum route can be selected. There are number of studies where computer-based methods, using computer technology and optimization techniques, have been employed to assist planners in evaluating high number of alternative routes (Ichihara et al., 1996; Akay and Sessions, 2005; Aruga et al., 2005; Akay et al., 2012a).

Solving transportation problems such as shortest path, maximum flow, and optimum task allocation, computer-based network analysis method provides accurate and quick solutions (Akay et al., 2012b). In the solution process of network method, various parameters such as cost, travel time, and length are assigned to the network links and then the shortest or optimal path is selected by searching the alternatives (Zhan, 1997). A network analysis approach is a potentially powerful approach to solving transportation and routing problems.

Suitable plans for forest transportation should involve some technical factors such as road length, road types, road conditions, and vehicle speed, (Tucek, 1999). Road types and road conditions effect vehicle speed which then reflects transportation time (Akay and Erdaş, 2007). Besides, longer distance increases transportation time.

In recent years, GIS-based decision support systems have been utilized to improve the efficiency of fire management stages including planning, managing, and decision making (Burgan et al 1998; Sampson et al 2000; Kucuk et al., 2005). Advances in computer and GIS technology have also made it possible to use GIS-based network analysis based modules such as Network Analyst in ArcGIS software for solving transportation problems (Akay and Sakar, 2009). ArcGIS Network Analyst is a powerful extension that provides network-based spatial analysis including routing, travel directions, closest facility, and service area analysis.

In this study, a GIS-based decision support system utilizing the Network Analyst extension within ArcGIS 10 was developed to assist fire managers in determining the fastest travel routes to fire areas. The decision support system was applied in the city of Erbil, located

in the north of Iraq. The study area was classified as second degree sensitive to forest fire. Multiple network analyst simulations were conducted to identify the optimal travel route and associated response times of nine fire response teams to 10 fire areas that were generated using historical data. The simulations accounted for road surface and condition, and sensitivity of forest areas to fire.

## **2. Material and Methods**

### **2.1. Study area**

Study area is the city of Erbil, which is located about 350 km north of Baghdad in northern Iraq. The city of Suleimanya is located at the southeast of Erbil, Dohuk and Mosul are at the west, and Kirkuk is located at the east. There is an international border of Turkey and Iran along the north and northeast of Erbil (Figure 1).



Figure 1. The city of Erbil in Iraq

The study area is located within 35°28'46"-37°19'4" North and 43°18'23"-45°5'15" East coordinates. The study area covers about 1.5 million ha land. In the study area, the average elevation and ground slope is about 814 m and 22.46%, respectively. In the study, the optimum routes were investigated for 10 different potential fire locations, considering nine different fire stations including Erbil center, Dashty hawler, Shaqlawa, Khabat, Koya, Soran, Sidakan, Mergasor and Barzan. The locations of fires and fire stations were indicated in Figure 2.

The city center is laying on wide plain area, however, its districts and sub-district are in the hilly and mountainous areas. The height of the mountains increases to the direction of the north and north east. Halgurd top is the highest point of Hasarost mountain with the height of

3607 m. The tree species in the area are *Quercus infectoria* Oliv., *Quercus libani* Oliv., *Quercus brantii* Lindl., *Quercus aegilops*., *Pistacia eurycarpa* Yalt., *Pistacia khinjuk* Stocks, etc.

There are nine different fire stations in the study area; Erbil center, Dashty-Hawler, Shaqlawa, Khabat, Koya, Soran, Sidakan, Mergasor and Barzan. All of the fire stations were visited, crew and equipment status determined and UTM (Universal Transverse Mercator) coordinates with the height were recorded by using handheld GPS. Figure 3 indicates some of the views from fire stations in the study area.

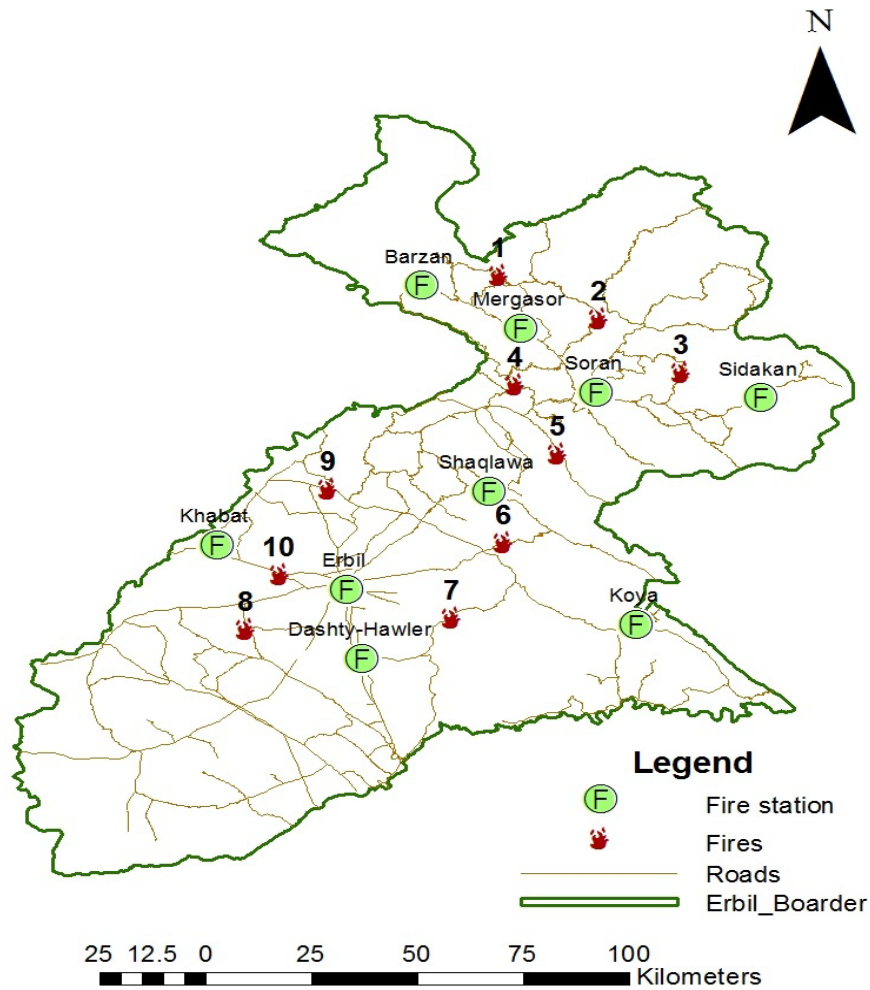


Figure 2. The study area map indicating fire stations



Figure 3. Some of the fire stations evaluated in the study

## 2.2. Road Network

The road network map was generated based on topographical map of the study area. In order to develop network database, average travel time of fire trucks on each road section was computed based on road length and average speed of a fire truck, which varies depending on road type and road status. Thus, “Attribute Table” of the road map included fields for these parameters. The road length was calculated by “Calculate Geometry” tool in “Attribute Table”. The road type in the study area was defined as asphalt roads. The road conditions (good, average, poor) were determined based on information obtained from Highway Departments. Then, the average vehicle speed was estimated based on road type and conditions as 60 km/hr, 50 km/hr, and 40 km/hr for good, average and poor condition roads, respectively. Finally, travel time of the fire truck for each road section was computed based on Equation 1 by using “Field Calculator” tool in “Attribute Table”:

$$t_i = \frac{l_i}{v_i} 60 \quad (1)$$

$t_i$ : travel time on road section  $i$  (minutes)

$l_i$ : length of road section  $i$  (km)

$v_i$ : vehicle speed on section  $i$  (km/hr)

60: coefficient to convert time from hours to minutes

## 2.3. Landuse Classification

The landuse types map was generated based on LANDSAT 8 ETM image acquired in 2013. The systematic geometric and radiometric corrections have been done by the provider (the U.S. Geological Survey) to a quality level of 1G before delivery. Landsat’s thermal band has



a resolution of 60 m while the rest has 30 m, except the panchromatic band which has a resolution of 15 m. ERDAS Imagine software was used to classify the satellite imagery by supervised classification technique. Bands 1-5 and 7 of Landsat 7 ETM were used, while Thermal band (band 6) and panchromatic band (band 8) were excluded from the classification. In the image of the research forest, there was a high frequency of data variability due to background vegetation and ground materials. To reduce spatial frequency, “Convolution” function in ERDAS Imagine was used by applying 7X7 low-pass filter.

Supervised Classification method was then performed based on a set of user-defined classes, by obtaining the appropriate spectral signatures from the data. “User-Defined Polygon” function was employed to lower the chance of underestimating class variance since it involved a high degree of user control. Once a set of reliable signatures were created, supervised classification was performed using the Maximum Likelihood (statistically-based classifier) technique. After classification, the landuse types were divided into five main classes including forest, shrub, urban, water, and others. In the recoding process, open grounds, agriculture, etc. were assigned into the class of “others”. Finally, the accuracy assessment of the supervised classification was performed by systematically selecting 250 sample points from the recoded image. Forest and shrubs are combined into a single class called forest, considering that they are subject to fires.

#### **2.4. Network analysis**

Network Analyst extension in ArcGIS software works based on the methodology of network analysis. It provides network-based spatial analysis including routing, service area, closest facility, travel directions, and new location-allocation analysis (Figure 5). Using a sophisticated network model, users can easily build networks based on GIS database. Network Analyst also enables users to dynamically model realistic network conditions such as turn and height restrictions, speed limits, and traffic conditions.

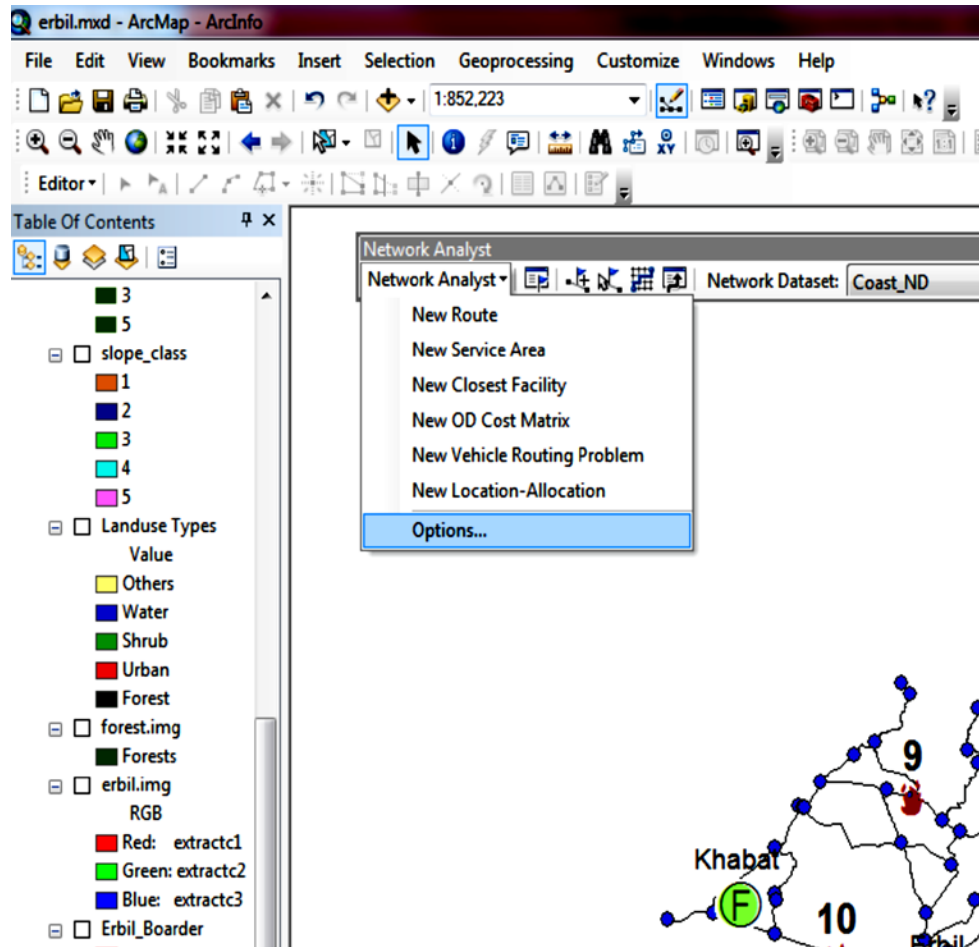


Figure 4. Network Analyst extension in ArcGIS 10

In order to run methods of Network Analyst extension, a network database should be generated. In this study, firstly, a Personal Geodatabase under ArcCatalog module was generated, and then, network dataset was produced based on road types map containing travel time information for each road section in the study area. Finally, links (ND\_Edges) and nodes (ND\_Junctions) data layers were generated by using network database.

After having network database, the New Closest Facility and New Service Area methods under Network Analyst extension was used to explore routing solutions. The New Closest Facility method was used to find the fastest access routes from each initial response team to the potential fire areas in the study area. Then, the response team with the minimum travel time was determined for each potential fire area. In addition, other initial response teams with the second or third shortest arrival time and their access routes can be identified in a case

where an initial response team with the minimum travel time is not sufficient in terms of equipment or number of firefighting personnel.

The New Service Area method was also used to evaluate accessible and inaccessible forest areas by the initial response teams according to the critical response time. As mentioned before, the critical response time varies depending on the fire sensitivity degree. The study area was classified as the second degree sensitive area, which requires critical response time of 30 minutes.

The New Service Area method works similar to a GIS buffer analysis. A service area point is first located in the network system and is considered as a center point from which other portions of the network can be reached given a user-defined total link value threshold. This reachable area comprises the service area. In this study, the locations of the initial response teams were considered as service area points and service areas are then the forest areas that can be reached within the total link value as defined by the critical response time. Therefore, the locations and numbers of initial response teams that are capable of reaching a fire area within the critical response time were evaluated through this approach.

### **3. Results and Discussion**

#### **3.1. Road Network**

The results indicated that total length of the road network in the study area was computed as 2502.92 km (Figure 5). All of the roads were asphalt roads. Considering road conditions in the study area, it was found that 57.06% of the road network was in good condition, while 29.75% and 13.19% of the roads were in average and poor conditions, respectively (Table 1).

#### **3.2. Landuse types**

The results of the classification process indicated that there were five different landuse types in the study area. The accuracy assessment of the supervised classification was also performed. The overall classification accuracy and kappa statistics were 92% and 0.89, respectively (Table 2). Table 3 indicates areal distribution of landuse types (Figure 6).

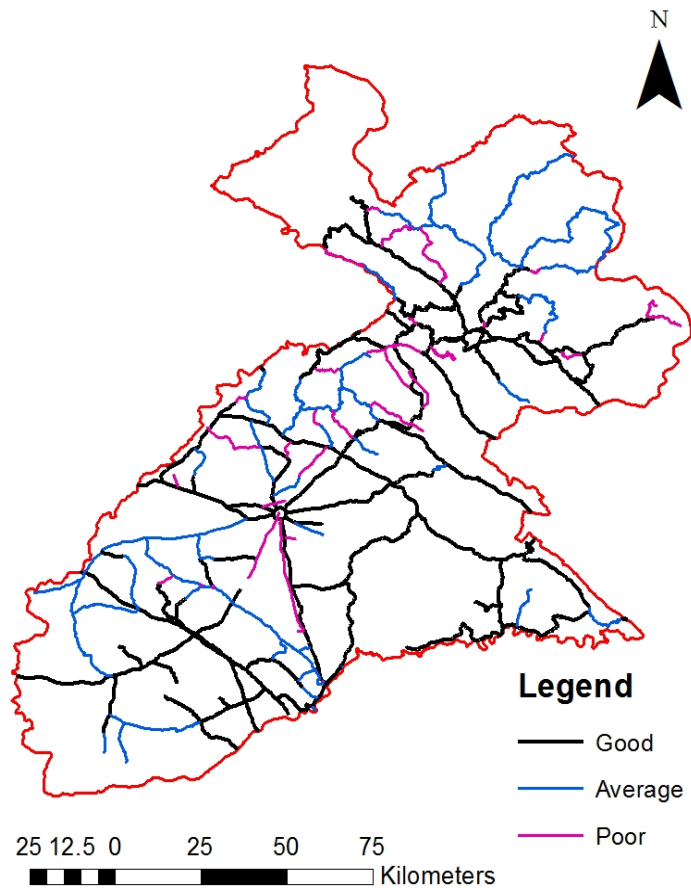


Figure 5. Road network map

Table 1. The length information about road types in the study area

Road Lengths (km)	Total Length	Road Conditions		
		Good	Average	Poor
	2502.92	1428.16	744.66	330.10

Table 2. Accuracy assessment matrix table

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	User Accuracy
Shrub	82	80	80	97.56	100.00
Forest	18	11	10	55.56	90.91
Urban	55	67	53	96.36	79.10
Water	50	48	46	92.00	95.83
Others	91	94	87	95.60	92.55
Totals	296	300	276		

Table 3. The areal distribution of the landuse types in the study area

Landuse Types	Area (%)
Shrub	26.98
Forest	12.04
Urban	10.89
Water	7.44
Others	42.65

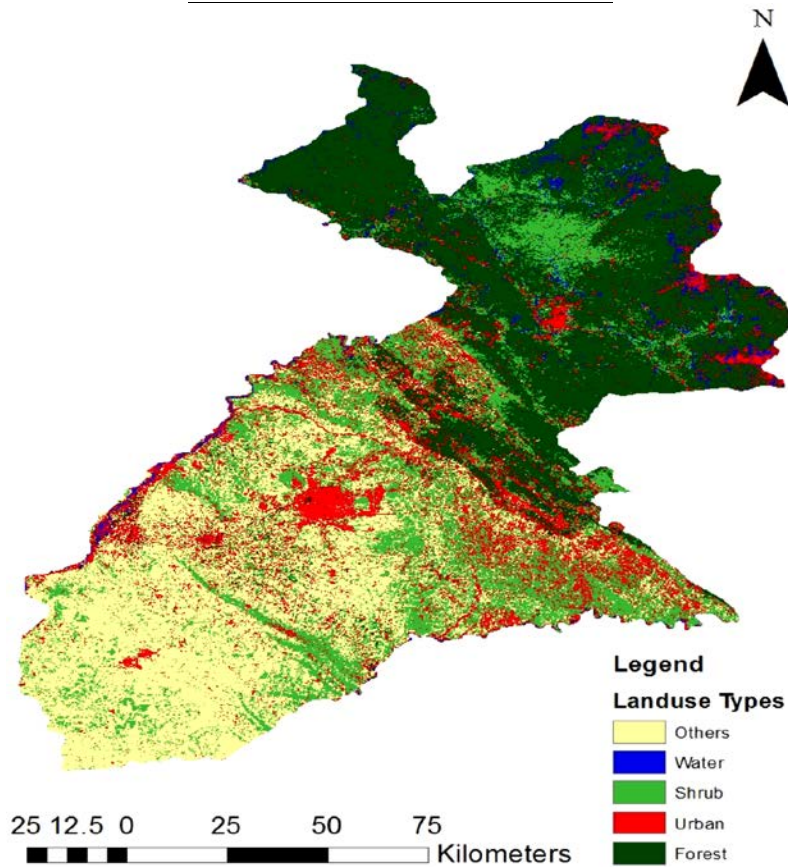


Figure 6. Landuse types

### 3.3. Network Analysis

#### New Closest Facility

The fastest access routes for each firefighting team to the potential fire areas in the study area were determined using the New Closest Facility method (Table 4). Results indicated that there is a close relationship between the travel time and road length, as well as between travel time and road condition. Firefighting teams that reached potential fire areas within the

minimum arrival time were identified considering fastest access route. Although the decision support system found the fastest access routes to the potential fire areas, six of these fires were not accessible by the teams within the critical response time. Since the potential fire areas were in areas sensitive to forest fires at the second degree, the critical response time was considered to be 30 minutes. Only four of the potential fire areas were reached within the critical time.

### New Service Area

The areas that can be reached by initial response teams within a critical response time were determined by the New Service Area method. Since the study area consisted of areas sensitive to fires at the second degrees, the buffer areas that can be reached through the road network within 30 minutes were investigated. Results indicated that the teams could reach only 6.88% of the study area within 30 minutes (Figure 7).

The GIS tools were used to combine the reachable areas and forest land databases to determine forest areas that could be reached within critical response times (Figure 8). It was found that the firefighting teams can reach 17.64% of the forested areas within 30 minutes. The rest of the forest area (82.36%) could be reached by the teams within critical response time.

Table 4. The arrival time (minutes) of firefighting teams to each potential fires

Fire Stations	Potential Fires									
	1	2	3	4	5	6	7	8	9	10
Erbil	146	132	138	91	100	36	45	<b>27</b>	<b>34</b>	<b>15</b>
Dashty-Hawler	164	150	157	110	119	54	<b>25</b>	47	53	34
Shaqlawā	105	91	97	51	60	<b>32</b>	67	74	44	58
Khabat	170	156	162	115	124	64	75	41	42	16
Koya	176	162	168	121	130	46	48	98	77	84
Soran	48	34	<b>33</b>	<b>26</b>	<b>32</b>	97	125	131	87	115
Sidakan	82	68	41	60	66	132	159	165	122	150
Mergasor	<b>31</b>	<b>31</b>	58	44	50	115	143	149	105	133
Barzan	34	57	87	73	78	144	172	178	134	162

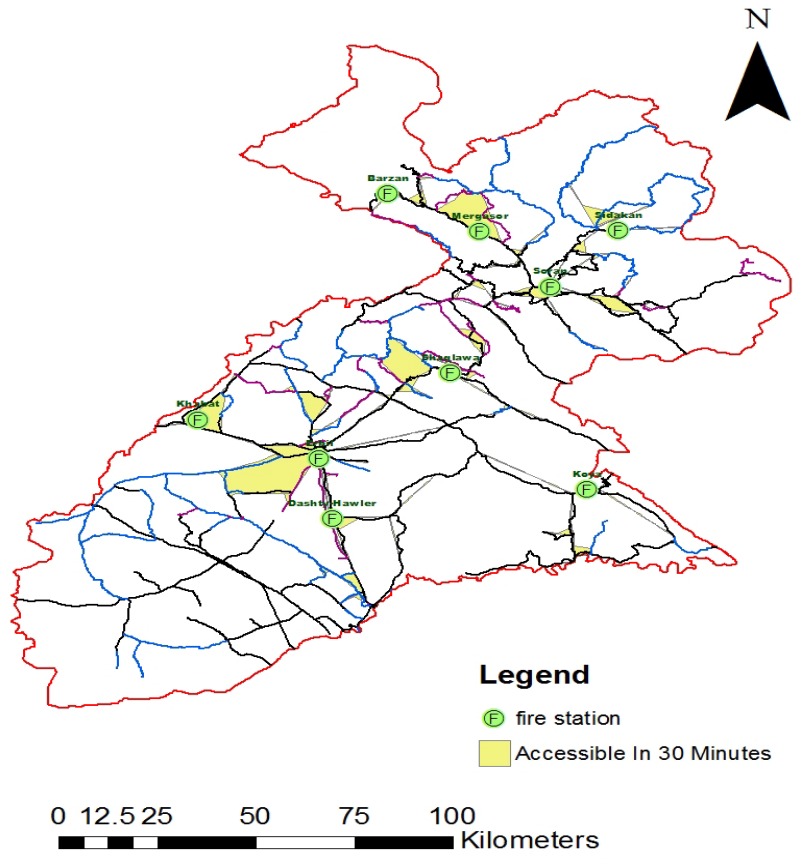


Figure 7. The accessible areas within 30 minutes in whole study area

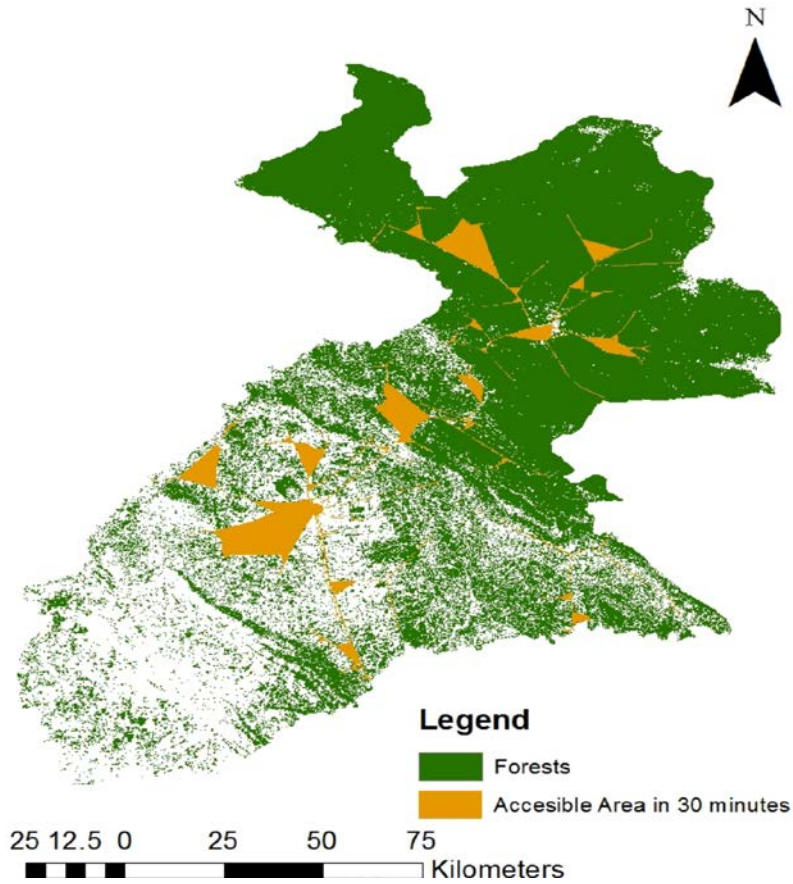


Figure 8. The accessible forested areas within 30 minutes

#### 4. Conclusions

GIS (Geographical Information System) based system has been developed to decide the route which minimizes the arrival time to the forest fire areas. The study area was city of Erbil, located in the north of Iraq. In the study area, nine fire stations teams located in Erbil were considered in execution of the system. The network analyst method under “Network Analyst” extension of ArcGIS 10 platform was used to systematically search for optimum routes. In application, 10 potential fire locations were considered to run network analysis.

The total length of the road network in the study area was found as 2502.92 km. The roads were asphalt paved roads. It was also found that more than half of the road network was in good condition, while about 30% and 14% of the roads were in average and poor conditions, respectively. The topographical analysis indicated that about 62% of the study area was covered by land with low and very low ground slope, while rest of them was medium, high and very high slope.



Based on classification process, shrub lands covers about 27% of the study area, followed by forest (12%), urban (11%), and water (7%). About 43% of the area was covered by other land use types. In network analysis application, forest and shrubs are combined into a single class called forest, which totally covers about 40% of the study area.

The fastest access routes for each firefighting team to the potential fire areas in the study area were determined using the New Closest Facility method. Six of these fires were not accessible by the teams within the critical response time of 30 minutes. Only four of the potential fire areas were reached within the critical response time. Results indicated that there is a close relationship between the travel time and road length, as well as between travel time and road condition.

The areas that can be reached by initial response teams within a critical response time were determined by the New Service Area method. Results indicated that the teams could reach only 6.88% of the study area within 30 minutes. Considering only forested areas, it was found that the firefighting teams can reach 17.64% of the forested areas within 30 minutes. About 82% could be reached by the teams within critical response time.

## 5. References

- Akay, A.E., Sessions, J. 2005. Applying the Decision Support System, TRACER, to Forest Road Design, *Western Journal of Applied Forestry*, 20(3):184-191.
- Akay, A.E., Sessions, J., Bettinger, P., Toupin, R., and Eklund, A. 2006. Evaluating the Salvage Value of Fire-killed Timber by Helicopter – Effects of Time Since Fire and Yarding Distance, *Western Journal of Applied Forestry*. 21(2): 102-107.
- Akay, A.E., Erdaş. O. 2007. Network Model Approach in Transportation Planning of Forest Products. *Istanbul University, Faculty of Forestry Journal, A-Series*. 57(2):1-20.
- Akay, A.E., Sakar, D. 2009. Using GIS Based Decision Supporting System in Determining Optimum Path that Provides the Transportation to Fire Zone at the Shortest Time. *The Chamber of Turkish Engineers and Architects. The Congress of Geographic Information Systems*. 02-06 November. Izmir, Turkey.
- Akay, A.E., Sivrikaya, F., Sakar, D. 2010. Evaluating the Efficiency of Fire Helicopter Located in Arsuz-Antakya in Fire Fighting Activities. *The 1st International Turkey & Japan Environment and Forestry Symposium*. 02-05 November, Trabzon, Turkey.

- Akay, A.E., Doucas K., Erdaş O., Oğuz H., Sivrikaya F. 2012a. Using GIS Techniques to Determine Fire Protection Zones Considering Forest Road Network. Forest Engineering: Concern, Knowledge and Accountability in Today's Environment Hotel Croatia, October 8 - 12. Dubrovnik (Cavtat), Croatia.
- Akay, A.E., Wing, G.M., Sivrikaya, F., Sakar, D. 2012b. A GIS-Based Decision Support System for Determining the Shortest and Safest Route To Forest Fires: A Case Study in Mediterranean Region of Turkey. Environmental Monitoring and Assessment. 184(3):1391-1407.
- Aruga, K., Sessions, J., Akay, A.E. 2005. Heuristic Techniques Applied to Forest Road Profile. The Japanese Forest Society, J. For. Res. 10(2):83-92.
- Bilici, E. 2009. A Study on the Integration of Firebreaks and Fireline with Forest Roads Networks and It's Planning and Construction (A Case Study of Gallipoly National Park) Istanbul University. Faculty of Forestry Journal Series: A. 59(2):86-102.
- Burgan, R.E., Klaver, R.W., Klaver, J.M. 1998. Fuel Models and Fire Potential From Satellite and Surface Observations. International Journal of Wildland Fire 8(3):159-170.
- Demir, M., Kucukosmanoglu, A., Hasdemir, M., Ozturk, T., Acar, H.H. 2009. Assessment of Forest Roads and Firebreaks in Turkey. African Journal of Biotechnology 8(18): 4553-4561.
- Ertugrul, M. 2005. The Situations of Forest Fires in the World and in Turkey. ZKU Bartın Faculty of Forestry Journal, 7(7):43-50.
- GDF, 2008. Fire Action Plan. General Directorate of Forestry. Kahramanmaras Forest Regional Directorate, Kahramanmaras. 106 p.
- Guido, R., Van der Werf, J.T., Randerson, G., James Collatz, L., Giglio, P.S., Kasibhatla, A.F. 2004. Continental-scale partitioning of fire emissions during the 1997–2001 El Nino/La Nina period. Science, 303:73-76.
- Ichihara, K., Tanaka, T., Sawaguchi, I., Umeda, S., Toyokawa, K. 1996. The Method for Designing the Profile of Forest Roads Supported by Genetic Algorithm. The Japanese Forestry Society, Journal of Forestry Research. 1:45-49.
- Kucuk, O., Bilgili, E., Durmaz, B.D. 2005. Importance of Fuel Maps in Determination of Fire Potential. Süleyman Demirel University. Faculty of Forestry Journal, A(1):104-116.
- Sampson, R.N., Atkinson, R.D., Lewis, J.W. 2000. Mapping Wildfire Hazards and Risks, Food Product Press, 10 Alice Street, Binghamton, NY 13904-1580 USA, 343 p.
- Tucek J, Pacola E. 1999. Algorithms for Skidding Distance Modeling on a Raster Digital Terrain Model. J For Engin. 10(1):67-79.
- Zhan, F.B. 1997. Three Fastest Shortest Path Algorithms on Real Road Networks: Datastructures and Procedures. Journal of Geographic Information and Decision Analysis. 1:70–82.

# Forest Road Network Effect on Forest Fire: A Case Study of Turkey

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Forest fires are one of the most important elements that destroy forests and causing enormous environmental and economic damage as well as loss of the human life. Especially in Mediterranean region, forest fires have a great importance and natural risk. Determining forest fires, there are so many variables or factors and these variables are somehow related. A fire depends on many factors, such as topography, vegetation type, distance from roads and proximity to settlements. Human activities in settlement areas may dramatically increase forest fire risk. Thus, forests located near roads have more fire tendency. In this study, Kahramanmaraş Regional Directorate of Forestry was chosen as a case study area. 1186 forest fire ignition points were determined according to starting point of the recorded forest fires from 2002 to 2014 by the Kahramanmaraş Regional Directorate of Forestry. Roads in the planning unit were digitized with a 1/4000 to 1/5000 screen view scale using ArcGISTM 10.0. According to distance from the roads for forest fire, buffer zones thrown into the road such as < 100 m, 100-250 m, 250-500 m, 500-1000 m, >1000 m with the ArcGISTM 10.0 software. The relationship between number of fires and fire intensity with distance from the roads was investigated. It is observed that, the distance form roads decreases, the number of forest fire and intensity increases.

**Keywords: Buffer zone, Distance from roads, Forest fire, GIS**

## 1. Introduction

Forest fires, which is a natural process, seriously damage forest ecosystem, affect sustainability of forest resource and come out environmental, ecological and biological effect on vegetation (Akay et al. 2012; Koutsias et al. 2014). Forest fires have most serious ecological problems and their high frequency and intensity annually affect large areas of forest land in the Mediterranean basin (FAO 1992). Every year, large amounts of forest areas, 5 million ha in the world, 550000 ha in Mediterranean region and 10000 ha in Turkey have been damaged by forest fire (Eroğlu 2009; GDF 2011; Sivrikaya et al. 2014).

Coastal band in Turkey is very sensitive area where is following 1700 kilometers (km) of Aegean and Mediterranean coasts for forest fires (GDF 2008). In Mediterranean and Aegean regions, forests contain generally *Pinus brutia* which are extremely fire sensitive species have special conditions in terms of fires. As well as intensive human activities such as residential, tourism and agricultural are also very fundamental issues for this region (GDF 2008; Çoban and Eker 2010).

The spatial patterns and structure of forest fire ignitions have vital importance because fire ignitions play important role in the spatial pattern of fire regimes (Kernan and Hessl 2010; Narayanaray and Wimberly 2012). Fire regimes are generally related to geographic location and usually summarized by extent, seasonality, severity, frequency and spatial distribution (Karena et al. 2008). The spatial pattern of forest fires affects species composition, creating spatially heterogeneous fuel conditions and plant forest age classes, (Perry et al. 2011). Identifying the spatio-temporal features of fire regimes has proven difficult (Falk et al. 2007).

Transportation systems more specifically, forest roads are one of the most important parameters for the forest landscape to maintain all forest resource values. Forest roads may restrict fire spread as fire breaks and assisting fire fighters for fire suppression activities (Price and Bradstock 2010; Narayanaraj and Wimberly 2011). Forest roads have direct and indirect effects related to ecological and physical, landscape scale and socio-economics effects (Forman and Alexander 1998; Gucinski et al. 2001). Forest transportation system may affect fire regimes due to increased fire ignition (Franklin and Forman 1987). Therefore, forests located near roads are more fire prone. Human activities that happen in the transportation corridors may increase possibilities of fire. However, roads reduced fire size as a result of increased accessibility for fire suppression activities and physical barriers to fire movement, (Covington and Moore 1992).

Human-caused ignitions generally happen along transportation corridors. Many studies have indicated that human-caused fires are located in proximity to forest road and human settlements. Accidental or deliberate human-caused fires result from a combination of factors, and environmental conditions that are conducive to fire (Narayanaray and Wimberly 2012). Considering that 97.5% of the human impact of forest fires, roads have an important effect for prevention and protection of forest ecosystem. Therefore, forests located near roads are more fire prone (Başaran et al. 2004).

Recent studies have indicated that, forest roads have a stronger effect to prevention of fires (Price and Bradstock 2010). Fire suppression activities are more effective close to roads due to making easy to access and, roads act as a physical barrier for stopping the fire spread. At the same time, fires are detected rapidly near or close to roads. For all these reasons, forest roads are likely to contribute to smaller fire sizes (Narayanaray and Wimberly 2012).

In this study the relationship between number of fires and fire intensity with distance from the roads was investigated. In this reason, forest fire ignition points were determined according to starting point of the recorded forest fires from 2002 to 2014 for Kahramanmaraş Regional Directorate of Forestry. With the help of this points and using distance from road parameters, sensitive areas for forest fires were determined.

## **2. Methods**

### **2.1 Study area**

The study area is located in Kahramanmaraş Regional Directorate of Forestry (37° 34' 32" N and 36° 54' 48" E). The study area consists of Kahramanmaraş, Adıyaman, Gaziantep, Kahramanmaraş, Antakya, Dörtöyl, Kilis, Gaziantep Forestry Enterprise Directorates (Figure 2). The Kahramanmaraş Regional Directorate of Forestry, which is vulnerable to forest, is situated in the Mediterranean region with high temperatures and low to nonexistent precipitation during the fire season. Of the 2.805.523 ha total area, 818,875 ha is forested and the rest is non-forested. The main tree species in the area include *Pinus brutia*, which is one of the most sensitive species for fire and *Quercus sp.* (Oak).

## **3. Material**

The fundamental data used in this research are forest fire ignition points. This points were determined to according to starting point of the recorded forest fires from 2002 to 2014 by the Kahramanmaraş Regional Directorate of Forestry. Topographic maps of Kahramanmaraş Regional Directorate of Forestry with 1/25 000 scale were gathered. Digitizing road data, this input data were obtained.

### **3.1 Method**

This study examines the relationship between roads and forest fires and the role that roads play in fire ignitions. We examined the spatial relationship between forest fires and roads by mapping forest fire occurrence locations and their proximity to roads across the Kahramanmaraş Regional Directorate of Forestry. 1286 forest fire ignition points were determined according to starting point of the recorded forest fires from 2002 to 2014. Roads in the planning unit were digitized with a 1/4000 to 1/5000 screen view scale using ArcGISTM 10.0. According to distance from the roads for forest fire, buffer zones thrown into the road

such as < 100 m, 100-250 m, 250-500 m, 500-1000 m, >1000 m with the ArcGISTM 10.0 software. We use Geographic Information System (GIS) analysis to examine the spatial relationship between roads and forest fires more closely. The relationship between number of fires and fire intensity with distance from the roads was investigated.

#### 4. Results and Discussion

We overlaid fire ignition point for the Kahramanmaraş Regional Directorate of Forestry on the road proximity data to determine the spatial relationship between forest fire occurrences and roads. The relationship between number of fires and fire intensity with distance from the roads was investigated and the road distance distribution for all the fires was listed in Table 1.

The influence of proximity to road and other human infrastructure appears to vary noticeably with region (Cardille et al. 2001). In Kahramanmaraş Regional Directorate of Forestry, totally 1186 fires occurred for years between 2002 and 2014. Higher road density was positively correlated with fire in Kahramanmaraş Forest Regional Directorate. Depending on the distance from roads, 306 forest fires occurred in < 100 m buffer zones. It was determined that 100-250 m buffer zone 334, 250-500 m zone 306, 500-1000 m zone 171 and > 1000 m zone 69 forest fires take placed. Equal number of fires occurred in both < 100 m zone and 250-500 m zone (Table 1).

Table 1. Number and Percentage of Burning Areas in Buffer Zones

Buffer Width (m)	Fire		Burned	
	Number	Percent (%)	Area (ha)	Percent (%)
<100	306	25,8	3802,86	48,7
100-250	334	28,2	2014,54	25,8
250-500	306	25,8	1538,87	19,7
500-1000	171	14,4	280,41	3,6
>1000	69	5,8	174,80	2,2
Total	1186	100	7811,48	100

Our examination of the spatial relationship of roads to wildfires we found that 94 % of all wildfires nationwide are caused by humans. Of these human-caused wildfires, 28 % forest fires occurred < 100 m buffer zone, % 28 in 100-250 m zone %, 25,8 in 250-500 m zone, % 14,4 500-1000 m zone and 5,8% > 1000 m zone, respectively.

Considered as area, distance from road < 100 m buffer zones burned 3802,86 ha. These are accounts for 48.7% in the total burned area. It was identified that 2014.54 ha area burned 100-250 m buffer zone and respectively 1538.87 ha in 250-500 m zone, 280,41 ha in 500 -1000 m zone and 69 ha in > 1000 m zone. Distance to roads was negatively related with fire ignition probability, meaning a decreasing fire occurrence frequency at increasing distances to roads. In Kahramanmaraş Regional Directorate of Forestry, 48,7 % of burned areas occurred at less than 100 m from the nearest road and 45,5 % were within a distance of 500 m

Fire risk is higher such as picnic areas, agricultural areas and roads where more intense people activities are occurred. Human-induced fires are increasing day by day in parallel with the increase of human activities in and around forests. Due to human activities, Forest located in agriculture and housing areas and in close proximity to the road lines, vulnerable to forest fires. It is understood that depending on the relationship between proximity of road and forest fire, first 100 m distance have the most sensitive area (Nevişçi et. al. 1999).

## 5. Conclusions

In recent years, GIS has emerged as a powerful tool for studying and monitoring the relationship between the forest fire and distance from roads. Changing fire regimes depend on roads may have substantial ecological impacts. Our results support the hypothesis that humans are shifting the spatio-temporal pattern of the fire regime. Population density was the more significant variable estimating the location of ignitions that resulted in larger burned areas in Kahramanmaraş, and its importance increased for ignitions turning into burns larger than 1000 ha.

Distribution of fires across the landscape is shifting so that the majority of fires are burning closer to forest roads. Distance from road is the most important criterion of human criteria in fires occurrence in Kahramanmaraş Regional Directorate of Forestry. Importance of forest roads in forest fire occurrence has also been confirmed by other researchers (Loranzo et. al. 2008; Zumbrunnena et. al. 2010; Eskandari et. al. 2013). Increasing distance from road, both forest fires and their occurrence both numerically and as area decreasing. The results of this research have great importance in management and prediction of future fires in study area because we can prevent the future fires in study area forests by more cares in areas with high road density.

## 6. References

- AKAY A. E., WING, M. G., SIVRIKAYA, F., ŞAKAR, D. 2012. A GIS-based decision support system for determining the shortest and safest route to forest fires: a case study in mediterranean region of Turkey. *Environ Monit Assess*, 184:1391–1407, DOI 10.1007/s10661-011-2049-z
- BROSOFKSKE, K. D., CLELAND, D. T. & SAUNDERS, S. 2007. Factors influencing modern wildfire occurrence in the Mark Twain National Forest, Missouri. *Southern J Appli Forestry*, 31:73-84.
- ÇOBAN, H. E., EKER, M. 2010. Analysis of forest road network conditions before and after forest fire. FORMEC, Forest Engineering: Meeting the Needs of the Society and the Environment, Padova – Italy
- EROĞLU, V. 2009. Önsöz. I. Orman Yangınları ile Mücadele Sempozyumu, 07-10 Ocak, Antalya, Tebliğler Kitabı, p,
- FORMAN, R.T.T. and ALEXANDER L.E. 1998. Roads and their major ecological effects. *Ann. Rev. Ecol. Systematics*, 29:207-231
- FRANKLIN, J.F. and FORMAN, R.T.T. 1987. Creating Landscape Pattern by Forest Cutting: Ecological Consequences and Principles. *Landscape Ecol.*, 1:5-18
- GDF 2008. Yanan Alanların Rehabilitasyonu ve Yangına Dirençli Ormanlar Tesisi Projesi; Serik-Taşğıl. (YARDOP Project), General Directorate of Forestry, <http://www.ogm.gov.tr>
- GUYETTE, R. P., MUZIKA, R. M. and DEY, D.C. 2002. Dynamics of an anthropogenic fire regime. *Ecosystems*, 5:472-486.
- HESSBURG, P. F., & AGEE, J. K. 2003. An environmental narrative of Inland Northwest United States forests, 1800-2000. *Forest Ecol Manag.* 178:23-59.
- KOUTSIAS, N., BALATSOS, P., KALABOKIDIS, K. 2014. Fire occurrence zones: kernel density estimation of historical wildfire ignitions at the national level, Greece. *J Maps*, 10(4): 630-639.
- KERNAN, J.T., & HESSL, A.E. 2010. Spatially heterogeneous estimates of fire frequency in ponderosa pine forests of Washington, USA. *Fire Ecol.* 6:117-135.
- MAINGI, J. K. & HENRY, M. C. 2007. Factors influencing wildlife occurrence and distribution in eastern Kentucky, USA. *Int J Wildland Fire*, 16:23-33.
- NARAYANARAJ, G. & WIMBERLY, M. C. 2011. Influences of forest roads on the spatial pattern of wildfire boundaries. *Int J Wildland Fire*, 20:792-803. doi:10.1071/WF10032.
- NARAYANARAJ, G., MICHAEL C., W. 2012. Influences of forest roads on the spatial patterns of human- and lightning-caused wildfire ignitions. *Applied Geography* 32:878-888



- PERRY, D. A., HESSBURG, P. F., SKINNER, C. N., SPIES, T. A., STEPHENS, S. L., TAYLOR, A. H., et al. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and Northern California. *Forest Ecol Manag*, 262:703-717.
- PRICE, O. F., & BRADSTOCK, R. A. 2010. The effect of fuel age on the spread of fire in sclerophyll forest in the Sydney region of Australia. *Int J Wildland Fire*, 19:35-45.
- SIBOLD, J.S., VEBLEN, T.T., & GONZÁLEZ, M. E. 2006. Spatial and temporal variation in historic fire regimes in subalpine forests across the Colorado Front Range. *J Biogeogr*. 33:631-647.
- SIVRIKAYA F., SAĞLAM B., AKAY A. E., BOZALI N. 2014. Evaluation of forest fire risk with GIS. *Pol. J. Environ. Stud*. 23:187-194
- SYPHARD, A. D., RADELOFF, V. C., HAWBAKER, T. J., & STEWART, S. I. 2009. Conservation threats due to human-caused increases in fire frequency in Mediterranean climate ecosystems. *Conserv Biol*, 23:758-769.
- SYPHARD, A. D., RADELOFF, V. C., KEELEY, J. E., HAWBAKER, T. J., CLAYTON, M. K., STEWART, S. I., et al. 2007. Human influence on California fire regimes. *Ecol Appl*, 17:1388-1402.
- SYPHARD, A. D., RADELOFF, V. C., KEULER, N. S., TAYLOR, R. S., HAWBAKER, T. J., STEWART, S. I., et al. 2008. Predicting spatial patterns of fire on a southern California landscape. *Int J Wildland Fire*, 17:602-613.
- VEGA GARCIA, C., WOODARD, P. M., TITUS, S. J., ADAMOWICZ, & LEE, B. S. 1995. A logit model for predicting the daily occurrence of human caused forest fires. *Int J Wildland Fire*, 5:101-111.
- YANG, J., HE, H. S., SHIFLEY, S. R., & GUSTAFSON, E. J. 2007. Spatial patterns of modern period human-caused fire occurrence in the Missouri Ozark Highlands. *Forest Science*, 53:1-15.
- YANG, J., HE, H. S., STURTEVANT, B. R., MIRANDA, B. R., & GUSTAFSON, E. J. 2008. Comparing effects of fire modeling methods on simulated fire patterns and succession: a case study in the Missouri Ozarks. *Can J Forest Res*, 38:1290-1302.
- YANG, J., HE, H. S., STURTEVANT, B. R., MIRANDA, B. R., & GUSTAFSON, E. J. 2008. Comparing effects of fire modeling methods on simulated fire patterns and succession: a case study in the Missouri Ozarks. *Can J Forest Res*, 38, 1290-1302.

**TABLES**

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**FIGURES**

Figure 1. The fire-sensitive regions map for Turkey (GDF 2008)

Figure 2. Geographic location of the study area

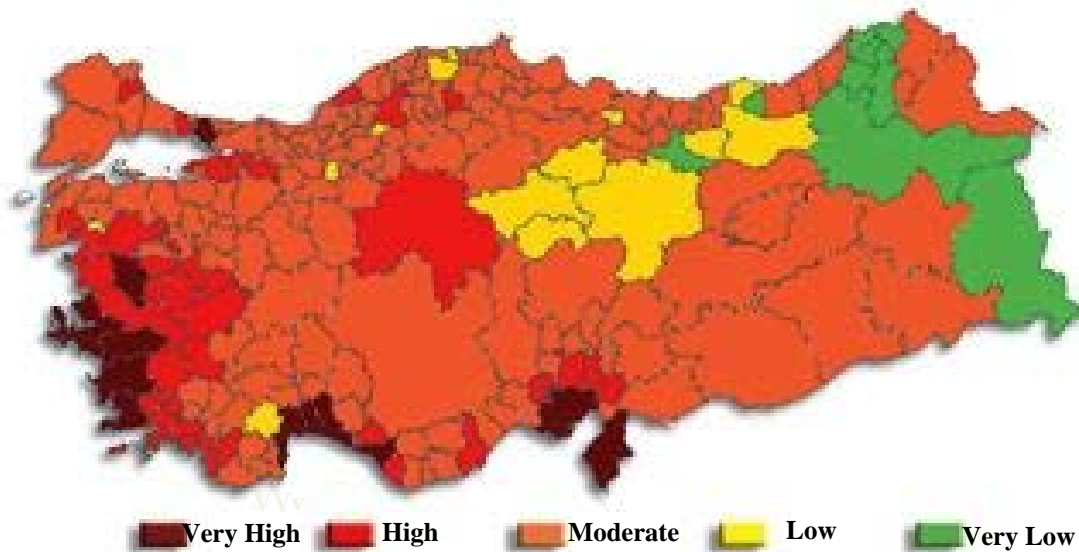


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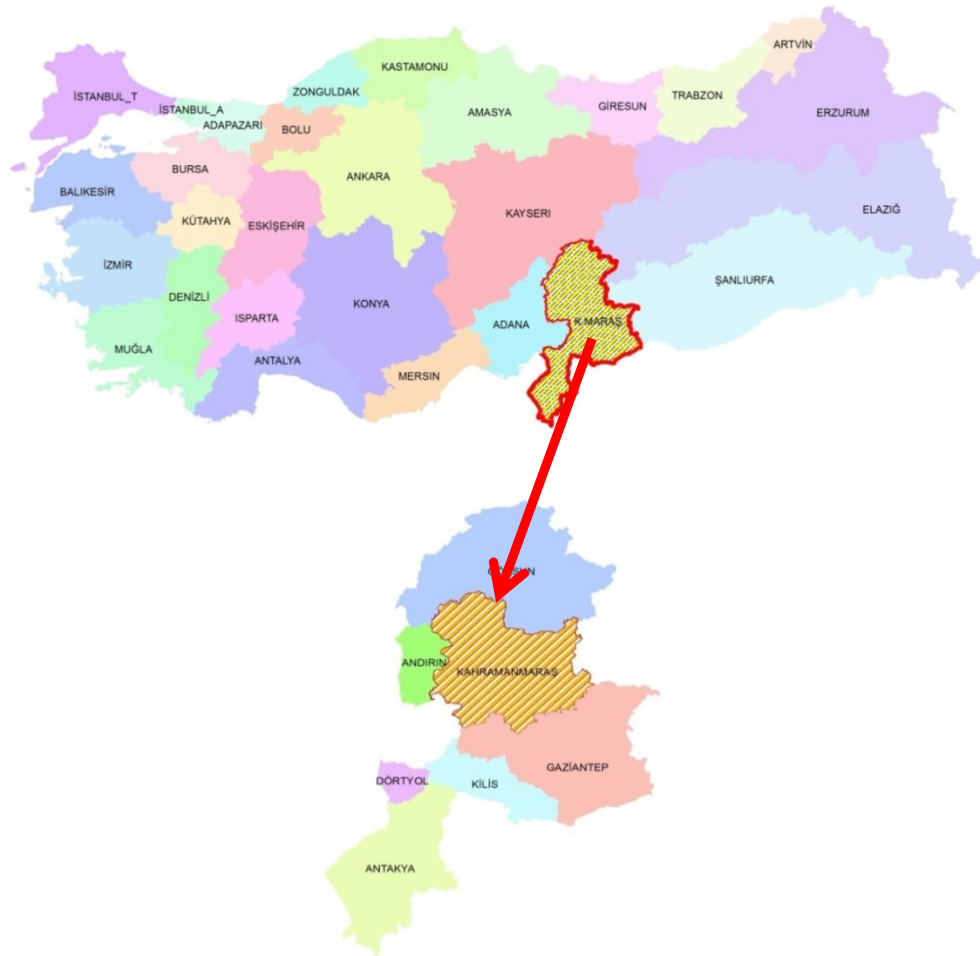


Figure 2. Geographic location of the study area

## **XII. Concurrent Session 5A – Small-scale Operations and Ergonomics**

### **Manual and Mechanized Semi-commercial Thinning Trial with Biomass Extraction in a Small-scale Forest Operations**

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Difficulties of the past 20 years to find enough funding and workers to perform pre-commercial thinning have resulted in large areas of dense, untreated, stands in New-Brunswick. These stands are now grown beyond the traditional window of operation. Treating those stands by using a semi-commercial thinning is now considered as an option, but little is known in terms of its financial feasibility in that region. The goal of this trial was to perform a preliminary study of the productivity and cost of the different options that landowners were considering in order to identify which option, if any, should further be investigated. A manual and a mechanized harvesting system commonly available to non-industrial private landowners were tested in two different harvesting intensities. Four product extraction options were tested to verify if the sale of some products could offset some of the treatment costs: pulpwood only, pulpwood & biomass (tops and branches), all products in biomass, no product extraction. Results suggest that both the manual and the mechanized system have comparable cost per ha, but the mechanized system was 6 times faster. Extraction of pulpwood showed to offset some of the costs resulting in a net cost for a semi-commercial thinning ranging somewhere between 500 \$/ha and 700 \$/ha. Extraction of biomass showed, at best, to cover for its costs but it greatly increased damages to residual trees making this option undesirable for a stand improvement treatment.

**Keywords:** Semi-commercial thinning, small scale forest operations, mechanized harvesting, biomass

#### **1. Introduction**

The Northwestern region of New-Brunswick, Canada, has a strong and diverse forest products industry that is supplied mostly by public forests and industrial freeholds. Small private woodlots in the region nonetheless amount to more than 100 000 hectares distributed

among 2150 landowners (Erdle and Norfolk 2005) and supply an annual average of 135 thousand m<sup>3</sup> of wood (Forest Management 2012).

The area is dominated by even-aged stands that are typically managed in a simple sequence starting with a clear-cut of the existing stand, followed by either natural regeneration or plantation. At age 10 to 15, the majority of the stands are very dense and are treated to a pre-commercial thinning with brush saws. At that age, trees are well below the merchantable diameter for pulpwood. No products are extracted, so the thinning is performed at a net cost of 900\$ to 1000\$ per hectare. At age 30, the stands (or plantations) are usually ready for a commercial thinning from below, where the majority of the cut trees have reached merchantable size. The first commercial thinning usually pays for itself with the sale of pulpwood and stud logs.

Non-commercial silviculture (i.e. site preparation, plantation, pre-commercial thinning) on private woodlots is supported by limited public funding and the required workforce has been a challenge to find in the last decades. This has resulted in large areas of dense, untreated, stands. These stands, that are now 25 to 35 years-old, are grown beyond the traditional window of operation for pre-commercial thinning. However, because of their high density, diameter growth of trees was limited, resulting in a relatively low number of merchantable size trees. Treating them to a semi-commercial thinning is now considered as an option to get diameter growth back on track.

Semi-commercial thinning is defined here as a thinning treatment where the majority of **the cut stems have not yet reached merchantable size, but where a certain volume of** merchantable volume is cut and can be extracted. This treatment has never officially existed in this area and is not a common treatment elsewhere in Canada, hence little is known on its financial feasibility.

The promoters had three sets of questions that they wanted to cover:

- 1) The mechanization of harvesting operations: Woodlot owners are still harvesting a significant portion of the wood using manual and small scale operations, but changes in the type of landowners and economic considerations are gradually forcing mechanization. On the other hand, silviculture treatments such as pre-commercial thinning are currently all performed manually, even in industrial forests. The trials should explore the benefits and drawbacks of manual and mechanized operations.
- 2) The maximization of wood products utilization: The region has not only a good pulp and timber industry, but also an important market for biomass from a 35 MW cogeneration facility that consume 750 000 metric tonnes (green) annually. Questions, around whether or not it could make sense to extract any or all of the potential products from thinning stands that are at a semi-commercial thinning stage, deserve to be answered in that context.

- 3) Stability and growth response of the residual stand: Intensity of thinning greatly influences the immediate economics of the treatment, as a more aggressive harvest provides more volume per hectare to be extracted. On the other hand, trees in these stands have an elevated height to diameter ratio, suggesting that they are more susceptible to blowdown. In the absence of any experience with this type of thinning in this region, the ideal intensity of thinning is therefore not known.

As a consequence of the high level of uncertainty and of the large number of initial considerations that the promoters wanted to address, it was decided to conduct a preliminary study that would cover a large number of factors on a limited area, this to guide a subsequent but more robust study. The goal of this preliminary study was to try the range of semi-commercial thinning options that landowners were currently considering to identify which one, if any, should further be investigated. More specifically, the objectives were:

1. Determine the productivity and cost of a manual and of a mechanized harvesting system performing two intensities of semi-commercial thinning in non-industrial private forest operations.
2. Explore the feasibility of extracting tops and non-merchantable stems as a biomass product for energy production.

## 2. Methodology

### Study site

A 9.8 ha sector of 33 years-old, dense, mixed stand, dominated by balsam fir (table 1) was selected in Northwestern New Brunswick (lat. 47° 11' 50" à 47° 12' 39" ; long. 68° 52' 34" à 68° 53' 11"). The stand originated from a clearcut in the early 1980's. It was divided in 3 experimental blocks each with 3 experimental units covering approximately one hectare (60 m wide X 175 m long). In every block, a control unit was kept for growth and yield follow-up. The other two units were randomly assigned a thinning intensity.

Table 1. Summary of stand characteristics

Basal area (merchantable)	18.9 m <sup>2</sup> /ha
Density (merchantable)	1 460 stems/ha
Density (total)	13 138 stems/ha
Total volume	136 m <sup>3</sup> /ha
Merchantable volume	81 m <sup>3</sup> /ha
Total biomass	122 dry metric tonnes / ha
Quadratic mean diameter (merchantable)	12.8 cm

Quadratic mean diameter (total)	5.9 cm
Dominant height	15 meters
Species composition by volume	Balsam fir (44%)
	Trembling Aspen (19%)
	White birch (12%)
	Red maple (10%)
	Other (14%)

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## Harvesting systems

Selected harvesting systems are representative of non-industrial private landowners of the area. The manual system was composed of three experienced loggers using chainsaws and of a 4X4 agricultural tractor (Massey Ferguson 396) coupled to a 5 meter long tandem log trailer with hydraulic loader (Woody loader). One of the loggers was responsible for operating the tractor. The mechanized system was composed of a 8 years-old (2004) Rocan Enviro harvester equipped with Logmax 3000 head, and of a timberjack 810 six wheel forwarder (unknown age). The operators had more than 10 years of experience on that type of equipment.

For both systems, the biomass extracted at roadside was grinded using a Morbark grinder model 30/36 and a truck mounted loader.

## Thinning treatments

The prescription called for either a light thinning, leaving 2500 stems per hectare, or a heavy thinning, leaving 1500 stems per hectare. The operator and fellers were asked to aim for a given tree spacing rather than for a residual basal area. For the light thinning, an average spacing of 2 meters between residual trees was prescribed with a minimum of 1 meter between any two trees. This corresponds to the current guideline for pre-commercial thinning in New-Brunswick (NBDNR 2004). For the heavy thinning, the average spacing requested between trees was increased to 2.6 meters, which corresponds to the current guideline for semi-commercial thinning in the province of Quebec (closest region that performs semi-commercial thinning) (Agence de mise en valeur des forêts privées du Bas-St-Laurent 2009). Trees to be left standing were not marked. Workers were asked to prioritize leaving trees of good vigor and good form. Softwood trees were to be prioritized over hardwoods and, shade tolerant hardwoods over the intolerant ones.

Extraction trails were spaced at every 20 meters. Workers were asked to maintain trail width at a minimum, given their equipment size. Trails effectively put in place for the farm

tractor had a width that varied between 2.5 and 3 meters while those set for the forwarder had a width ranging from 3 and 3.5 meters.

### Extracted products

Different product extraction options were tried to determine technical feasibility and to verify if the sale of some products could offset some of the treatment costs (table 2). Pulpwood extraction, in length of 2.44 meters with a minimum of 9 cm in diameter, is the most common method of performing semi-commercial thinning. As such, this option was tested in the four combinations of harvesting systems and thinning intensities. Because of market constraints, pulpwood had to be kept separated according to four species groups: softwoods; aspen; birches; maples.

The extraction of tree tops and of non-merchantable size trees as a biomass product for energy production was also tested for both harvesting systems in the heavy thinning and in the mechanized system of the light thinning. This meant that the loggers and the harvester operator had to make piles of biomass separate from the pulpwood piles. To facilitate the piling, stems were cut in variable lengths between 1.5 to 5 meters.

A variant of the pulpwood and biomass extraction was tried by processing the biomass portion (tops and non-merchantable stems) into “sticks” after grossly delimiting the stems. For the mechanized system, in addition to the pulpwood option and the pulp and biomass option, two other product extraction options were tested. Following observations of the challenges of neatly piling tree tops and non-merchantable trees and the production of low volumes of pulpwood, the option of processing every tree into biomass sticks of random lengths was tried. This option meant delimiting each stem all the way to the top, and cutting them in lengths of less than 5 meters. Finally, the option of not extracting any products was tried in the light thinning.

Table 2. Combinations of harvesting system, thinning intensity and product extraction tested.

Harvesting system	Thinning intensity	Product extracted
manual	light	pulpwood
manual	heavy	pulpwood
manual	heavy	pulpwood & biomass



manual	heavy	pulpwood & sticks
mechanized	light	pulpwood
mechanized	light	all wood into sticks
mechanized	light	no products
mechanized	heavy	pulpwood
mechanized	heavy	pulpwood & biomass
mechanized	heavy	pulpwood & sticks

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### Data collection

The semi-commercial nature of this treatment forces to simultaneously measure productivity in terms of area treated per productive hour and in terms of the amount of products harvested per productive hour. General productivity data was collected by technicians onsite during the entire trial. They measured the area treated per worker on a daily basis. Volume of pulpwood processed was determined by measuring top and bottom diameter of every log along the extraction trail and by sampling lengths. For extraction productivity, log volumes were measured at roadside for each trip. Biomass production could only be grossly estimated. When the biomass was extracted from the stand, the number of tractor and forwarder loads was kept on record with a visual estimation of the proportion of the basket that was filled. The biomass was then kept in separate piles at roadside according to its origin of treatment combination. Subsequently, the biomass was grinded with simultaneous loading of transport trailers. Each roadside biomass pile was grinded and loaded separately, with a technician keeping track of the biomass piles that filled each trailer. In the event of a biomass pile resulting in a partially filled trailer, the volume of the trailer that was filled by the biomass pile was visually estimated by the technician. Finally, the green weight of each truck was measured by the scale at the mill that bought it. We acknowledge that this method of estimating the produced biomass is really coarse, but it was adequate for the purpose of identifying if further investigation into this potential treatment is warranted.

Productive hours were measured by the technicians and the workers themselves who noted the time at which they started and ended their work and by noting the reason and length of time of delays longer than 2 minutes.

To provide a more detailed picture of the work, a time and motion study was performed on a sample of the work (one technician was dedicated to this while a second one did some time and motion on a part time basis). The time was measured using handheld computers with TS1000 software from FPIinnovations.

### 3. Results and discussion

#### Production and residual stand

The manual harvesting operations took place between the 1st and the 16th of November 2011. The target residual density was reached without too much trouble (table 3) and was consistent throughout the stand. On the other hand, high variation in the volume per hectare of pulpwood and in the biomass per hectare harvested was observed between the four variants tested (table 4). This was caused by to the combination of initial stand variability and the limited area treated during the observation. This was especially apparent for the heavy thinning combined to the pulpwood and biomass extraction where the density was relatively higher (>30000 stems/ha with a few residual trees from the previous stand).

The mechanized operations took place between the 14th and the 21st of November 2011. Post-treatment inventory plots suggest that the residual stand density was above target for both thinning intensities (table 3). The amount of pulpwood and biomass extracted per hectare between the heavy thinning variants was highly variable due to stand variability in the limited area treated during observation (table 4).

The felling and piling of products using either system was performed without causing significant damage to the residual trees. The extraction of pulpwood resulted in very limited damages to the residual trees (visual appreciation only). On the other hand the extraction of biomass, especially in the unprocessed form (not in delimbed sticks), caused more extensive damages following either the farm tractor or forwarder. The high tree density and the tops and branches tangled in a fairly long mass (3 to 6 meters) made it challenging to move between residual trees and it was almost impossible not to damage some trees. While the amount of damage was not systematically measured, it was so extensive that the extraction of biomass was judged technically infeasible in the context of this silviculture treatment that aims at improving the growth of the residual stand.

Table 3. Stand density, in stems per ha, before and after treatment

	Manual system Light thinning	Manual system Heavy thinning	Mechanized Light thinning	Mechanized Heavy thinning
initial stand	13 435	16 871	12 951	12 847
residual	3 163	1 633	3 438	2 743
removal	76 %	90 %	73 %	79 %

Table 4. Area treated and products extracted during time and motion observations

Harvesting system	Thinning intensity	Product extracted	Total time observed (pmh)*	Area treated (ha)	Pulpwood extracted (m <sup>3</sup> /ha)	Biomass extracted (gmt/ha) <sup>†</sup>
manual	light	pulp	12.54	0.229	33.2	0
manual	heavy	pulp	11.86	0.120	58.6	0
manual	heavy	pulp & bio	21.79	0.120	88.4	95.6
manual	heavy	pulp & sticks	10.19	0.089	40.0	33.4
mechanized	light	pulp	4.20	0.294	29.6	0
mechanized	light	all in sticks	5.50	0.177	0	56.3
mechanized	light	no products	4.91	0.268	0	0
mechanized	heavy	pulp	9.08	0.591	48.9	0
mechanized	heavy	pulp & bio	1.84	0.105	36.0	95.6
mechanized	heavy	pulp & sticks	1.83	0.067	15.9	29.3

\* pmh = productive machine hours, includes operational delays

<sup>†</sup> gmt/ha = green metric tonnes per hectare

## Felling, processing and piling productivity

The high variability of initial stand conditions made it difficult to isolate the influence of thinning intensity and of the products extracted. Nonetheless, for the manual system, heavy thinning appeared to reduce the area treated per hour, but showed little influence on the volume of pulpwood cut and piled per hour (table 5). In the variant where biomass was extracted, the extra work required for piling tops and branches near the extraction trails occupied 28% of the workers time thus reducing their productivity. The variant where trees were delimbed all the way to the top and the resulting sticks piled for extraction showed to be less demanding physically on the workers. The proportion of time used to process biomass was increased from 8% to 14% compared to the variant where top and branches were piled. On the other hand, the proportion of the time used for piling came down from 28% to 23% and workers clearly showed less sign of fatigue. In all cases of biomass piling, workers seemed to have excessively “cleaned” the site by piling almost everything that could be piled. Efficiency could have been gained by leaving behind some of the smallest branches and tops.

For the mechanised system, no real differences could be observed between the two thinning intensities. The slightly reduced productivity observed in the light thinning without any processing of the trees had more to do with differences in stand conditions. Nonetheless, the operator mentioned having more difficulties dropping certain trees in that variant if he tried doing it without processing a portion of the stem (using the rollers in the harvesters head accelerated dropping trees and helped not getting tangled). Hence, processing trees to extract pulpwood took little time while having the benefit of reducing the size of the crown of trees being put on the ground. Further processing the rest of the tree to extract biomass sticks showed a reduction of productivity. Analysis of the time and motion data showed no difference in the proportion of time used for processing between producing pulpwood with or without sticks. The extra time needed in the biomass variant was rather used to position the harvesting head and cut small unmerchantable trees to be processed into sticks, rather than simply crushing them as was done for a portion of the unmerchantable trees when only extracting pulpwood.

Even with the variable stand conditions, it was clear that the mechanized system was more productive, covering 4 to 10 times more area per pmh than the manual system.

Table 5. Thinning and processing productivity

Harvesting system	Thinning intensity	Product extracted	Rate of treatment (ha/pmh)	Time required (pmh/ha)	Pulpwood cut and piled (m <sup>3</sup> /pmh)	Biomass cut and piled (gmt/pmh)
manual	light	pulp	0.018	54.7	0.61	0.00
manual	heavy	pulp	0.010	98.9	0.59	0.00
manual	heavy	pulp & bio	0.005	182.2	0.49	0.52
manual	heavy	pulp & sticks	0.009	114.2	0.35	0.29
mechanized	light	pulp	0.070	14.3	2.07	0.00
mechanized	light	all in sticks	0.032	31.2	0.00	1.81
mechanized	light	no products	0.055	18.3	0.00	0.00
mechanized	heavy	pulp	0.065	15.4	3.18	0.00
mechanized	heavy	pulp & bio	0.057	17.6	2.04	5.43
mechanized	heavy	pulp & sticks	0.036	27.5	0.58	1.07

For the extraction of products to roadside, a few interesting observations were made. First, the pulpwood extracted was composed of four species group that had to be kept separate (softwoods, aspen, birches, maples), which meant that volume per hectare of each group was low. Both the farm tractor and the forwarder were able to load and maintain species separation for two species group at a time. Hence, they had to cover the same trail area twice for relatively low volumes. This certainly explains in part the low productivity observed (table 6).

For the manual system, the extraction of biomass sticks showed to be almost twice as productive as the extraction of unprocessed biomass. This was explained not only by the higher payload, but also on the reduced time required for loading. The unprocessed biomass showed to be a challenge to load while trying to limit damages to residual trees. Furthermore, it showed to be a safety issue for the operator standing at the controls (controls for the loader were mounted on the trailer). Piles of unprocessed biomass often have branches protruding that can pass through the safety mesh that is supposed to protect the operator.

For the mechanized system, the scenario where all the wood was processed into sticks without any kind of separation gave the highest productivity. This was explained by the presence of much bigger piles along the trail, requiring less travel during loading and by not having to maintain product separation in a load. When extracting unprocessed biomass or sticks in scenarios where the pulpwood was kept separate, the productivity was much lower mainly due to the much smaller piles along the trail.

Table 6. Transport to roadside productivity

Harvesting system	Thinning intensity	Product extracted	Pulpwood extraction (m <sup>3</sup> /pmh)	Number of loads observed	Biomass extraction (gmt/pmh)	Number of loads observed
manual	light	pulp	3.17	2		
manual	heavy	pulp	4.05	5		
manual	heavy	pulp & bio	3.38*	3*	2.64	18
manual	heavy	pulp & sticks	3.38*	3*	4.68	2
mechanized	light	pulp	6.00	1		
mechanized	light	all in sticks			12.15	4
mechanized	light	no products				
mechanized	heavy	pulp	6.97*	9*		
mechanized	heavy	pulp & bio	6.97*	9*	5.73	4
mechanized	heavy	pulp & sticks	6.97*	9*	5.36	2

\*Loads from two or more treatment variations combined in this result

### Treatment cost

Actual costs and mill prices were used to determine the net cost of performing each thinning variant (table 7). None of the variants generated an immediate profit (table 8). For the manual system, extracting pulpwood allowed to offset some of the cost of thinning. Light

thinning was the least costly option at a net cost of 482 \$/ha. The heavy thinning, which is closest to the current semi-commercial thinning intensity in the nearby province of Québec, was performed at a cost of 733 \$/ha. The observed cost for that variant is close to the average estimated cost of 835 \$/ha used in the province of Québec (Agence de mise en valeur des forêts privées du Bas-St-Laurent 2015). Extracting biomass, on the other hand, did not seem to provide any clear financial benefits. The extraction of biomass in the form of sticks was the least costly option, but differences in pulpwood volume per hectare between variants contributed to making this option less desirable.

The mechanized system showed to be least costly when only the pulpwood was extracted, with the exception of the heavy thinning variant with unprocessed biomass. As stated before, the pulpwood with biomass variant was observed in a section of the stand that was much denser than the rest of the stand, yielding much more pulpwood and biomass. The heaviest thinning intensity was the least costly at a rate of 539 \$/ha. From the observations made, it is very unlikely that the extraction of biomass could contribute in the reduction of overall thinning costs in common stand conditions.

Table 7. Rates used in financial calculations

Loggers (\$/pmh)	22.00
Farm Tractor and trailer (\$/pmh)	42.00
Harvester (\$/pmh)	110.00
Forwarder (\$/pmh)	80.00
Pulpwood Transportation cost to the mill (\$/m <sup>3</sup> )	10.00
Pulpwood mill price (\$/m <sup>3</sup> )	45.00
Biomass grinding (\$/gmt)	6.10
Biomass transportation cost to the mill (\$/gmt)	10.00
Biomass mill price (\$/gmt)	38.00

Table 8. Distribution of costs and revenues.

Harv. syst.	Thin.	Product extr.	Costs (\$/ha)						Revenues (\$/ha)		Net value of thinning (\$/ha)
			Cut & pile	Pulp. roadside*	Pulp. transp. to mill	Bio. transp. roadside*	Bio. grinding	Bio. transp. to mill	Pulp.	Bio.	
manual	light	pulp	1204	441	332	0	0	0	1494	0	(482)
	heavy	pulp	2176	608	586	0	0	0	2638	0	(733)
	heavy	p. & bio	4009	1098	884	1509	580	950	3978	3631	(1439)
	heavy	p. & sticks	2512	497	400	300	204	334	1802	1270	(1176)
mechanized	light	pulp	1572	395	296	0	0	0	1331	0	(931)
	light	sticks	3427	0	0	371	344	563	0	2141	(2565)
	light	no prod.	2014	0	0	0	0	0	0	0	(2014)
	heavy	pulp	1689	561	489	0	0	0	2201	0	(539)
	heavy	p. & bio	1937	413	360	1335	583	956	1619	3631	(332)
	heavy	p. & sticks	3020	183	159	438	179	293	717	1115	(2441)

\*Travel distance standardized to 85 meters

#### 4. Conclusion

This trial tested a range of semi-commercial thinning options that non-industrial landowners in New Brunswick are considering for stands that have grown beyond the pre-commercial stage. The results of this preliminary study suggest that treating dense natural stands to a semi-commercial thinning is technically feasible with either a manual or mechanized system. Given the variability in initial stand conditions encountered, thinning costs appeared to be in the same range for both harvesting systems. Extraction of pulpwood showed to offset



some of the costs of thinning in both systems suggesting a net cost ranging somewhere between 500 \$/ha and 700 \$/ha.

Extraction of biomass, whether processed into sticks or unprocessed, showed to cover for its costs only in the best stand conditions. However, for the manual system, this task was very demanding physically and raised safety issues. Furthermore, for both systems, the extraction phase of biomass appeared to be a significant cause of damage to residual trees. The extent of the damages observed was sufficient to suggest that this option may not be viable given the implicit stand improvement goal of a thinning treatment.

In the context of a shrinking workforce and of limited funding to support silviculture on small non-industrial forest, a heavy thinning using a mechanized system extracting pulpwood, appears as the most promising option for a semi-commercial thinning treatment.

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## 6. References

- Agence de mise en valeur des forêts privées du Bas-St-Laurent. 2009. Programme de mise en valeur des forêts privées - Cahiers d'instructions techniques. Rimouski, Qc. 130 p.
- Agence de mise en valeur des forêts privées du Bas-St-Laurent. 2014. Programme de mise en valeur des forêts privées - Cahiers d'instructions techniques. Rimouski, Qc. 130p.
- Agence de mise en valeur des forêts privées du Bas-St-Laurent. 2015. Grille de taux 2015-2016. Available online at [www.agence-bsl.qc.ca/Mission/Programmes/Programmes.htm](http://www.agence-bsl.qc.ca/Mission/Programmes/Programmes.htm); last accessed on June 23, 2015.
- Erdle, T. and Norfolk, C. 2004. Analysis of Future Forest Condition and Wood Supply for Private Woodlots in New Brunswick. Faculty of Forestry and Environmental Management. University of New Brunswick. Fredericton, NB.
- Forest Management (2012). New Brunswick's private woodlot forests: future timber supply potential and forest dynamics (Private Forest Task Force Report - Appendix C). New Brunswick Department of Natural Resources; Forest Management. Fredericton, N.-B. 36 p.

NBDNR (2004). Forest Management Manual for New Brunswick Crown Land. Fredericton, N.B.,  
New Brunswick's Department of Natural Resources.

# Practical Options of Small-scale Forest Operations and Management for Non-industrial Landowners in Japan: Timber Product Improvement and Regional Woody Biomass Utilization

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There have previously been two conventional options of forest management and harvesting methods for small-scale forest owners in Japan. One is the outsourcing of silvicultural treatments and harvesting operations to a forest owners' cooperative or logging contractors. The other is that of family-based labor with harvesting carried out by mini-forwarders or short-span cable systems. In the latter option, low productivity is compensated with value-adding activities such as intensive silvicultural management for the production of high quality niche timber products, the cultivation of non-industrial forest byproducts, self-processing of harvested timber, etc. In recent decades a further option has become available, i.e., self-harvesting operation oriented to the production of “normal” quality timber. This option is most effectively realized with a high-density spur road network and using small-sized winch equipped excavators. There are three important enabling factors: government subsidy for spur road construction, technological outreach of methods of spur road construction that are adapted to steep terrain, and the uptake of low quality wood recovery systems (“wood stations”) organized by local communities. These allow every local forest owner or contractor to ship recovered low quality timber for a designated constant selling price. The station then stores the shipped timbers, classifies them, and re-sells them to wood chip companies or woody biomass utilization plants. The existence of such enterprises and the additional revenue stream they generate has encouraged local small-scale forest owners to resume management of formerly abandoned forest stands.

**Keyword:** Small scale forestry, small-sized harvesting system, self-employed labor, by-products, woody biomass utilization

## 1. Introduction

One of the most urgent challenges in the forest and forestry sector in Japan is how to increase harvesting volumes in order to match the growing forest stock resources (Forest

Agency 2014a, 2014b). Until now it has been considered that the increased levels of logging system mechanization are the most appropriate solution, coupled with aggregation of small dispersed forest stands into larger lots. That is because there are many individual small private forest owners: 75% own less than 5 hectares (ha) and 88% own less than 10 ha (Forest Agency 2014a). The majority of small woodland owners are old and find it increasingly difficult to undertake forest management and logging operations by themselves. They are beginning to outsource such works to contractors such as Forest Owners' Cooperatives or private forestry contractors. However, there is renewed interest in part of the sector in self-employed logging and shipping of harvested products to supply wood markets or biomass utilizing facilities.

In this paper, first we present four case studies of private forest owners in the Kochi prefecture in mid-western Japan. Each completed a questionnaire about their management strategies: we attempt here to interpret current trends among private forest owners. Linking this with additional reported information on regional utilization of woody biomass, we propose practical options for small-scale forest operations and management for non-industrial landowners in Japan.

## **2. Methods**

We selected four typical private forest owners in the Kochi prefecture, one of Japan's 47 municipal blocks. The Kochi prefecture is located in mid-western Japan, has relatively steep terrains compared to other prefectures, and has an active forestry sector. We visited each of the owner's sites and interviewed their approach to forest management. Figure 1 illustrates the location of each site, coded A, B, C, and D. We attempt to link this information to additional details such as the status of road network, method of logging system, main products from the forests, etc.

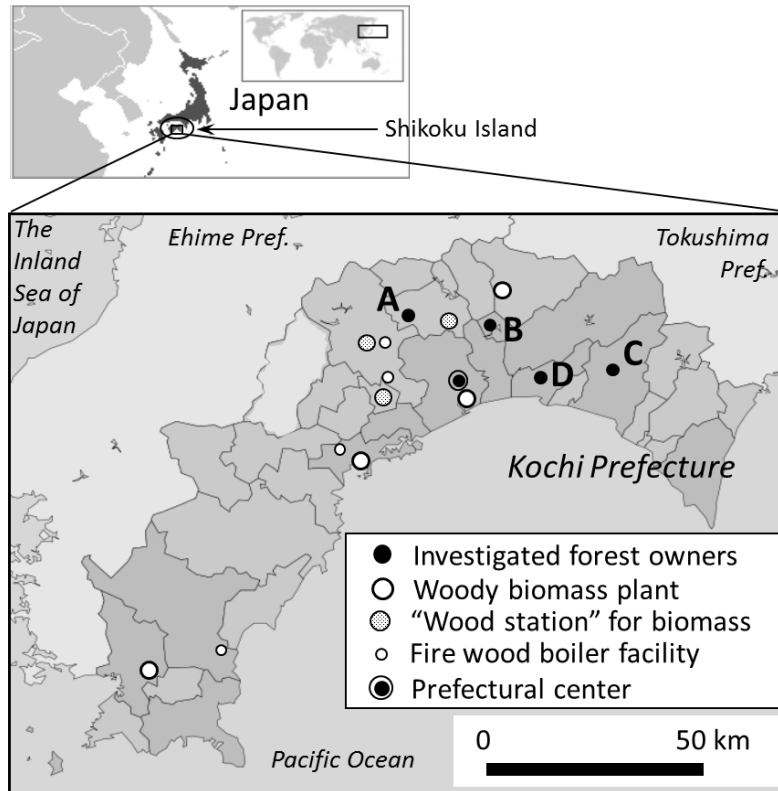


Figure 1. Location map of the investigated forest owners' sites and woody biomass related plants and markets in the Kochi prefecture, Japan.

Note: Map images are modified from those of Wikipedia Web (<http://ja.wikipedia.org/>).

### 3. Results

Table 1 summarizes the results of our investigation into the four cases. For all four, the main species planted were Sugi (Japanese Cedar) and Hinoki (Hinoki Cypress), Japan's most popular conifer plantation species.

Case A was a single forest owner who manages less than 10ha of forest land. A 2.0 meter wide road network is used by a mini-forwarder, which is propelled by rubber crawlers, has 1-2 tonne of loading capacity, and is usually equipped with a winch in order to accomplish short range cable logging (Nakahata et al. 2014). For normal timber production, the owner entrusts harvesting operations to the crews of a nearby Forest Owners' Cooperative. In addition, he also cultivates pole-sized timber, known as "Migaki maruta" (polished timber), for use in the construction and maintenance of traditional Japanese wooden houses (Shugi Kitayama Forestry Culture Association 2015). After processing and polishing the poles himself, they command a high price in sales to house builders, almost ten times that of an equivalent

volume of normal timber. Part of his forest is used for cultivating two broad leaved trees, Sakaki (*Cleyera japonica*) and Shikimi (*Illicium anisatum*), for ornamental usage. Twigs of 30-50cm length are used in Buddhist and Shintoist daily ritual decorations (Editorial Staff 1966), a popular Japanese customs especially in the local area. The sale of these twigs is a useful side business to his more mainstream forestry activities.

Table 1. Four case studies of private forest owners

Case/item	A	B	C	D
Municipality	Tosa town	Nankoku city	Aki city	Kounan city
Ownership	Private	Private company	Private company	Private, multiple owners
Area	Less than 10ha	188ha	ca. 330ha	N.A. (ca. 20ha)
Road density	N.A.	85m/ha	150m/ha	N.A.
Road width	2.0m	2.5m	3.0m	3.5m
Logging system	Mini forwarder*	Mini forwarder, 3t class excavator equipped with grapple	2t truck, 8t class excavator equipped with grapple and winch	Tower yarder, processor (13t class excavator base)
Logging crew	Self-employed labor, contractor (Forest Owners' Cooperative or private forestry contractors)	Contractor (private forestry contractor)	Self-employed logging crew	Contractor (Forest Owners' Cooperative)
Products	Saw timber, polished pole (self-processed), ornamental twigs	Saw timber, pulp wood	Saw timber, pulp wood	Saw timber, pulp wood
Date of investigation	Jan. 23, 2015	Oct. 22, 2014	Nov. 22, 2014	Dec. 5, 2014

\*: Mini forwarder has 1-2t loading capacity, is equipped with winch, and propelled by crawlers.

The Case B forest owner is a private company located outside of the prefecture. It uses a private forestry contractor for almost all forest management operations such as the construction and maintenance of the road network, thinning, etc. The contractor uses a 3

tonne-class excavator for road construction, a mini forwarder and an excavator equipped with grapple for logging, and a light-weight truck (350kg loading capacity) for maintenance work. The main products are timber for good quality saw logs and pulp wood for low quality logs.

The forest owners in Case C were a family owing several large forest lots amounting to several hundred hectares. They organize a forest management company that manages this area and other similar areas. They prepared a road network with a density of 150m/ha in order to allow winch logging over short distances of up to 20-30m. Forest management works and logging operations are also performed by the same company. The main machines are 8 tonne-class excavators equipped with a grapple and winch. The well maintained 3.0 meter wide roads allow 2 tonne-class trucks to transport logs from the logging site.

In Case D, a Forest Owners' Cooperative in the area consolidated different forest owners' stands into a single lot. The consolidation was implemented under the "Forest and Forestry Revitalization Plan" that was developed by the Ministry of Agriculture, Forestry and Fisheries in December 2009 (Forestry Agency 2010). The plan also enhanced the mechanization of harvesting operation by introducing high-performance machines such as European tower yarders. The Forest Owners' Cooperative in this area started to use one such tower yarder in 2011 and has accomplished some effective logging operations with the machine (Setiawan et al. 2012; Nakazawa et al. 2012). Because the tower yarder is normally used over logging distance of 100-200m, the required road density is low at around 50m/ha. However, the machines, which include a 13 tonne-class excavator-based processor, are large, so road width has to be rather wide at 3.5m. Within this area most of forest owners are landowners with little intension to undertake forest management works themselves. The Forest Owners' Cooperative enables thinning operations to take place through the economy of scale achieved by consolidating adjacent forest stands and forest owners.

#### **4. Discussion**

Three of the four cases described above use small scaled logging systems with narrow (2-3m) road networks. In general, the operational efficiency of logging systems with smaller scaled machines is lower than that with larger scaled machines. On the other hand, larger scaled machines incur higher hourly costs. The resulting overall cost, i.e., hourly cost divided by productivity, will be lower only if the accomplished performance of the system is sufficiently high compared with its hourly cost (Setiawan et al. 2013). Figure 2 illustrates the relationships between productivity, hourly cost, and the resulting overall cost for a mini-forwarder system and a tower-yarder system (Suzuki et al. 2015). These productivities were obtained from

related studies (Taniyama 2004; Nakazawa et al. 2012; Nakahata 2014) and the hourly costs were calculated by a conventional methodology (Miyata 1980; National Forestry Extension Association in Japan 2001). Data from a swing yarder system (Setiawan et al. 2013) are also shown in Figure 2; the swing yarder is normally a 13 tonne-class excavator equipped with a grapple and a combination of winch drums that enable running skyline logging operations over distances of up to 100m.

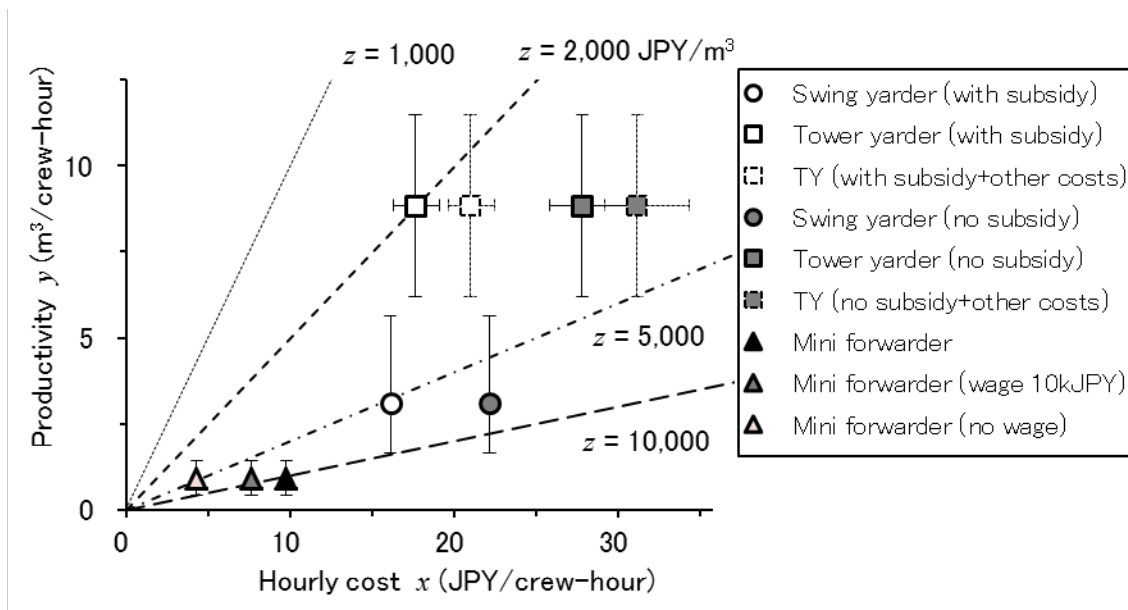


Figure 2. Relationship between productivity, hourly cost, and resulting cost.

Notes: Modified from Suzuki et al. (2015).  $x$ , hourly cost (JPY/crew-hour);  $y$ , productivity ( $\text{m}^3/\text{crew-hour}$ );  $z$ , resulting cost ( $\text{JPY}/\text{m}^3$ ;  $z = x / y$ ). Error bars indicate max and min. 1,000 JPY (Japanese Yen) = 8.29 USD (US dollar) (SMBC 2015).

As Figure 2 shows, both productivities and hourly costs of the systems with larger machines are higher than those of smaller systems, and the productivities are sufficiently high that resulting net costs are lower than for systems using smaller machines. It should be noted that resulting costs of the mini forwarder system are almost 10,000 JPY (Japanese Yen) whereas typical saw timber price is 10,000 JPY or lower (Nakahata et al. 2013). When the labor cost is not taken into account (for example because of self-employment), the resulting cost of the mini forwarder system reduces to around 5,000JPY and becomes competitive. A similar situation was observed in an the implementation of a local woody biomass recovery project, operated from 2007 to 2011. In that case, the recovered amount of residue logs shipped using a smaller forestry system was much larger than that achieved by larger systems. The main reason for this



was that operators in the smaller system were self-employed and able to compensate labor costs into their operational costs (Suzuki et al. 2009 and 2013). That is, private forest owners tend to choose smaller sized systems which have rather low performance but also demand low investment costs. Toyama et al. (2012) analyzed long term forest management regimes using a total cost simulator in order to propose the best alternatives under a range of forestry scenarios. Although their model adopted a typical mechanized harvesting system, they pointed out in their discussion section that their findings might have been different had they considered the use of small scale, self-employed systems (Toyama et al. 2012).

The low efficiency of small scaled systems is partly due to the extent of motor-manual processing. However, the market price of timber per volume ranges widely (7,000 to 40,000JPY/m<sup>3</sup>) even for small diameter timber (Nakahata et al. 2013). This is mainly due to the wide variation in detail and demand for sawn timber. In other words, there is a possibility of raising sale prices by offering more precise choice of diameter and bucking length. This is something that can be achieved more easily when motor-manual bucking with a chainsaw than in a machine bucking system with a processor.

The forest owner in Case A attempts to maximize profits by self-processing polished poles and the cultivation of ornamental/religious ritual twigs. A new market for low quality timber has recently emerged in many places that suits many private forest owners, generally known as a “wood station”. Wood station enterprises are operated by local communities for the collection of low quality timber such as logging residues, shipped by individual forest owners with a designated constant selling price. These are used for local woody biomass facilities such as firewood boilers for hot spar facilities, or else transported to chipping companies for use in the pulp wood sector. As shown in Figure 3, the cost per kWh is currently lower for woody biomass fuels than fossil fuel (Suzuki et al. 2014; Takamura et al. 2015).

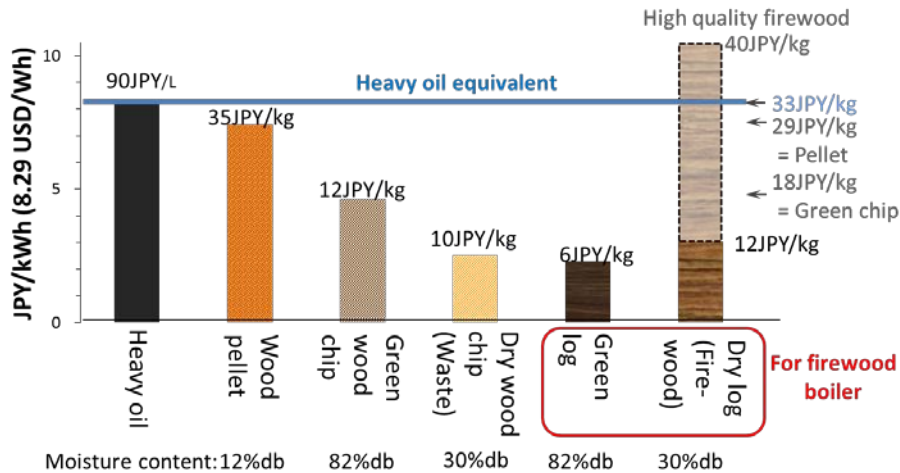


Figure 3. Price per energy (kWh) of heavy oil and woody fuels.

Notes: Modified from Suzuki et al. (2014). One JPY (Japanese Yen) = 8.29x1,000 USD (US dollar) (SMBC 2015).

Large woody biomass installations such as power generation plants need vast amount of wood fiber (for example, 100,000m<sup>3</sup>/year is required to sustain a 5000kW of output). For the supply of such large plants, large scale recovery systems are more suitable. There are four such large woody biomass plants in the Kochi prefecture (Figure 1). The principal suppliers of wood fiber to these plants are logging contractors and Forest Owners' Cooperatives.

For small scale utilization of woody biomass, such as log or chip boilers, smaller scale recovery systems are most appropriate. Figure 4 compares the total cost of the boilers for hot spar facilities with an output of 220kW, which use around 300m<sup>3</sup>/year (Suzuki et al. 2012 and 2014). The total combined cost, considering both fixed and variable costs, of woody fuels is lower than that of fossil fuel. The cost is lowest for boilers using dry chip. However, firewood boiler costs are also significantly lower than the fossil fuel alternative. Firewood boiler facilities, combined with a wood station recovery system nearby, are now an emerging trend in small scale woody biomass utilization in Kochi and also in other areas of Japan (Figure 1).

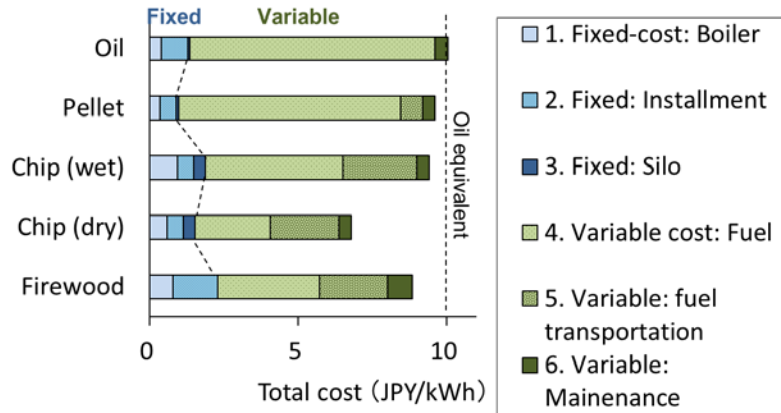


Figure 4. Total cost for hot spar boiler facilities (220kW output).

Notes: Modified from Suzuki et al. (2014). One JPY (Japanese Yen) = 8.29x1,000 USD (US dollar) (SMBC 2015).

## 5. Conclusions

We considered four case studies of private forest owners, each typical of the patterns observed throughout Japanese forestry. For private forest owners with fewer than 100 ha, Cases A and D represent the most practical options. Case A is characterized by the use of small scale machines on narrow roads, a self-developed management plan, implementation of intensive silvicultural practice resulting in high quality timber production, and in some cases the outsourcing of some operations to private forestry contractors or a Forest Owners' Cooperative. Case D is more suitable forest owners who cannot carry out actual management works by themselves, with all operations entrusted to Forest Owners' Cooperatives. In turn, these Cooperatives consolidate such forest owners, prepare appropriate road networks, and are thus able to perform harvesting operations using large scale, highly efficient systems.

There is one more option to consider here, a modified version of Case A: a self-harvesting operation oriented for the production of "normal" quality timber. In the last decade numbers of young forest workers entering the sector have increased as a result of enhanced government support (Forestry Agency 2011, 2014a, 2014b). Government subsidy for road network construction and the technological outreach of methods of narrow road construction adapted to steep terrain are also contributing factors. Combined with emerging low quality timber utilization system such as those typified by wood station enterprises, numbers of self-operating small scale private forest owners can be expected to increase in rural areas. It can also be expected that local small-scale forest owners will resume forest management in

previously abandoned stands because of increases in income from normal forest management activities.

## 6. References

Editorial Staff. 1966. Shinto Symbols (Part 2). *Contemporary Religions in Japan* 7 (2): 89-142.

Available online at [nirc.nanzan-u.ac.jp/nfile/3164](http://nirc.nanzan-u.ac.jp/nfile/3164); last accessed June 11, 2015.

Forestry Agency. 2010. Annual Report on Forest and Forestry in Japan, Fiscal Year 2009 (Summary). Annual Report Group, Policy Planning Division, Forestry Agency, Ministry of Agriculture, Forestry, and Fisheries (MAFF), Tokyo. Available online at [www.rinya.maff.go.jp/j/kikaku/hakusyo/21hakusho/pdf/21\\_e.pdf](http://www.rinya.maff.go.jp/j/kikaku/hakusyo/21hakusho/pdf/21_e.pdf); last accessed June 12, 2015.

Forestry Agency. 2011. Annual Report on Forest and Forestry in Japan, Fiscal Year 2010 (Summary). Annual Report Group, Policy Planning Division, Forestry Agency, Ministry of Agriculture, Forestry, and Fisheries (MAFF), Tokyo. Available online at [www.rinya.maff.go.jp/j/kikaku/hakusyo/22hakusho/pdf/22\\_e.pdf](http://www.rinya.maff.go.jp/j/kikaku/hakusyo/22hakusho/pdf/22_e.pdf); last accessed June 12, 2015.

Forestry Agency. 2014a. Annual Report on Forest and Forestry for Fiscal Year 2013. Annual Report Group, Policy Planning Division, Forestry Agency, Ministry of Agriculture, Forestry, and Fisheries (MAFF), Tokyo. Available online at [www.rinya.maff.go.jp/j/kikaku/hakusyo/25hakusyo/index.html](http://www.rinya.maff.go.jp/j/kikaku/hakusyo/25hakusyo/index.html); last accessed June 12, 2015. (in Japanese)

Forestry Agency. 2014b. Annual Report on Forest and Forestry in Japan, Fiscal Year 2013 (Summary). Annual Report Group, Policy Planning Division, Forestry Agency, Ministry of Agriculture, Forestry, and Fisheries (MAFF), Tokyo. Available online at [www.rinya.maff.go.jp/j/kikaku/hakusyo/25hakusyo/pdf/h25summary.pdf](http://www.rinya.maff.go.jp/j/kikaku/hakusyo/25hakusyo/pdf/h25summary.pdf); last accessed June 11, 2015.

Miyata, E.S. 1980. Determining fixed and operating cost of logging equipment. USDA For. Serv. Gen. Tech. Rep. NC-55. 16p.

Nakahata, C., Aruga, K., Uemura, R., Saito, M. and Kanetsuki, K. 2014. Examining the optimal method to extract logging residues from small-scale forestry in the Nasunogahara area, Tochigi prefecture, Japan. *Small-scale Forestry* 13: 251-266.

- Nakahata, C., Aruga, K., Takei, Y., Yamaguchi, R., Saito, M. and Kanetsuki, K. 2013. Examining the optimum extraction rate of extracting thinned woods in the Nasunogahara area. *Journal of the Japan Forest Engineering Society* 28: 17-28. (in Japanese with English summary)
- Nakazawa, M., Yoshida, C., Sasaki, T., Jinkawa, M., Tanaka, Y., Suzuki, H., Uemura, T., Ito, T., Yamasaki, T., Oya, S., Furukawa, K. and Imatomi, Y. 2012. Development of thinning system with a tower yarder newly introduced from Europe: Productivity of uphill yarding under the cable. *Journal of the Japan Forest Engineering Society* 27: 175-178. (in Japanese with English summary)
- National Forestry Extension Association in Japan Eds. 2001. Management of the Mechanization. National Forestry Extension Association in Japan, Tokyo. 239p. (in Japanese)\*
- Setiawan, A.H., Suzuki, Y., Nishimori, H., Gotou, J. and Yamasaki, T. 2012. Line tension of tower yarder system equipped with intermediate supports: measurement of skyline tension and intermediate support load. In Proc. of International Ergonomic Workshop of IUFRO RG3.03: Ergonomic Challenges in Future Forest and Forestry, October 1-4, 2012, Nagoya, Japan. (CD-ROM, 8pp)
- Setiawan, A.H., Suzuki, Y., and Gotou, J. 2013. Classification of forest operations with regard to hourly cost to productivity balance - A proposal of a framework for analysis of the relationship between hourly cost and productivity using a simple chart -. *Journal of the Japan Forest Engineering Society* 28:143-148.
- Shugi Kitayama Forestry Culture Association. 2015. Kitayama forestry products. Shugi Kitayama Forestry Culture Association, Kyoto. Available online at [www.yamasyo-ys.com/kyoto-shugi/products](http://www.yamasyo-ys.com/kyoto-shugi/products); last accessed June 11, 2015.
- Sumitomo Mitsui Banking Corporation. 2015. Chart of exchange rate. Available online at [www.smbc.co.jp/kojin/kinri/chart.html](http://www.smbc.co.jp/kojin/kinri/chart.html); last accessed June 11, 2015. (in Japanese)\*
- Suzuki, Y., Setiawan, A.H. and Gotou, J. 2015. Timber harvesting systems in Japan's aging plantation forests: Implications for investment in construction of forest road networks. *Journal of the Japan Forestry Society* 97: (in press). (in Japanese with English summary)
- Suzuki, Y., Yamanaka, N. and Gotou, J. 2012. Sensitivity analysis of woody-biomass burning facilities on cost of facility and fuel comparing scale of the facilities and form of the woody biomass fuels. *Journal of the Japan Forest Engineering Society* 27: 165-174. (in Japanese)
- Suzuki, Y., Hatano, Y., Murakami, S., Okazawa, T., Sagayama, S., Gotou, J., Ichihara, T. and Miyoshi, K. 2009. Harvesting and Transportation of Logging Residue Logs Accumulated Along Road Side for Woody Biomass Plant in a Local Community. In Proc. of 2009 COFE:

Environmentally Sound Forest Operations, 32nd Annual Meeting of the Council on Forest Engineering, June 15-18, 2009, North Tahoe Conference Center, Kings Beach, California, Hartsough, B. and Stokes, B. (Eds.) (CD-ROM, 8pp)

- Suzuki, Y., Murakami, S., Gotou, J., Nakajima, K., Kitahara, F., Tarumi, A., Nakayama, T. and Tanouchi, H. 2013. Analysis of the amount shipped and the shipper's cost balance for recovered logging residue logs in the woody biomass utilization project of Niyodogawa town, Kochi prefecture, Japan. *Journal of the Japan Forest Engineering Society* 28: 41-50. (in Japanese with English summary)
- Suzuki, Y., Takamura, K., Watanabe, Y., Mori, D., Yoshida, T., Kitahara, F. Nakayama, T., and Gotou, J. 2014. Production-supply system and its cost of firewood as small scale dispersively located woody biomass fuel. *Journal of the Japan Forest Engineering Society* 29: 157-163. (in Japanese)
- Takamura, K., Mori, D., Gotou, J., Suzuki, Y.K. 2014. A case study of wood fuel utilization by community forestry for sustainable, cost-effective management of a local forest in Japan. *The International Forestry Review* 16(5):398.
- Taniyama, T. 2004. Thinning systems used mini-forwarder roads. *Journal of the Japan Forest Engineering Society* 18: 257-258. (in Japanese)
- Toyama, K., Tatsuhara, S. and Shiraishi, N. 2012. Simulation under Diverse Conditions for Profitable Thinning Regime and Clearcutting Age in Planted *Cryptomeria japonica* Forest. *Journal of the Japanese Forest Society* 94: 269-279. (in Japanese with English summary)

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# Noise and Vibration Exposure in Full-tree Logging Systems in the Southeastern U.S.A.

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In the Southeastern United States, logging equipment operators often work shifts in excess of 10 hours. Evidence suggests that exposure to noise and vibration may have adverse impacts on both worker health and productivity (Jack and Oliver 2008, Stansfeld and Matheson 2003). We monitored logging equipment operators at eight sites in the southeastern United States to better quantify the exposure to occupational noise and whole body vibration. Twenty-seven logging equipment operators were measured for exposure to noise and whole body vibration. Personal noise dosimeters were used to collect noise exposures while seat pad accelerometers were used to capture vibration exposures. Both sets of data were collected during at least four hours of representative machine operation. The data were collected from eleven wheeled skidder operators, eight wheeled feller-buncher operators, and eight loader operators from seven different logging crews. Wheeled skidders had the highest average whole body vibration exposure at 1.58 m/s<sup>2</sup> Aeq(8), wheeled feller-bunchers followed at 1.04 m/s<sup>2</sup> Aeq(8), and finally loaders at 0.64 m/s<sup>2</sup> Aeq(8), all of which exceeded the ISO 2631 recommended action limit. The value for skidders exceeded both the ISO 2631 exposure limit value and the European Union Directive exposure limit value (1.15 m/s<sup>2</sup>). The majority of the noise exposures were below the OSHA Action Limit of 85 dBA, but due to the long hours, almost all operators received more than the ISO EU recommended daily noise dose.

**Keyword:** Logging, vibration, noise

## 1. Introduction

Workers in the logging industry average nearly twice the injury rate of all private industry, and logging continues to be one of the most dangerous jobs in the United States. As recently as 2013, logging was listed as the occupation with the highest fatal injury rate (BLS 2013). So hazard reduction has been focused on reducing fatalities and acute, traumatic injuries. One of the most effective means of reducing these types of injuries has been increased

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mechanization in logging (Axelsson 1995, Bordas et al 2001). In the southeastern USA injury rates decreased with mechanized logging when compared to logging with manual tree felling operations (Roberts and Shaffer 2005).

Equipment operators now account for the largest portion of the logging workforce (Smidt 2011), and they replaced deckhands and chainsaw operators as the most frequently injured crewmember (Roberts et al 2005). Hazardous exposures to whole body vibration, repetitive motion, and long work hours have increased due to mechanization. The adverse effects of these exposures are very difficult to measure in workers compensation claims or federal injury surveys due to the chronic nature of the injuries. Assigning a cause at the time of treatment is difficult given that workers may change industries several times in their career.

Logging machine operators are exposed to an array of risk factors for the development of musculoskeletal disorders. These risk factors include whole body vibration (WBV), static and awkward postures, and repetitive movements (Bovenzi and Betta 1994, Jack and Oliver 2008, Neitzel and Yost 2010, Shan et al 2013, Tiemessen et al 2008,). Operators are also exposed to relatively high job stress, long hours, and are likely to be obese (Axelsson 1995, Lynch et al 2014, Smidt 2011). These factors contribute to frequent musculoskeletal complaints and hearing loss among logging machine operators (Axelsson 1995).

Whole body vibration (WBV) levels associated with logging equipment operation have been shown to exceed standards (Jack and Oliver 2008). These levels have been related to machine type (Neitzel and Yost 2002) or age of the equipment or the manufacturer (Davis and Kotowski 2007, Gerasimov and Sokolov 2009). This exposure has also been linked to the aggressiveness of the operator, with vibration levels in the vertical direction increasing by more than fifty percent with the most aggressive driver as compared to the least (Wegscheid 1994).

Long-term exposure to WBV has been found to contribute to fatigue, central nervous system disturbances, lower back pain and injuries, vision problems, and adverse effects to the digestive and genital/urinary systems (Bovenzi and Hulshof 1999, Neitzel and Yost 2002, Seidel 1993). Extended exposure to WBV has been found to significantly increase the potential for the development of low back pain (Tiemessen et al 2008, Bovenzi and Betta 1994, Bovenzi 1996, NIOSH 1997, Bovenzi and Hulshof 1999). Logging machine operators frequently work shifts in excess of 10 hours (Smidt 2011), and duration of exposure to WBV has been related to low back pain more consistently than the magnitude of the vibration (Bovenzi 1996). These negative health outcomes may explain why after many years in logging, machine operators are not able to maintain high levels of productivity (Synwoldt and Gellerstedt 2003).

Exposure to high levels of noise, those greater than 85 decibels, may contribute to noise induced hearing loss (NIHL). Logging equipment in the U.S.A. typically operated at noise levels



that exceed the OSHA standard's time weighted average (TWA) of 90 dBA for full shift exposure (Neitzel and Yost 2002, Fonseca 2009), and significant hearing loss may be common among equipment operators (Axelsson 1995, Fonseca 2009, Jack and Oliver 2008). Lewark (2005), however, stated based on his review of available research, that noise is only a minor problem for logging machine operators, but that noise levels greater than just 60 dBA could negatively impact operator concentration, mood, heart rate, and blood pressure. Some other research suggests that WBV when combined with noise exposure has a synergistic effect on NIHL (Jack and Oliver 2008, Seidel 1993).

It is generally accepted that logging equipment has improved over the past 20 years, but there is little research in the US quantifying operators' exposure to WBV and noise and improvements based on machine design. There are regulations regarding occupational noise exposure, but there are currently no regulations in the US covering occupational WBV exposure.

Low back pain and hearing loss are prevalent chronic injuries among logging equipment operators (Axelsson 1995, Hagen et al 1998, Neitzel and Yost 2002). With low back pain being repeatedly connected to WBV exposure (Tiemessen et al 2008, Bovenzi and Betta 1994, Bovenzi 1996, NIOSH 1997, Bovenzi and Hulshof 1999) and noise known to cause noise induced hearing loss, these risk factors became the focus of this experiment. The goal of this research was to describe the WBV exposure and occupational noise exposure of US southeastern logging operators.

## **2. Methods**

A research proposal was submitted and accepted by the Internal Review Board at Auburn University, Auburn, Alabama. Twenty-seven logging equipment operators were measured for exposure to noise and WBV. Data were collected on 12 different days over an eight-week period in the summer of 2014 from seven different logging crews. The research involved recruiting logging machine operators for observation on the job for a duration of four or more hours. To be included in the study, a logging crew had to have at least one skidder, one loader, and one feller-buncher in operation on any given day. Some crews had a fourth machine in operation, and in those cases, that operator was also observed. This fourth machine was typically a second wheeled skidder, although one crew was in the process of purchasing a new loader, so one operator was observed in the old loader, and a second was observed in the new loader once it was in use. Crews were chosen based on the logging system used (mechanized rather than manual) and their relative proximity to Auburn, Alabama, U.S.A.

Participants included eleven wheeled skidder operators, seven wheeled feller-buncher operators, and nine loader operators.

Observation included an accelerometer (Larson Davis) placed on the seat of the machine. The device was placed under the ischial tuberosities (“sit bones”) of the operators in accordance with ISO 2631 guidelines. Accelerometer data recorded the vibration exposure of the operator with biodynamic root-mean square acceleration in three mutually perpendicular axes (x, y, and z) in accordance with ISO 2631 – 1 1997. The accelerometer was placed before the shift, and removed after at least four hours of self-reported representative work. Personal noise dosimeters (Cirrus doseBadge) were also used. They were placed on the shoulder of an operator in their hearing zone. The shoulder was selected based on operator preference. The dosimeters were data logging and measured the noise exposure on two channels. The first channel was set to the OSHA permissible exposure limit, which is based on a 90 dBA criterion level, 80dBA threshold level, a 5dBA exchange rate, 115 dBA ceiling, and a slow response. The second channel was set to the ISO European Union standards with an 80 dBA criterion level, a 3 dBA exchange rate, and fast response.

Observations were conducted over multiple days when at least 4 hours of a typical shift for each machine did not occur on the first day. Dosimeters and accelerometers were calibrated pre and post shift, and data was downloaded directly to a personal computer immediately after collection.

At the end of the observation, a body part discomfort scale was administered to participants. The scale lists parts/areas of the body (neck, upper back, lower back, and right and left shoulder, elbow/forearm, wrist/hand, hip/thigh/buttock, knee, ankle/foot), and has the user check the amount of discomfort experienced in that body part/area. The scale went from zero indicating no discomfort, to ten, indicating worst discomfort ever. Participants were also asked to have anthropometric measurements taken. Anthropometric data was necessary to provide appropriate descriptive data on the participants to account for any operator characteristics that might confound analysis of machine characteristics. This took place before the shift and required no more than an hour.

Participants were also asked to complete a survey. The survey was developed to assess worker demographics, frequency of machine use, machine preference, machine age, time spent in particular postures, and neck and back pain experienced over the past year. It included 10 sections with a total of 34 items, taking no more than 30 minutes to complete. Participants were allowed to either complete the survey on their own pre or post shift, or to have it given orally.

### 3. Results and Discussion

Average age of participants was 41 (20-64) with two responses left blank and a standard deviation of 11.2. The average years in logging was 16 (1-40), and average equipment age was 2.5 years (0-10). Most machines were manufactured by John Deere (20). Only 7 were not (4 Caterpillar and 3 Tiger cat). Twenty (74%) of the machines had air suspension seats.

Survey responses were collected for 26 participants (96% response rate), and of those, 96% (24) reported experiencing at least mild neck or back pain over the previous year, and 80% (20) believed that pain was at least in part related to their work in the logging industry. This was consistent with previous research on pain experienced by logging machine operators. In several surveys in Sweden, 40-60 percent of logging machine operators reported experiencing pain or ache in the neck or shoulders over the previous year. Swedish loggers, who have highly mechanized logging processes much like the southern United States, also had very high rates of neck pain and MSDs (Lewark 2005, Synwoldt and Gellerstedt, 2003).

Dosimeter data was collected on all 27 participants. Total dosimeter run time was 251:26:48, with a mean dosimeter run time of 9:10:46. The average TWA was 77.17 dBA (53.9-88.8), but because so many exposures exceeded eight hours, it is more descriptive to look at the Equivalent Continuous Level of noise level recorded (LAeq). When a noise varies over time, the LAeq is the equivalent continuous sound that would contain the same sound energy as the time varying sound. It can be thought of as a type of average, where noisy events have a significant influence. The average LAeq was 82.90 dBA(73.7-88.8) and the average dose based on the ISO EU standard with the more conservative and more widely accepted 3dBA exchange rate was 120.59% (9-371). We found no notable differences in average exposure by machine: feller-buncher 78.24 (58.5-86.5), loader 73.63 (53.9-85.3), and wheeled skidder 79.38 (64.0-88.8).

Total accelerometer run time was 128:45, with an average accelerometer run time of 4:46 per machine (Total/Average, machine = 53:20/4:50, wheeled skidder; 36:05/5:09, feller-buncher; 39:20/4:22, loader). Total average vibration exposure for Aeq(8) across all vectors was 1.05 m/s<sup>2</sup>. All of the average values were above the ISO recommended exposure action limit and above the European Union Directive of 0.5m/s<sup>2</sup> for Aeq(8).

Average Aeq(8) for loaders was found to be 0.64 m/s<sup>2</sup>. There is no current data on vibration exposure from loaders of this type (knuckleboom, trailer mounted), and the values in this small sample were the lowest of the three machines. However, this value is still above the ISO recommended action limit and within the ISO health guidance caution zone. Wheeled feller-bunchers followed with an Aeq(8) at 1.04 m/s<sup>2</sup>. This value is also above the ISO exposure

action limit, and also above the ISO exposure limit value. Wheeled skidders had the highest average whole body vibration exposure at 1.58 m/s<sup>2</sup>. This is above both the ISO exposure action limit and the exposure limit value, it is also the only average that was above the European Union Directive exposure limit value of 1.15m/s<sup>2</sup> Aeq(8).

Table 1: Average equivalent acceleration by machine.

Machine	N	Aeq8	Hours
		Mean (SD)	Mean (SD)
Feller	7	1.04 (0.42)	5.15 (3.39)
Loader	9	0.64 (0.32)	4.37 (2.13)
Skidder	11	1.58 (0.34)	4.85 (2.42)
Skidder*	10	1.49 (0.19)	4.3 (1.68)

\*extreme value removed

An ANOVA was performed to detect possible differences in the mean Aeq8 per machine group. This test was significant ( $p < 0.001$ ). One of the skidder measurements was noticeably higher than others (Aeq8 = 2.455, over 10 hours measured), so another ANOVA was performed after removing this data point, and the test remained significant. Post-hoc tests using the Tukey correction for multiple comparisons indicates that the average skidder Aeq8 level was statistically different from both the feller and loader, but there was no difference between feller and loader.

Although research on WBV and noise exposure in logging equipment in Europe is rather vast, the available research on WBV and noise exposures in the logging industry in the US is still lacking. There have been several studies in North America that measured vibration from typical forest machines, mainly skidders (Cation et al., 2008; Golsse, 1990; Golsse, 1992; Hope and Golsse, 1987; Neitzel and Yost, 2002; Wegscheid, 1994), and there is a general sense that machines have improved over time both in terms of operator comfort and maintenance characteristics (Axelsson 1995).

All average recorded WBV exposures exceeded the ISO 2631 guideline for an eight-hour workday. These exposures are likely impacting operator health and productivity. Operators in this sample reported high rates of neck and back pain. Pain is indicative of possible musculoskeletal issues, a likely result of long term exposure to WBV, especially when combined with the awkward postures, repetitive movements, and frequent jarring common in logging machines. Also, it has been noted that the ISO standard does not take this jarring into account, and underestimates health risks associated when shocks are present (Bovenzi 1996). Operators are frequently encountering shocks from trees, tree stumps, rocks, and sharp changes in the

terrain. So, it is likely the exposure values would be even higher were shocks better incorporated. The roughness of the terrain is also likely to have a large effect on the vibration levels, as well as operator choices in path and speed.

Almost all noise levels were below the action level of 85 dBA, but due to the long hours, almost all operators received more than the ISO EU permissible daily dose. The constant noise over a ten or more hour shift, although not over the limit, would certainly wear on the operators.

Neitzel and Yost (2002) reported high utilization of hearing protection (83.7%) in 2002 among workers in large forestry products companies, but no use of hearing protection was observed during this research. When asked about hearing loss, participants indicated this was not a high priority issue. The lack of use may be related to a lack of hazard recognition or knowledge, and may also have to do with a perception that the use of hearing protection indicates a personal weakness of some kind. Neitzel and Yost (2002) observed large forestry companies while this study observed small logging firms (fewer than 12 employees), which may have contributed to the limited compliance with hearing conservation practices.

A limitation of this study is that sample size was small, but there is no reason to believe that these results are not typical for other full tree harvesting systems utilizing a wheeled skidder, feller-buncher, and loader in the southeastern U.S.A. Another weakness was the fact that observation only took place during one season, so it does not account for any possible seasonal variations in work practices or workload.

#### **4. Conclusion**

As the logging industry moves toward mechanization, we have seen that injury and fatality rates are stable. However there is limited surveillance data to detect increases in musculoskeletal disorder occurrence among logging workers. To make any reasonable progress on reduction in hazard exposure, logging contractors will have to focus on chronic adverse health effects resulting from cumulative exposures. A long term or large population based surveillance is needed to understand whether WBV and noise are problems in southern logging. The larger study should involve the collection of accelerometer and personal noise dosimeter data on many more participants across crews on a variety of machines, with observation over a variety of conditions and seasons.

There is clearly a strong relationship between long-term exposure to WBV and many negative health outcomes (fatigue, central nervous system disturbances, lower back pain and injuries, vision problems, and adverse effects to the digestive and genital/urinary systems).

Several of these would impact productivity, and more importance should be placed on reducing lifetime exposure in logging machine operators. As this exposure takes place over several years, it would be difficult to assess at what point the damage is done. Logging machine operators may not stay with one machine their career. New operators are usually assigned the skidder. With increasing skill and experience those operators may move to the loader or the feller-buncher. The career path could reduce the lifetime vibration exposure, but the health effects may have already taken their toll. Research should be done to see if job shifting during a career as a logging machine operator could mitigate some of the health effects associated with that long-term exposure to WBV.

Hazard control for WBV can be partially accomplished through owner and operator education into the health effects of vibration exposure. Manufacturer's improvement in design may also reduce these exposures. Owners should train operators to balance productivity with slower speeds and avoidance of obstacles, steep rises, or sharp dips in terrain to reduce vibration and jolting and jarring. Owners should also allow and even encourage operators to take frequent short breaks and to change postures while operating as often as possible. The implementation of administrative controls like job rotation and instituted breaks are also options. Those solutions would require more research and education of operators and owners on the costs and benefits of these measures.

All of the machines in this study had average vibration levels recorded that were less than the WBV levels delivered to operators in the research conducted by Neitzel and Yost and reported in 2002. The skidders in this study, despite delivering vibration exposures above recommended limits from both ISO and the EU, still had levels less than those studied by Wegschied (1994). This supports the idea that advancements are being made, but further improvements are still needed. European countries have already implemented regulations for WBV exposure, and it would be prudent for US manufacturers, owners, and operators to reduce the level of WBV exposure as much as practical.

Noise is still an issue in these machines, and long-term exposure can be disabling. It does appear that the exposures are mainly a concern because of the long work hours. Reduced exposure to noise would likely be a benefit with any of the measures aimed at the reduction of WBV exposure. Future efforts should include further investigation into the inclusion of shocks into whole body vibration standards and guidelines and work on a more thorough body of research examining whether or not there are any combined impacts of noise and vibration.

## 5. Literature

- Axelsson, S. 1995. Occupational safety and health in forestry: an international study. Research notes number 280. ISSN 0282-2377.
- Bordas, R. M., Davis, G. A., Hopkins, B. L., Thomas, R. E., and Rummer, R. B. 2001. Documentation of hazards and safety perceptions for mechanized logging operations in east central Alabama. *J. of Agricultural Safety and Health*. 7(2): 113-123.
- Bovenzi, M. 1996. Low back pain disorders and exposure to whole-body vibration in the workplace. *Seminars in Perinatology*. 20(1): 38-53.
- Bovenzi, M. and Betta, A. 1994. Low back disorders in agricultural tractor drivers exposed to whole-body vibration and postural stress. *Appl. Ergonomics*. 25(4): 231-41.
- Bovenzi, M. and Hulshof, C. T. 1999. An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low-back pain (1986-1997). *Int. Arch. Occup. Environ. Health*. 72: 351-365.
- U.S. Bureau of Labor Statistics (BLS). 2013. <http://stats.bls.gov>.
- Cation S, Jack R, Oliver M, Dickey JP, Lee-Shee NK. 2008. Six degree of freedom whole-body vibration during forestry skidder operations. *Intl. J. of Ind. Ergonomics* 38: 739-757.
- Davis, K. G. and Kotowski, S. E. 2007. Understanding the ergonomic risk for musculoskeletal disorders in the United States agriculture sector. *Am. J. Ind. Med.* 50: 501-511
- Fonseca, A. A. 2009. Hearing assessment of forest loggers. Department of Construction Management and Industrial Engineering. Louisiana State University, Baton Rouge. P. 105.
- Gerasimov, Y. and Sokolov, A. 2009. Ergonomic characterization of harvesting work in Karelia. *Croatian J. of Forest Eng.* 30: 159-170.
- Golsse J. M. 1990. Evaluation of skidder seats for reducing whole-body vibration. In: Technical Report: FERIC. 8.
- Golsse J. M. 1992. Ergonomic evaluation of feller-buncher cabs and controls. In: Technical Note: FERIC. 8.
- Hagen, K. B. and Vetlesen, K. 1998. Neck/shoulder and low-back disorders in the forest industry: relationship to work tasks and perceived psychosocial job stress. *Ergonomics*. 41(10): 1510-1518.
- Hope P. A. and Golsse J.M. 1987. Analysis of whole-body vibration levels during skidding. In: Technical Report : FERIC. 22.
- ISO 2631-1: 1997. Mechanical vibration and shock – evaluation of human exposure to whole-body vibration.

- Jack, R. J. and Oliver, M. 2008. A review of factors influencing whole-body vibration injuries in forestry mobile machine operators. *Intl. J. Forest Eng.* 19(1): 51-65.
- Lewark, S. 2005. Scientific reviews of ergonomic situation in mechanized forest operations. Swedish Agricultural University. Uppsala. ISSN 1651-114X Number 2. Institutionen för skogens produkter och marknader.
- Lynch, S. M., Smidt, M. F., Merrill, P. D., and Sesek, R. F. 2014. Incidence of MSDs and neck and back pain among logging machine operators in the Southern U.S. *Journal of Ag Safety and Health* 20(3): 211-218.
- National Institute of Occupational Safety and Health. 1997. Musculoskeletal disorders and workplace factors: a critical review of epidemiological evidence for work-related musculoskeletal disorders of the neck, upper extremity and low back. NIOSH, DHHS Publication number 97-141.
- Neitzel R, Yost M. 2002. Task-based assessment of occupational vibration and noise exposures in forestry workers. *AIHA J (Fairfax, VA)*. 63:617-627.
- Roberts, T., Shaffer, R. M., and Bush, R. J. 2005. Injuries on mechanized logging operations in the southeastern United States in 2001. *Forest Prod. J.* ISSN: 0015-7473.
- Seidel, H. 1993. Selected health risks caused by long-term, whole-body vibration. *Am. J. Ind. Med.* 23: 589-604.
- Shan, X., Ning, X., Chen, Z., Ding, M., Shi, W., and Yang, S. 2013. Low back pain development response to sustained trunk axial twisting. *European Spine J.* DOI 10.1007/s00586-013-2784-7. [www.springerlink.com](http://www.springerlink.com).
- Smidt, M. F. 2011. A description of forest industries and forest occupations with focus on forestry workers' jobs and injury and illness surveillance. 34th Council on Forest Engineering Annual Meeting. Session 1. June 13.
- Stansfeld, S. A. and Matheson, M. P. 2003. Noise pollution: non-auditory effects on health. *British Medical Bulletin.* 68: 243-257.
- Synwoldt, U. and Gellerstedt, S. 2003. Ergonomics initiatives for machine operators by the Swedish logging industry. *Applied Ergonomics.* 34:149-156.
- Tiemessen, I. J. H., Hulshof, C. T. J., and Frings-Dresen, M. H. W. 2008. Low back pain in driver exposed to whole body vibration: an analysis of a dose-response pattern. *Occup. Environ. Med.* 65: 667-675.
- Wegscheid E. 1994. Another look at skidder ride vibration. *J. of Forest Eng.* 5:21-32.



# Exposure of Mobile Chipper Operators to Wood Dust and Diesel Exhaust

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The current boom of forest biomass is making chippers increasingly popular among forest operators. This motivates concern about the potential exposure of chipper operators to wood dust and diesel exhaust, both recognized cancer agents. However, no studies have yet determined the exposure of chipper operators to wood dust and diesel exhaust (PAHs, BTEX) which makes it difficult to estimate the level of occupational hazard and suggest suitable countermeasures. This study surveyed both industrial and small-scale chipping operations, conducted in the northern Apennine. During the survey 60 samples were collected using standardized methods. For the purpose of the tests, each operator carried wearable active samplers connected to suction pumps, as well as passive samplers. When operators sat inside an enclosed cab, samples were also collected outside the cab in order to gauge the effectiveness of a protected work station. Exposure to dust varied widely with wood conditions and operation type, and it occasionally exceeded the 5 mg/m<sup>3</sup> legal limit. Operators working inside a cab were three times less exposed than operators working outside, and they were never exposed to concentrations exceeding the legal limit. In contrast, we could not detect any measurable exposure to BTEX, while exposure levels for PAHs were very low. PAH concentration was significantly higher inside cabs than outside. None of the operators involved in this research was exposed to BTEX or PAHs above occupational exposure limits

**Keywords:** biomass; forestry; chipper operators

## 1. Introduction

In recent years, interest in replacing fossil fuels with renewable energy sources has increased throughout the world (Krausmann et al. 2008, Vasco and Costa 2009, Hall and Scarse 1998, Nurmi 2007).

Chipping is a fundamental process of all energy wood chains because renders the wood material into homogeneous particles suitable for automated heating plants (Strehler 2000). It also reduces the apparent volume of forest residues, facilitating handling and transportation (Angus-Hankin et al. 1995, Pottie and Guimier 1985).

The growing interest in forest biomass is making mobile chippers increasingly popular, launching a trend towards even larger industrial machines (Spinelli and Magagnotti 2010).

It is already known that the working environment in logging operations can be very dusty (Mitchell 2011) and chipping process generates a quite considerable quantity of wood fines.

Hardwood dust and diesel exhaust are considered as cancer agents by the International Agency for Research on Cancer (IARC 1995, IARC 2012). This justifies concern about the potential exposure of mobile chipper operators to wood dust and diesel engine exhaust.

It is extremely important to determine exposure to wood dust because high exposure levels can cause occupational diseases (Moscato et al. 2002) and the irritant effect of wood dust is well documented (Senear 1933, Woods and Calnan 1976, ILO 1983). The most common effects involve the respiratory tract and the eyes (Holness et al. 1985, Li et al. 1990, Pisanello et al. 1991, Liou et al. 1996)

In Italy, the legal limit for the exposure to inhalable fraction of wood dust is 5 mg/m<sup>3</sup> for hardwood or any mixture of hard and softwood (D.Lgs. 81/2008), in line with European Directive 38/1999, based on an 8-hour working day.

However, upper airway symptoms may manifest at exposure levels as low as 1 mg/m<sup>3</sup> (Foà et al. 2008), which is also the recommended exposure limit according to the US National Institute for Occupational Safety and Health (NIOSH).

Exhaust gas of diesel engines contains many chemical compounds in gaseous and particulate form (Groves and Cain 2000, Sydbom et al. 2001, Kagawa 2002, Penconek et al. 2013), influenced by fuel quality, motor technology and motor maintenance (Rogge et al 1993, Jones et al 2004, Maricq 2007, Nelson et al. 2008, Valle-Hernandez et al. Zhang et al. 2011, Su et al. 2004, Burtscher 2005). Improved motor design and fuel composition have caused a reduction in diesel motor emissions (Olsson et al. 2011, Ono-Ogasawara and Smith 2004), but these are still potentially dangerous. The size of particulate and gases produced by diesel engines is small enough to enter the respiratory tract (Zaebst et al. 1991, Moskal et al. 2006) and the brain through the olfactory nerves (Oberdörster et al. 2004). This is true of benzene, toluene, ethylbenzene and xylenes (BTEX) and polycyclic aromatic hydrocarbons (PAHs). Exposure to exhaust gas may have immediate effects, such as nausea, coughing and migraine (Rudell et al. 1999, Reger et al. 1982). Long-term exposure has negative effects on the cardiovascular and respiratory systems (Langrish et al. 2011, Fujeda et al. 1998, Pandya et al 2002, Dockery and Pope 1994).

The exposure of chipping operators to wood dust, PAHs and BTEX has never been studied. This makes it difficult to estimate occupational risk and suggest measures to avoid and minimise risk.

The aims of this research were:

- 1) to determine the exposure of mobile chipper operators to wood dust, PAHs and BTEX;
- 2) to verify if exposure differed between industrial and small-scale operations;
- 3) to measure possible abatement of exposure afforded by placing the operator inside an enclosed cab;
- 4) to check for any correlations between exposure levels and other measurable operational factors (wood moisture content, air humidity, chipper productivity, fuel consumption, mean chip length and percent incidence of fine particles in the chip product..

## 2. Materials and methods

The research was conducted on 28 commercial chipping operations in the northern Apennine ranges of Central Italy. Two types of chippers were tested: powerful industrial chippers (300-400 kW) used by professional operators and small-scale chippers (100-150 kW) for non-continuous use.

Industrial operations included both truck-mounted and forwarder-mounted chippers working at landing and fed with a knuckleboom loader (Figure 1). A single operator, sitting inside an enclosed cab, steered the machine.

Figure 1. Examples of typical industrial operation: chipper truck and truck-mounted chipper steered by a single operator sitting inside the enclosed cab



Small-scale operations were equipped with tractor-powered and tractor-towed chippers with a crew of two or three operators who worked near the chipper infeed opening (Figure 2). In most cases, a loader was assisting the feeding and moved the wood from the stacks to the edge of the infeed opening, where operators picked it up and pushed it in.

Figure 2. Small-scale chippers fed manually or by hydraulic grapple



The study included 179 samplings: 60 for wood dust (41 of which were personal samples), 59 for BTEX (40 personal) and 60 for PAHs (41 personal). The duration of each sampling session ranged between 3 and 8 hours.

During the tests, chipper operators wore different specific samples to collect the inhalable fraction of wood dust and to measure exposure to BTEX and PAHs.

The wood dust sampler was an active SKC button sampler connected by transparent flexible tube to a Gilian 5000 pump set at a flow of 4 l/min. The sampler was in steel and had a porous curved-surface inlet designed to improve the capacity to collect inhalable dust, and the same time, to avoid access to oversize “projectile” particles thrust toward the samples. Collection of such particles would bias the sampling because they are too heavy for being inhaled with the respiration. The sampler contained a fibreglass membrane that intercepted any wood dust aspirated by the pump through the holes in the shield.

Exposure to BTEX was determined with a Radiello® passive personal sampler and exposure to PAHs was measured with a two-stage active IOM sampler with teflon membrane and XAD2 amberlite phial connected to a Gilian 5000 pump set at 2 l/min.

On industrial operations, the selectors were worn by the operator inside the cab and a second complete set was mounted outside the cab, where the operator would be if the machine was not fitted with a cab (figure 3). This was done to quantify the protection afforded by the cabin in terms of reduction of exposure to wood dust and exhaust gas.

Figure 3: The operator wore a set of samplers and another set was mounted outside the cabin (bag on upper right)



On small-scale sites, all operators involved in chipping wore a sampling unit.

The portable pumps were attached to the worker's belt and the samplers were placed to a distance of 10 cm from the operator's face, to the right or to the left depending on whether the operator was right-handed or left-handed.

During sampling, the pumps were periodically checked for correct functioning and position of the devices.

During each test, a portable weather station was used to record air temperature, air humidity and air pressure.

Machine productivity and fuel consumption were determined with suitable time studies (Magagnotti and Spinelli 2012). Special attention was paid to separated work time from delay time, when the engine may be turned off. Quantity of chips produced during each test was determined by measuring all chips loads with a certified weighbridge. Chip samples were collected to determine moisture content and particle size distribution.

At the end of each sampling, the Radiello cartridge and the pump membranes were removed and placed in their containers. On reaching the office and before sending them to the laboratory, the membranes for wood dust were further shielded and stored in a dry place, whereas the exhaust gas samplers were placed in a freezer.

Between one sampling and the next, the pumps were recalibrated with a reference flow meter to correct any changes in performance and maintain the flow at 4 l/min for wood dust and 2 l/min for exhaust gas.

Data were statistically analysed using Statview for Windows (SAS 1999)

### 3. Results

The study highlighted a significant difference between operation types, in terms of productivity and fuel consumption. Compared to small-scale operations, industrial operations were 5.6 times as productive and used 3.5 times as much as fuel per hour. Fuel consumption per unit product was 37% lower for industrial operations.

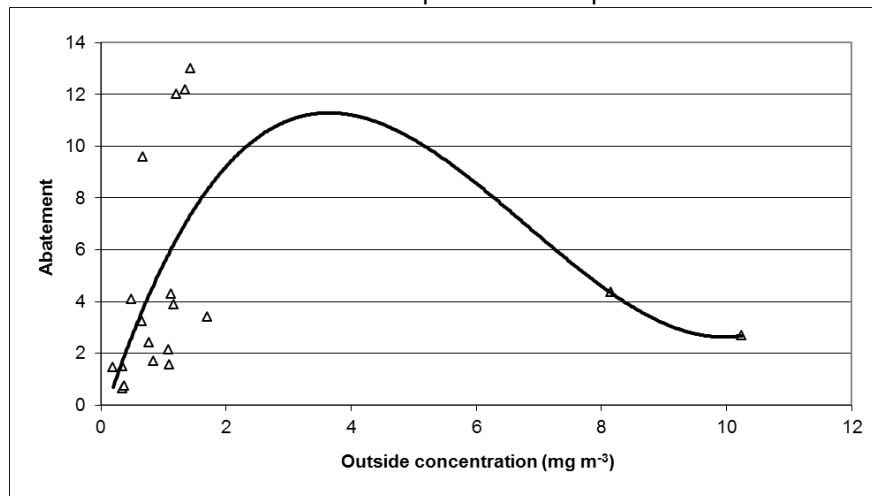
Table 1 shows values of exposure to wood dust in both operations. The maximum limit of 5 mg/m<sup>3</sup> was only exceeded twice, during industrial operations and outside the protected cab environment.

Table 1 – Mean, minimum and maximum values of exposure to wood dust

	Small-scale	Industrial	
		External	Internal
	mg/m <sup>3</sup>	mg/m <sup>3</sup>	mg/m <sup>3</sup>
Mean exposure	1.08	1.75	0.57
Minimum exposure	0.22	0.19	0.07
Maximum exposure	3.66	<b>10.24</b>	3.83
Standard deviation	0.89	2.68	0.89

The cab sharply reduced exposure to wood dust and operators working inside a cab were three times less exposed the operators working outside. It was interesting to observe that the protective effect of the cab seemed to increase with the concentration of wood dust outside, up to a certain point, above which it fell sharply (Figure 4).

Figure 4. The protective effect of the cab seems to increase with the concentration of wood dust outside the cab up to a certain point



The concentration of wood dust outside the cabin was related to wood moisture content and productivity. As expected, the concentration of wood dust increased with productivity and decreased with moisture content. For the same moisture content, industrial operations produced more wood dust than small-scale operations, due to the greater quantity of material chipped per unit time. Fortunately, most of the operators on industrial sites work inside a cab. Operators on small-scale operations were more exposed to wood dust. In most cases, they do not work full time with the chipper but alternate chipping with other tasks.

On all operations, concentrations of BTEX and PAHs were well below legal limits (Table 2). In samples obtained outside the cab, BTEX were always below quantification limits. Carcinogenic PAHs in personal samples were always below quantification limits, whereas in two environmental samples concentrations were extremely low. The hydrocarbons that more often exceeded quantification limits were naphthalene, fluorene and phenanthrene.

Table 2 Exposure to PAHs and naphthalene in exhaust gas

	PAHs	naphthalene
	µg m-3	µg m-3
<b>Small-scale operations</b>		
Mean exposure	0.207	0.159
Standard deviation	0.241	0.203
Minimum exposure	0.009	0.000
Maximum exposure	0.814	0.664
<b>Industrial operations – external</b>		
Mean exposure	0.131	0.067
Standard deviation	0.158	0.106
Minimum exposure	0.006	0.000
Maximum exposure	0.508	0.348
<b>Industrial operations – internal</b>		
Mean exposure	0.434	0.281
Standard deviation	0.373	0.323
Minimum exposure	0.012	0.000
Maximum exposure	1.354	1.227

The highest PAH levels were measured inside the cab and exposure values were higher in winter, when it was necessary to turn on the cab heating. Exhaust gas may have entered through the heating system or been trapped in the cabin due to poor ventilation. The finding could also have depended on a combination of factors, such as air fresheners, detergents, fluids or spare parts kept inside the cab.

#### 4. Conclusions

The results were generally encouraging. No operator was exposed to concentrations of wood dust, PAHs or BTEX above the current legal limits. Exposure to benzene and PAHs was practically zero, whereas for wood dust it was quantifiable and this aspect should be considered when choosing the type of chipper and in planning work sites. Measures to reduce exposure to wood dust should not only concern the chipping operation but also maintenance. Technological development of motors and good maintenance play an important role in reducing exposure to PAHs and BTEX. Protection against PAHs, BTEX and wood dust should be a priority, since these substances are not only irritants but also dangerous carcinogens that can cause severe occupational diseases.

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#### 5. References

- Angus-Hankin, C., B. Stokes, and A. Twaddle. 1995. The transportation of fuel wood from forest to facility. *Biomass Bioenerg.* 9:191-203
- Burtscher H. 2005. Physical characterization of particles emissions from diesel engines: a review. *J Aerosol Sci.* 36:896-932
- Dockery D.W., C.A.Pope. 1994. Acute respiratory effects of particulate air pollution. *Ann. Rev. Publ. Health* 15:107-32
- Foà V., P.E. Cila, I. Martinotti, and P.A. Bertazzi. 2008. Esposizione a polveri di legno: la valutazione delle SCOEL (Scientific Committee on Occupational Exposure Limits). In "Polveri di legno: salute e sicurezza" Edizioni CIMAL ISBN 978-88-902124-3-7, 63-68
- Fujieda S., D. Diaz-Sanchez, and A. Saxon. 1998. A combined nasal challenge with diesel exhaust particles and allergen induces in vivo IgE isotype switching. *Am. J. Respir. Cell. Mol. Biol.* 19:507-512
- Groves J., J.R. Cain. 2000. A survey of exposure to diesel engine exhaust emissions in the workplace. *Ann. Occup. Hyg.* 44:435-447
- Hall D.O., J.I. Scarse. 1998. Will biomass be the environmentally friendly fuel of the future? *Biomass Bioenerg.* 15:357-367



- Holness D.L., A.M. Sass-Kortsak, C.W. Pilger, and J.R. Nethercott. 1985. Respiratory function and exposure-effect relationships in wood dust-exposed and control workers. *J. Occup. Med.* 27:501-506.
- IARC. 2012. Diesel and gasoline engine exhaust and some nitroarenes. Press release 213. Available from [http://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213\\_E.pdf](http://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf) (accessed 25 Mar 2013)
- IARC. 1995. IARC Monographs on the Evaluation of Carcinogenic Risks to Human, vol 62 Wood dust and formaldehyde. Lyon:IARC
- ILO. 1983 -Woods. In: *Encyclopaedia of Occupational Health and Safety*. vol. II, pp. 2308-2316. International Labour Organization, Geneva.
- Jones C., A. Chughtai, B. Murugaverl, and D. Smith. 2004. Effects of air/fuel combustion ratio on the polycyclic aromatic hydrocarbon content of carbonaceous soot from selected fuels. *Carbon.* 42:2471-84
- Kagawa J. 2002. Health effects of diesel exhaust emissions – a mixture of air pollutants of worldwide concern. *Toxicology.*181-182:349-53
- Krausmann F., K.H. Erb, S. Gingrich, C. Lauk, and H. Haberl. 2008. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecol. Econ.*65: 471-487
- Langrish J.P., X. Li, S. Wang et al. 2012. Reducing personal exposure to particulate air pollution improves cardiovascular health in patients with coronary heart disease. *Environ. Health Perspect.* 4120(3):367–72
- Li D., L. Yuan, S. Yi, and Z. Jiang. 1990. Effects of wood dust exposure on respiratory health: cross-sectional study among farmers exposed to wood dust. *Am. J. Ind. Med.* 17:84-85.
- Liou S.H., S.Y. Cheng, F.M. Lai, and J.L. Yang. 1996. Respiratory symptoms and pulmonary function in mill workers exposed to wood dust. *Am. J. Ind. Med.* 30:293-299
- Magagnotti N., R. Spinelli (editors). 2012. COST Action FP0902: good practice guideline for biomass production studies. Florence, Italy: CNR IVALSA. 41 p. ISBN 978-88-901660-4-4. Available online <http://www.forestenergy.org/openfile/329>
- Maricq M. 2007. Chemical characterization of particulate emissions from diesel engine: A review. *J. Aerosol Sci.* 38:1079-1118
- Mitchell D. 2011. Air quality on biomass harvesting operations. Proceedings of the 34th Council on Forest Engineering annual meeting, Quebec City, Quebec, Canada, June 2011. 9pp ([http://www.srs.fs.usda.gov/pubs/ja/2011/ja\\_2011\\_mitchell\\_001.pdf](http://www.srs.fs.usda.gov/pubs/ja/2011/ja_2011_mitchell_001.pdf))

- Moscato G., A. Della Bianca P. Maestrelli, P. Paggiaro, C. Romano, R. De Zotti, A. Marabini, S. Voltolini, et. al. 2002. Features and severity of occupational asthma upon diagnosis: an Italian multicentric review. *Allergy* 57:236-242
- Moskal A., L. Makowski, T.R. Sosnowski et al. 2006. Deposition of fractal-like aerosol aggregates in a model of human nasal cavity. *Inhal Toxicol.* 18:725-731
- Nelson P., A. Tibbett, and S. Day. 2008 Effects of vehicle type and fuel quality on real world toxic emissions from diesel vehicles. *Atms. Environ.* 42:5291-5303
- Nurmi J. 2007. Recovery of logging residues for energy from spruce (*Picea abies*) dominated stands. *Biomass Bioenerg.* 31:375-380
- Oberdörster G., Z. Sharp, V. Aturei et al. 2004. Translocation of inhaled ultrafine particles to the brain. *Inhal Toxicol.* 16:389-399
- Olsson A.C, P. Gustavsson, H. Kromhout et al. 2011. Exposure to diesel motor exhaust and lung cancer risk in a pooled analysis from case-control studies in Europe and Canada. *Am. J. Respir. Care Med.* 183:941-948
- Ono-Ogasawara M., T.J. Smith. 2004. Diesel exhaust particles in the work environment and their analysis. *Ind. Health.* 42(4): 389-399
- Pandya R.J., G. Solomon, A. Kinner, and J.R. Balmes. 2002. Diesel exhaust and asthma: hypothesis and molecular mechanisms of action. *Environ. Health Perspect.* 110(1):103-113
- Penconek A., P. Drążyk, and A. Moskal. 2013. Penetration of diesel exhaust particles through commercially available dust half masks. *Ann. Occup. Hyg.* 57:360-373
- Pisaniello D.L., K.E. Connell, and L. Muriale. 1991. Wood dust exposure during furniture manufacture - results from an Australian survey and considerations for threshold limit value development. *Am. Ind. Hyg. Assoc. J.* 52(11):485-492
- Pottie, M. and D. Guimier. 1985. Preparation of forest biomass for optimal conversion. *FERIC Special Report SR-32, Pointe Claire, Canada.* 112 p.
- Reger R., J. Hancock, J. Hankinson et al. 1982. Coal miners exposed to diesel exhaust emissions. *Ann. Occup. Hyg.* 26:799-815
- Rogge W.F., L.M. Hildemann, M.A. Mazurek, G.R. Cass, and B.R.T. Simoneit. 1993. Sources of fine organic aerosol. Noncatalyst and catalyst-equipped automobiles and heavy-duty diesel trucks. *Environ. Sci. Technol.* 27:6366-51
- Senear F.E.1933. Dermatitis due to woods. *J. Am. Med. Assoc.* 101:1527-1532.
- Spinelli R. and N. Magagnotti. 2010. A tool for productivity and cost forecasting of decentralized wood chipping. *Forest Policy Econ.* 12 :194-198
- Strelher A. 2000. Technologies of wood combustion. *Ecol. Eng.* 16: 25–40.

- Sydbom A., A. Blomberg, S. Parnia, N. Stenfors, T. Sandström, and S.E. Dahlén. 2001. Health effects of diesel exhaust emissions. *Eur. Respir. J.* 17:733-46
- Su D.S., J.O. Müller, Jentoft et al. 2004. Fullerene-like soot from Euro IV diesel engine: consequences for catalytic automotive pollution control. *Topics in Catalysis*; 30/31:241-245
- Valle-Hernandez B.L., O. Amador Muñoz, A. Jazcilevich-Diamant, A.E Hernández-López, R. Villalobos-Pietrini, and R. Gonzàles-Oropeza. 2013. Polycyclic Aromatic Hydrocarbons in particulate matter emitted by the combustion of diesel and biodiesel. *Combust. Sci. Technol.* 185:420-434
- Vasco H., and M. Costa. 2009. Quantification and use of forest biomass residues in Maputo province, Mozambique. *Biomass Bioenerg.* 33:1221-1228
- Woods B., and C.D. Calnan. 1976. Toxic Woods. *Br. J. Dermatol.* 95 (13) 1-97.
- Zaebst D.D., D.E. Clapp, L.M. Blade et al. 1991. Quantitative determination of trucking industry workers' exposures to diesel exhaust particles. *Am. Ind. Hyg. Assoc. J.* 52(12):529-541
- Zhang J., K. He, X. Shi et al. 2011. Comparison of particle emissions from engine operating on biodiesel and petroleum diesel. *Fuel.* 90:2089-2097

### **XIII. Concurrent Session 5B – Productivity of Logging Operations III**

#### **Analysis on Economic Balance of a Clear Cutting Operation with Terrestrial LiDAR at Funyu Experiment Forest of Utsunomiya University, Japan**

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The present study applied terrestrial LiDAR with an optimal bucking algorithm to Japanese cypress and Japanese cedar at the Funyu experimental forest, Utsunomiya University, Japan. The root mean squared errors (RMSEs) between small end diameters of logs that were obtained below 10 m and measured using manual and terrestrial LiDAR were within 2 cm. Log diameters were normally rounded to 2 cm; therefore, the RMSEs were within allowable ranges. However, RMSEs were increased according to an increase in small end heights because of branches. Furthermore, the understory vegetation also disrupted laser scanning. The economic balance considering sweep from terrestrial LiDAR was estimated. As a result, the profit was estimated to be 177,511 yen, which was close to that estimated by manually measured data, at 195,500 yen. Without considering sweep, profit was overestimated as 214,175 yen. The use of an optimal bucking algorithm improved the profit to 233,576 yen (USD1 = 119 yen).

**Keyword:** Optimal bucking algorithm, Small end diameter of log, Sweep

#### **1. Introduction**

LiDAR technology is commonly used to obtain basic information about terrain and vegetation. Airborne LiDAR can measure crown surfaces and calculate the height and number of trees. Stem volumes and stand volumes can then be estimated using data including crown volume, tree height, and the number of trees (Ito et al, 2011). However, airborne LiDAR cannot directly measure stem shape and volumes (Kato et al. 2014). In contrast, terrestrial LiDAR has been used to obtain detailed descriptions of stem shape such as taper, sweep, and lean (Murphy et al. 2010). The present study applied terrestrial LiDAR with an optimal bucking algorithm (Nakahata et al. 2014) to Japanese cypress (165 logs from 24 stems) and Japanese cedar (18 logs from two stems) at the Funyu experimental forest, Utsunomiya University, Japan.

## 2. Materials and Methods

Study sites included 32- and 62-year-old Japanese cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*), which are major plantation species in Japan (Figure 1, Photo 1). Areas measured by terrestrial LiDAR (Photo 2) were 0.71 ha and 0.37 ha in size, and contained 1,138 and 441 trees in 32- and 62-year-old forests, respectively. Therefore, stand densities were 1,603 stems/ha and 1,192 stems/ha. Average DBH, height, and branch height were 18.79 cm, 16.08 m, and 5.8 m in the 32-year-old forest and 26.08 cm, 22.69 m, and 13.5 m in the 62-year-old forest. DBH, height, and diameters at 4- and 6-m heights were measured and compared with terrestrial LiDAR data obtained for 63 trees and 58 trees from 32- and 62-year-old forests, respectively (Table 1 and 2).

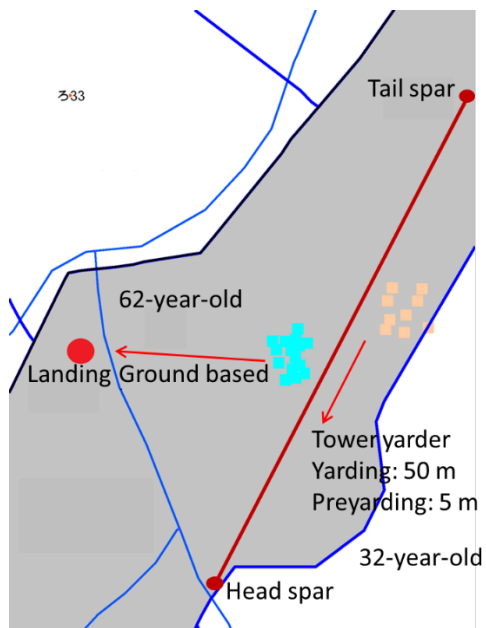


Figure 1 Study sites



Photo 2 Terrestrial LiDAR



Photo 1 Study sites (Left: 32-year-old, Right: 62-year-old)

Table 1 DBH and Height

	No.		Average		Error		RMSE	
	DBH	Height	DBH (cm)	Height (m)	DBH (cm)	Height (m)	DBH (cm)	Height (m)
32-year-old	63	63	18.79	16.08	-0.34	0.41	1.33	2.29
62-year-old	58	58	26.08	22.69	0.47	0.68	1.35	1.41
Total	121	121	22.28	19.25	0.05	0.54	1.34	1.92

xTable 2 Diameters at 4- and 6-m heights

	No.		Average		Error		RMSE	
	4 m	6 m	4 m (cm)	6 m (cm)	4 m (cm)	6 m (cm)	4 m (cm)	6 m (cm)
32-year-old	60	55	16.17	14.76	-0.61	-1.08	1.28	1.97
62-year-old	55	51	23.39	22.59	-0.03	0.05	1.11	1.20
Total	115	106	19.59	18.52	-0.33	-0.53	1.20	1.65

Time studies of a clearcutting operation were conducted in the 62-year-old forest (Figure 1). In total, 114 logs from 15 stems were extracted by a ground based system, which included the use of chainsaw felling, processor processing, and grapple loader piling. Additionally, 62 logs were extracted from 10 stems by a tower yarder (Table 3, Photo 3). The average yarding and preyarding distances were 50 m and 5 m, respectively. Productivity and costs were estimated based on results obtained from the time studies. Revenues were estimated using a price list that included length, sweep class, and diameter at a log auction market (Table 4). Sweep classes were classified by the ratio of sweep to small end diameters, including 12% for A, 12–20% for B, and 20% for C.

Table 3 Study sites in a clearcutting operation

	No. Stem	No. Log	Log volume (m <sup>3</sup> /log)
Ground based	15	114	0.082
Tower yarder	10	62	0.099
Total	25	176	0.088



Photo 3 Forestry machines (Left: tower yarder, middle: processor, right: grapple loader)

### 3. Results

Average errors (manually–LiDAR) of DBH and height were -0.34 cm and 0.42 m in the 32-year-old forest, and 0.47 cm and 0.68 m in the 62-year-old forest, respectively (Table 1, Figure 2). Root mean square errors (RMSEs) of DBH and height were 1.33 cm and 2.29 m in the 32-year-old forest, and 1.35 cm and 1.41 m in the 62-year-old forest, respectively. Log diameters were normally rounded to 2 cm; therefore, RMSEs of DBH were within allowable ranges. The RMSE of height in the 32-year-old forest was higher than that in the 62-year-old forest because of higher stand density.

Table 4 Price list

Japanese cypress				Japanese cedar			
Length (m)	Sweep class	Diameter (cm)	Price (yen/m <sup>3</sup> )	Length (m)	Sweep class	Diameter (cm)	Price (yen/m <sup>3</sup> )
2	A	6–14	3,000	2	A	6–14	2,800
		16–28	14,890			16–	6,980
		30–	33,000			B	6–14
	B	6–14	3,000		C	6–	2,800
		16–	6,890			6–	2,800
		6–	2,800			3	A
3	A	11–14	11,240	16–20	14,780		
		16–	20,583	22–28	13,300		
		B	6–14	2,800	B	6–28	2,800
16–28	17,760		30–	5,000			
C	6–		2,800	C		6–	2,800

4	A	10–14	17,090	3.65	A	22–28	12,200
		16–20	19,000			30–	13,820
		22–	25,800	4	A	22–28	15,480
						30–	14,660

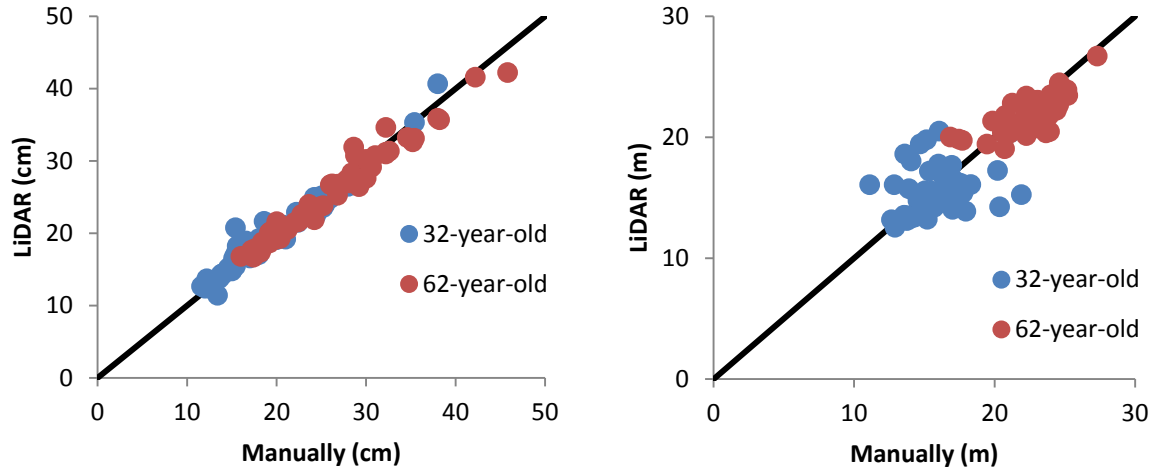


Figure 2 Results of DBH (left) and height (right)

Diameters of 63 and 58 trees at 4- and 6-m heights in the 32- and 62-year-old forests were measured manually. However, terrestrial LiDAR only detected diameters of 60 and 55 trees at 4- and 6-m heights in the 32-year-old forest, and 55 and 51 trees at 4- and 6-m heights in the 62-year-old forest due to the presence of branches, especially at 6 m (Table 2, Figure 3). Average errors of diameters at heights of 4 and 6 m were -0.61 cm and -1.08 cm in the 32-year-old forest, and -0.03 cm and -0.05 cm in the 62-year-old forest. RMSEs of diameters at 4 and 6 m were 1.28 cm and 1.97 cm in the 32-year-old forest, and 1.11 cm and 1.20 cm in the 62-year-old forest. RMSEs of measurements from the 32-year-old forest were higher than those from the 62-year-old forest. However, both RMSEs were still within allowable ranges.



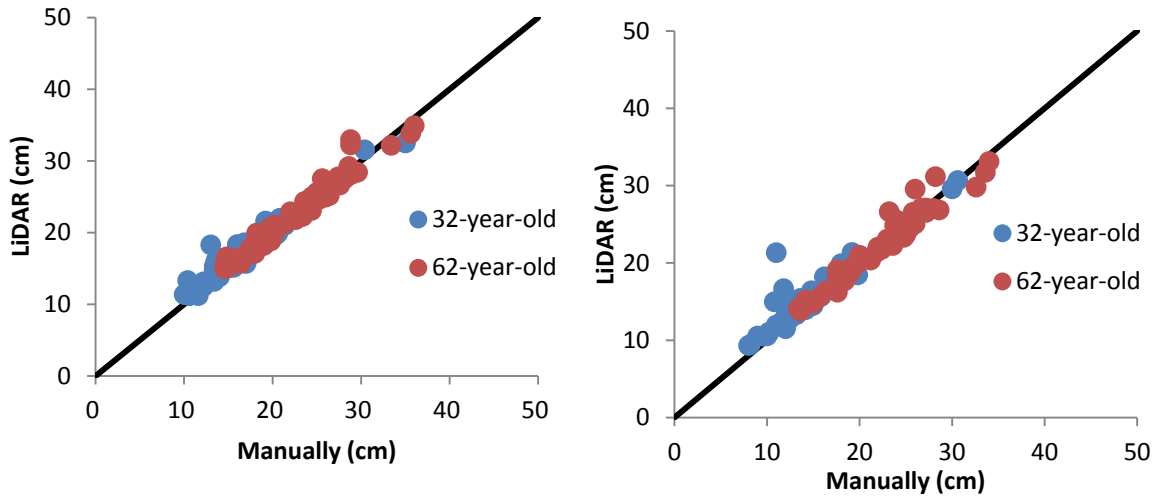


Figure 3 Results of diameters at 4- (left) and 6-m (right) heights

The small end diameters, sweep, and ratio of sweep to the small end diameter of 176 logs were measured manually. However, terrestrial LiDAR only detected 150 logs (Table 5). The average error of small end diameters was -1.85 cm and RMSEs were 3.33 cm. RMSEs were beyond allowable ranges. Errors and RMSEs increased with increasing small end heights because of branches (Figure 4). Furthermore, understory vegetation also disrupted laser scanning. Therefore, RMSEs below 5-m small end heights were higher than those between 5 and 10-m small end heights, especially sweep (Figure 5).

Table 5 Results of small end diameter, sweep, and ratio according to heights

Height	Manual Logs	LiDAR Logs	Small end diameter (cm)			Sweep (cm)			Ratio (%)		
			Average	Error	RMSE	Average	Error	RMSE	Average	Error	RMSE
- 5 m	32	32	22.83	-0.37	1.55	2.50	0.15	1.39	11.40	1.15	6.80
- 10 m	40	40	20.38	-0.75	1.43	1.04	-0.46	0.78	5.29	-1.85	3.71
- 15 m	38	33	16.63	-2.37	3.80	1.14	-1.50	2.60	7.03	-6.62	12.06
- 20 m	53	40	12.51	-3.44	4.46	1.38	-2.31	3.34	12.00	-11.38	17.52
20 m -	13	5	8.16	-4.02	6.88	1.68	-2.65	3.55	21.74	-12.43	15.17
Total	176	150	16.74	-1.85	3.33	1.48	-1.12	2.34	10.01	-5.15	11.62

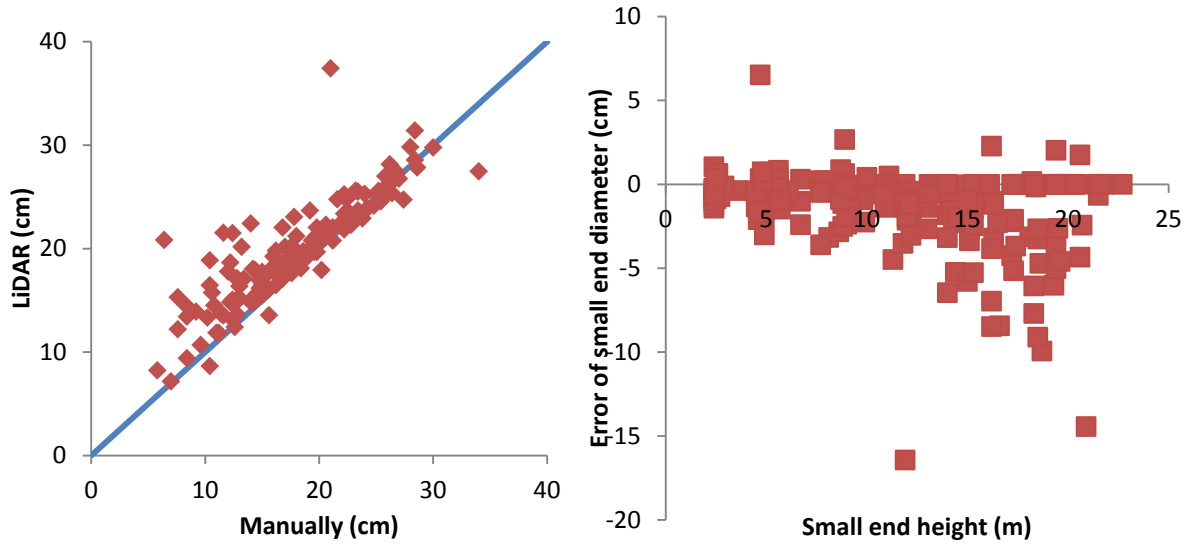


Figure 4 Results (left) and errors (right) of small end diameters

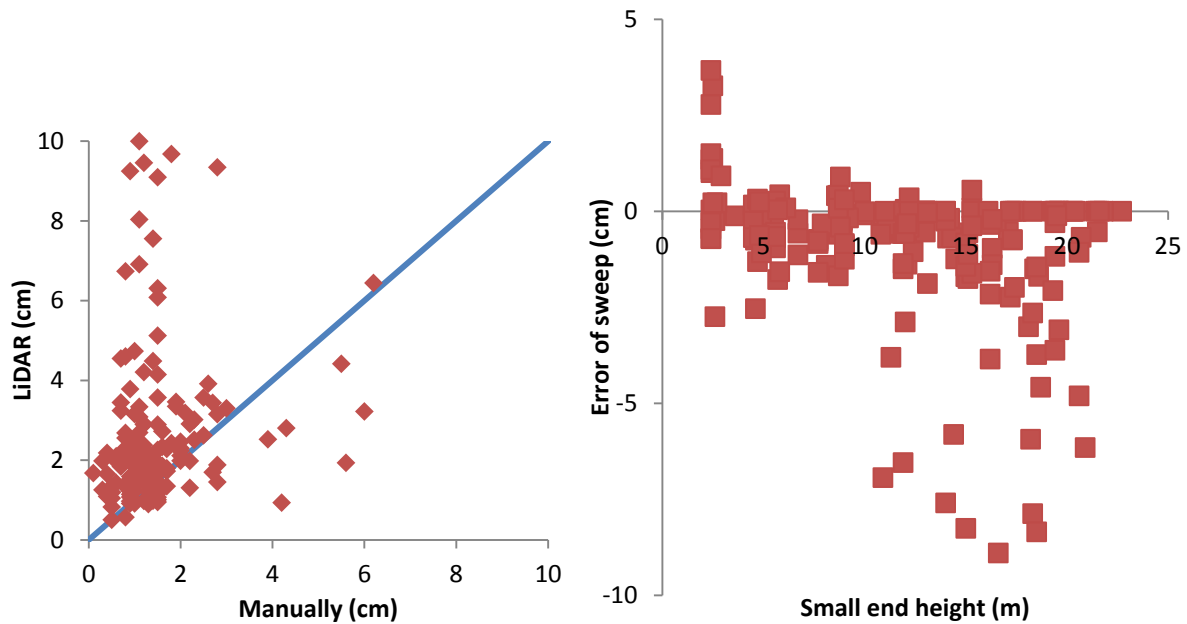


Figure 5 Results (left) and errors (right) of sweep

Logs were bucked into 14 4-m logs, 74 3-m logs, and 88 2-m logs (Figure 6). However, terrestrial LiDAR detected 14 4-m logs, 72 3-m logs, and 64 2-m logs. Terrestrial LiDAR could not detect two 3-m logs and 24 2-m logs. The 2-m logs were bucked from the bottom and top of trees for which laser scanning was disrupted by the understory and branches (Figure 7).

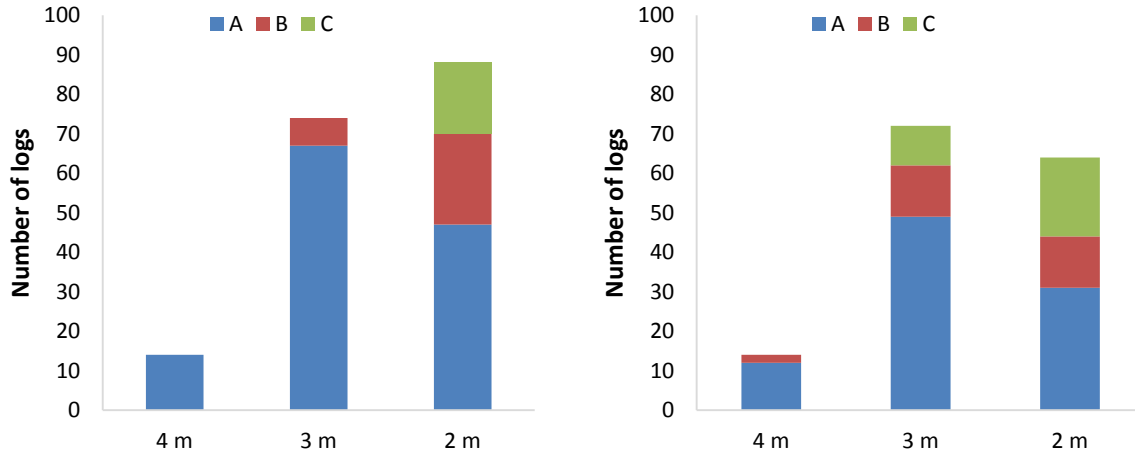


Figure 6 Sweep class distribution (left: manually measured, right: terrestrial LiDAR)

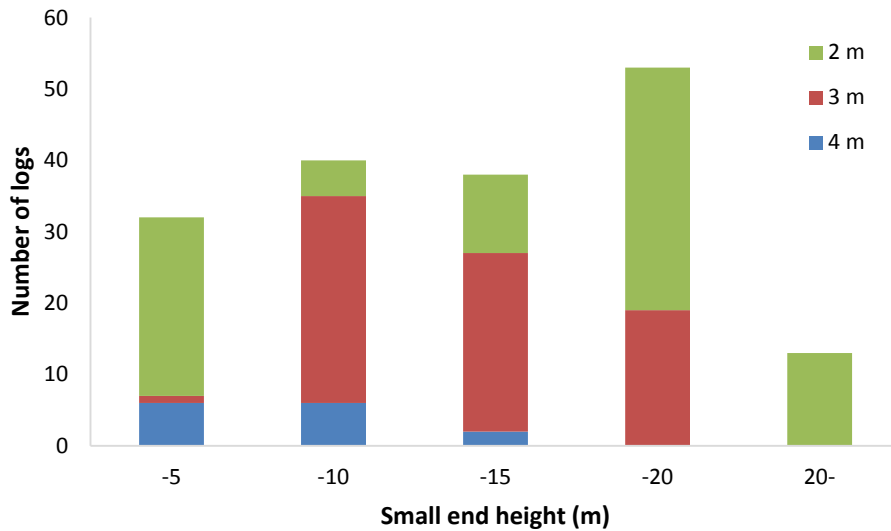


Figure 7 Log length distribution according to small end heights

Productivities  $P$  ( $m^3/h$ ) were estimated from time studies, and costs  $C$  (yen/ $m^3$ ) were estimated based on labor (2,609 yen/h), and machinery expenses (i.e., chainsaw, 402 yen/h; tower yarder, 2,759 yen/h; processor, 4,054 yen/h; and grapple loader, 2,359 yen/h).

$$\text{Chainsaw felling: } C_C = \frac{105}{vn} + 178 \text{ yen}/m^3 \quad (1)$$

$$\text{Tower yarder yarding: } C_T = 5x + 16y + 442 \text{ yen}/m^3 \quad (2)$$

$$\text{Processor processing: } C_P = \frac{(242vIa+23)n+156}{vIa \times n} \text{ yen}/m^3 \quad (3)$$

$$\text{Grapple loader piling: } C_G = \frac{150}{vIa \times n} + 246 \text{ yen}/m^3 \quad (4)$$

where  $V_n$  is the stem volume ( $m^3/\text{stem}$ ),  $x$  and  $y$  are yarding and preyarding distances ( $m$ ), and  $V_{la}$  and  $n$  are the average log volume from the stem ( $m^3/\text{log}$ ), and the number of logs from the stem, respectively.

In addition, truck transportation expenses were estimated as 1,300 yen/ $m^3$ . Handling fees for a Forest Owners' Co-operative were estimated as 3% of revenues. In the log auction market, handling fees were estimated as 5% of revenues and piling fees were estimated as 700 yen/ $m^3$ .

Next, economic balances were estimated considering sweep from terrestrial LiDAR. As a result, the profit was estimated as 177,511 yen, which was close to that estimated by manually measured data, at 195,500 yen (Figure 8). Although terrestrial LiDAR detected only 150 out of 176 logs, the revenues estimated by the LiDAR data were almost similar to those estimated by manually measured data, because logs that were not detected by terrestrial LiDAR were almost 2-m in length, which obtain relatively lower prices (Figure 9).

In this study, terrestrial LiDAR was used to obtain detailed descriptions of stem shape such as taper, sweep and lean. If terrestrial LiDAR was not used, sweep class was not classified. If all logs were classified as A for sweep class, the profit was overestimated at 214,175 yen. Therefore, terrestrial LiDAR was effective in obtaining a detailed description of stem shape and in estimating revenues considering sweep class. The use of an optimal bucking algorithm increased the profit to 233,576 yen.

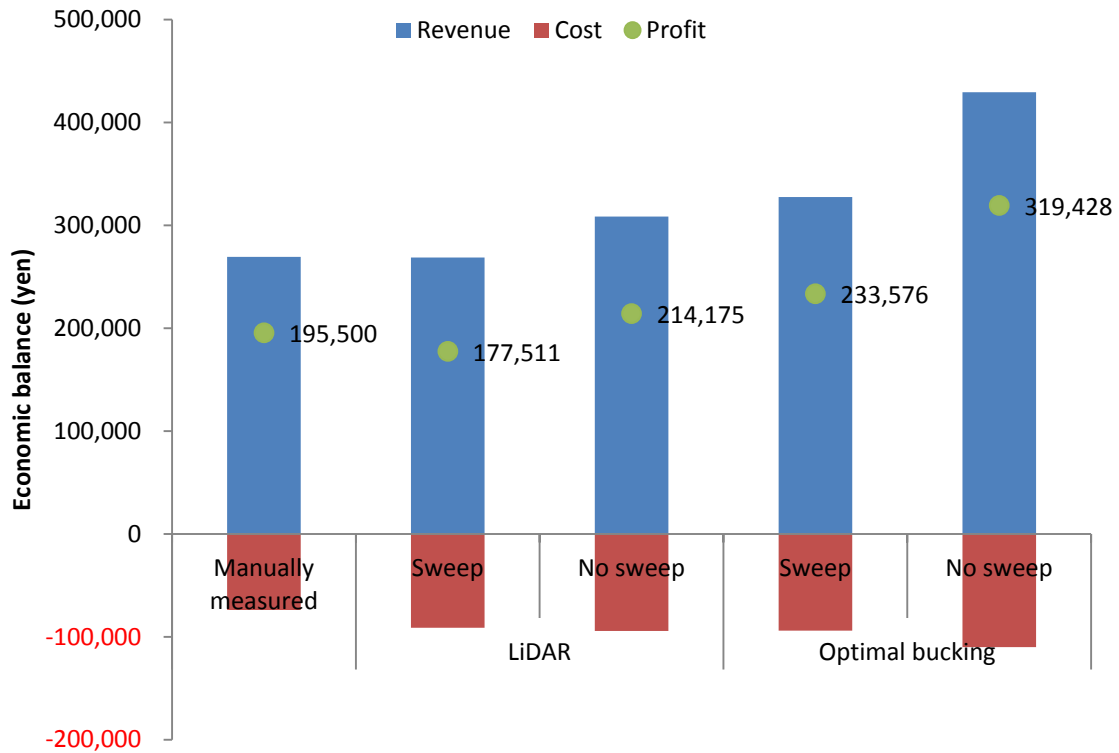


Figure 8 Economic balance

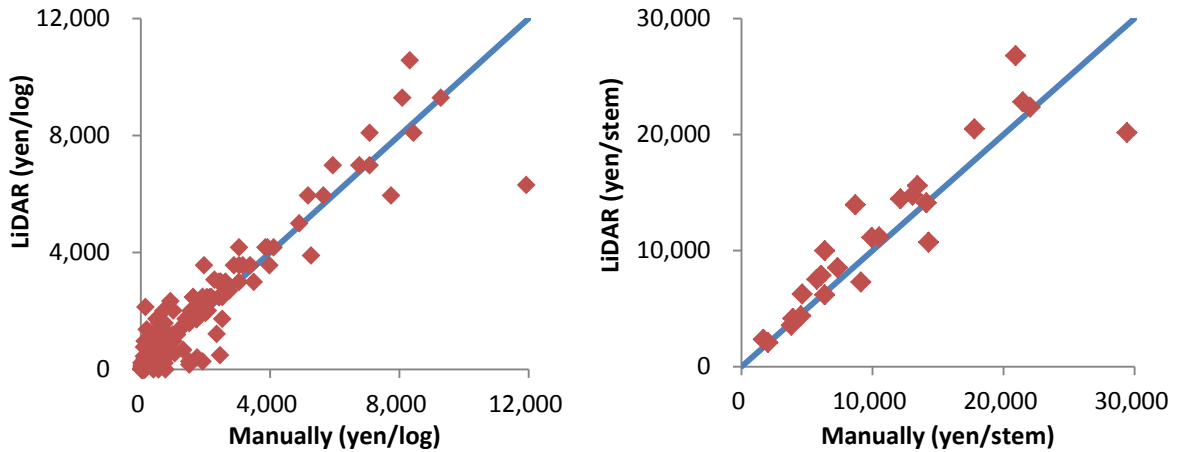


Figure 9 Revenue from logs (Left) and stems (Right)

#### 4. Discussions

In this study, the use of terrestrial LiDAR could provide a detailed description of stem shape. If terrestrial LiDAR was not used, sweep class was not classified. If all logs were classified

as grade A for sweep class, the profit was overestimated. Therefore, terrestrial LiDAR was effective in obtaining a detailed description of stem shape and in estimating revenues taking into account sweep class. However, large areas could not be measured or were difficult to measure with terrestrial LiDAR. The use of an optimal bucking algorithm successfully improved the profit in this study. However, the optimal bucking algorithm should be applied in the fields. Therefore, to reduce workload of terrestrial LiDAR measurements and to conduct real time optimal bucking, a harvester or other forestry vehicle-mounted LiDAR systems should be developed (Rossmann et al. 2010).

In July 2011, the “Feed-in Tariff (FIT) Scheme for Renewable Energy Use” was introduced in accordance with a new legislation entitled the “Act on Purchase of Renewable Energy Sourced Electricity by Electric Utilities.” Under the FIT program, electricity generated from a woody biomass is to be procured for 20 years at a fixed price (without tax) for unused materials such as logging residue: 32 yen/kWh, general materials such as sawmill residue: 24 yen/kWh, and recycled materials such as construction waste wood: 13 yen/kWh (Agency for Natural Resources and Energy, 2012). Incentives are offered for power generated from unused materials, which is expected to promote the use of logging residue in the near future. Tops and branches are dominant logging residues. However, terrestrial LiDAR could not accurately measure the tops and branches. Combining airborne and terrestrial LiDAR would allow the tops and branches to be measured more accurately (Kato et al. 2014).

## 5. Acknowledgement

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## 6. References

- Agency for Natural Resources and Energy (2012). Settlement of the details of the Feed-in Tariff scheme for renewable energy, including purchase price and surcharge rates, <[http://www.meti.go.jp/english/press/2012/0618\\_01.html](http://www.meti.go.jp/english/press/2012/0618_01.html)> (Accessed 18 June 2012).
- Ito, T., Matsue, K., Shuin, Y., and Naito, K. (2011). Estimating individual stem volumes of Sugi and Hinoki with different densities using airborne LiDAR. *Journal of the Japan Society of Photogrammetry and Remote Sensing*. 50(1): 18-26
- Kato, A., Ishii, H., Enoki, T., Osawa, A., Kobayashi, T., Umeki, K., Sasaki, T., and Matsue, K. (2014) Application of laser remote sensing to forest ecological research. *Journal of the Japan Forest Society*. 96(3): 168-181

- Murphy, G.E., Acuna, M.A., and Dumbrell, I. (2010). Tree value and log product yield determination in radiate pine plantations in Australia: comparisons of terrestrial laser scanning with a forest inventory system and manual measurements. *Canadian Journal of Forest Research*. 40: 2223-2233
- Nakahata, C., Aruga, K., and Saito, M. (2014). Examining the optimal bucking method to maximize profits in commercial thinning operations in Nasunogahara Area, Tochigi Prefecture, Japan. *Croatian Journal of Forest Engineering*. 35(1): 45-61
- Rossmann, J., Schluse, M., Schlette, C., Buecken, A., Krahwinkler, P., and Emde, M. (2010). Data fusion based multi-sensor system for high accuracy forest management. *Journal of Forest Planning*. 16: 263-271

# Thinning of Small Diameter Stands in Maine

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Maine consists of millions of acres of small diameter stands that are in need of intermediate treatments. A recent study by Hiesl et al. (2015) has shown that a whole-tree harvesting system can economically thin such stands. Data for this study was collected from one site only and part of the analysis was based on a simulation. In this paper we present a sensitivity analysis of three key input variables of that simulation (twitch size, trucking distance, and product value). We further included one observation from a second site into our analysis. Results show that product value has the greatest impact on profit, with a change of one dollar in product value being responsible for a 10% change in profit. Unit cost of production at the additional site is more than twice as high as reported by Hiesl et al. (2015), whereas profits are less than half. This clearly shows that there is lots of variation in unit cost and productivity based on feller-buncher productivity. One of the key differences between the two sites was the experience of the operators in small diameter stands. This research shows that the thinning of small diameter stands, using a small feller-buncher, can be profitable, but can also turn into a loss.

**Keywords:** New England, Northeast, CAT 501, biomass, wood chips

## 1. Introduction

Precommercial thinning (PCT) is a common silvicultural treatment used in the early management of conifer forests across North America and Europe (Bataineh et al. 2013; Olson et al. 2012; Zhang et al. 2006). The effects of PCT on tree growth have been investigated and documented for a wide range of forest types (Bataineh et al. 2013; Olson et al. 2012; Pitt and Lanteigne 2008; Zhang et al. 2006), however, this treatment represents a significant financial investment by the landowner which must be carried many years before a commercial harvest. In Maine, millions of acres of forestland are in need of PCT or have already passed the point of economic feasibility. The question that now arises is How can we treat these stands?

Clearly these stands need to be thinned to increase growth and yield. Whether or not this thinning is commercial or precommercial depends on whether or not any profits can be



made. One factor that determines whether a profit can be made is the cost of the equipment that is used to thin these stands, while another factor may be the operator experience and proficiency. A cut-to-length (CTL) harvesting system consisting of a harvester and forwarder is commonly used to thin softwood stands (see Hiesl and Benjamin 2013). Unpublished data of studies by Hiesl (2013) and Benjamin et al. (2013), however, indicate that thinning small diameter stands with a CTL system is undesirable due to an increase in break downs, such as thrown chains and a low productivity. The use of a whole-tree (WT) harvesting system consisting of a feller-buncher, grapple skidder, and slide-boom delimeter is also undesirable due to an increase in sorting time for unmerchantable stems (unpublished data of Hiesl 2013) and the high costs of feller-bunchers commonly used in Maine.

Using a smaller feller-buncher and replacing the slide-boom delimeter by a chipper is one option in the search of a profitable harvesting system to commercially thin small diameter stands. In the winter of 2013/2014 the Cooperative Forestry Research Unit at the University of Maine thinned a long-term herbicide and PCT research study (Bataineh et al. 2013; Newton et al. 1992a; Newton et al. 1992b), using such a system (Site A). Results of this study show similar productivity, unit cost, and profit, across three different removal intensities (Hiesl et al. 2015). This study, however, is lacking a sensitivity analysis of the input variables and a comparison of unit cost and profit to other sites. In 2013, data was collected from a similar harvest site using the same feller-buncher (make and model) but a different operator (Site B). Data from both sites can be used to evaluate the effect of operator and site conditions on unit cost of production and profit.

Our objectives were to conduct a sensitivity analysis for three of the major input variables (tree size, trucking distance, and product value) at Site A, and to compare the unit cost and profit of Site A to data collected from Site B.

## **2. Methods**

### **Site Selection**

Detailed information about Site A is described in the publications of Newton et al. (1992a), Newton et al. (1992b) and Bataineh et al. (2013). The study site is located in Somerset County, Maine (45.20°N, 69.70°W). Mean annual precipitation is 40 in., with 40% of it occurring from June through September. The site was clear-cut in 1970 and a herbicide screening trial designed to release naturally regenerated conifers from competing hardwoods was installed seven years later. Sixteen years after harvest, each herbicide treatment unit (approximately 2.5 acres each) was split, with one half being pre-commercially thinned to approximately 700 trees

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per acre and the other half left unthinned. During this study only the unthinned treatment units were commercially thinned.

In 2012, nine fifth-acre measurement plots were installed in a subset of the unthinned treatment units. Species, dbh, total height, and height to the base of the live crown were recorded for all trees >3 inches in dbh. Quadratic mean diameter at breast height (QMD) for these plots ranged from 4.0 in. to 5.4 in. with stand densities ranging from 1,300 to 2,225 trees per acre (Table 1). Based on stem density, all stands were dominated by balsam fir (*Abies balsamea* (L.) Mill.), and consisted of between 4% and 28% red spruce (*Picea rubens* Sarg.), 1% to 30% quaking aspen (*Populus tremuloides* Michx.), and up to 35% of other tree species such as paper birch (*Betula papyrifera* Marshall), yellow birch (*Betula alleghaniensis* Britt.), eastern white pine (*Pinus strobus* L.), and northern white cedar (*Thuja occidentalis* L.). Individual treatment units ranged in size from 1 to 1.8 acres (Table 1). Plot 10U was used as a training plot and was removed from further analysis.

A detailed description of the experimental design at Site A can be found in Hiesl et al. (2015). In short, three different thinning prescriptions, with three replications each, were implemented. The nominal thinning prescriptions were designed to remove 33%, 50%, or 66% of the standing softwood volume using a modified thinning-from-below prescription, which included the removal of large balsam fir (dbh > 8 in.) to ensure utilization of such trees before butt rot decreases their value (Tian 2002).

Site B was thinned in the summer of 2013. QMD, stand density, and basal area were similar to Site A (Table 1). Species composition, however, consisted entirely of hardwoods (American beech (*Fagus grandifolia* Ehrh.), bigtooth aspen (*Populus grandidentata* Michx.), sugar maple (*Acer saccharum* Marshall), and red maple (*Acer rubrum* L.)). The removal intensity at Site A was a 67% removal of basal area, which is comparable to the 50% volume removal prescription of Site A (Table 1).

## **Equipment Selection, Measurements, and Simulation**

All treatment units at Site A were thinned using a whole-tree harvesting system consisting of a CAT 501 feller-buncher and a John Deere 648 GIII grapple skidder. The CAT 501 feller-buncher was chosen for its narrow track width and small machine size. Although this machine is not widely used in Maine, productivity data of this machine in similar high density stands showed potential for economically feasible thinnings (Benjamin et al. 2013). A truck mounted Prentiss 325 loader was used to feed a Morbark Model 23 disk chipper. Detailed

information about the feller-buncher time collection, extraction time simulations, and volume estimates can be found in Hiesl et al. (2015).

Table 1: Individual tree and stand attributes for all treatment units and harvest sites.

Plot	Treatment unit (ac)	QMD* (in)	Stand Density (trees/ac)	Basal Area (ft <sup>2</sup> /ac)	Hardwood Component (%)	Prescription (%)*	BA Removed (%)	Removal (tons)	Feller-Buncher Productivity (tons/PMH)
<b>Site A</b>									
2U	1.2	4.4	1,685	177	21	33	57	109.8	22.5
4U	1.0	4.4	1,705	181	27	66	77	64.1	11.7
10U	1.2	4.6	1,485	171	23	33	62	64.2	11.5
13U	1.5	4.1	2,225	199	14	33	63	82.1	7.9
16U	1.4	5.4	1,300	207	7	66	80	99.5	11.7
18U	1.6	4.0	2,175	187	10	66	79	138.3	15.3
22U	1.8	4.2	2,220	217	2	50	68	138.6	16.3
24U	1.3	4.6	1,420	168	37	50	68	103.7	13.9
27U	1.2	4.6	1,485	169	15	50	69	73.8	15.5
<b>Site B</b>									
1	-	4.0	1,575	140	100	50 <sup>#</sup>	67	-	3.9

Note: QMD = quadratic mean diameter, BA = basal area, PMH = productive machine hours

\*Removal of standing softwood volume, #Estimated hardwood volume removal

Unit cost was calculated using hourly machine rates of \$103 to \$135 USD/PMH for the feller-buncher, \$90 to \$115 USD/PMH for the grapple skidder, \$40 USD/PMH for the loader, and \$62 to \$94 USD/PMH for the disk chipper. For the grapple skidder the number of twitches per treatment unit was estimated based on the harvest volume using an average twitch size of 3 tons. We assumed that the twitches were evenly distributed along the trails within the treatment unit. Trucking costs to the mill in this region are \$2.67 USD/mile (Benjamin 2014). Round-trip trucking distance for biomass chips was assumed to be between 30 and 60 miles. The average load size per truck was 26.7 tons. Mill delivered biomass chips value was supplied by an anonymous source in the industry at \$35 USD/ton. A more detailed description of the simulation setup for the wood extraction can be found in Hiesl et al. (2015).

Site B was also thinned by a CAT 501 feller-buncher and for the purpose of comparing the difference in unit cost and profit we assumed that the feller-buncher removed 105 tons from an area of 1.4 acres. These values represent the average condition of a treatment unit with a 50% volume removal (Table 1). The major difference at Site B was a different operator in the feller-buncher. An analysis of variance in combination with Tukey's HSD pairwise group comparison was used to compare the unit cost of production and profit between individual treatments and sites.

## Sensitivity Analysis

A sensitivity analysis was conducted to understand how profit reacts to small changes of an independent variable. For this we individually changed the input variables of twitch size, trucking distance, and product value at Site A. The baseline twitch size in this study was 3 tons. We changed the twitch size from 1.5 to 4.5 tons in increments of 0.1 tons to understand the sensitivity of profit to small changes in twitch size. The round-trip trucking distance for this analysis ranged from 10 to 110 miles, with an average of 60 miles as our baseline. We increased trucking distance in 10 mile increments. To understand the impact of product value on profit we used a range of \$20 to \$50 USD/ton, with one dollar increments.

### 3. Results

#### Sensitivity Analysis

A reduction in twitch size by half resulted in a profit reduction of over 40% (Figure 1 – top row). In general, a reduction of twitch size had a large negative effect on profit, whereas an increase in twitch size had a considerably smaller, but positive, effect on profit. This relationship holds true across all three removal intensities.

Changing the round-trip trucking distance resulted in a change in profit of up to 50% (Figure 1 – middle row). This change was positive with decreasing trucking distance but became negative with increasing trucking distance. Results clearly showed that reducing the trucking distance by 10 miles can increase profit by as much as 10%. The relationship between trucking distance and change in profit is negative linear and extends to the same amount in either direction.

The biggest impact on productivity was found when changing product value (Figure 1 – bottom row). An increase or reduction in product value of \$15 USD/ton could lead to a change in profit of up to 150%. Even a small reduction of \$1 USD/ton can decrease profit by up to 10%. The relationship between product value and change in profit is positive linear and extends to the same amount in either direction.

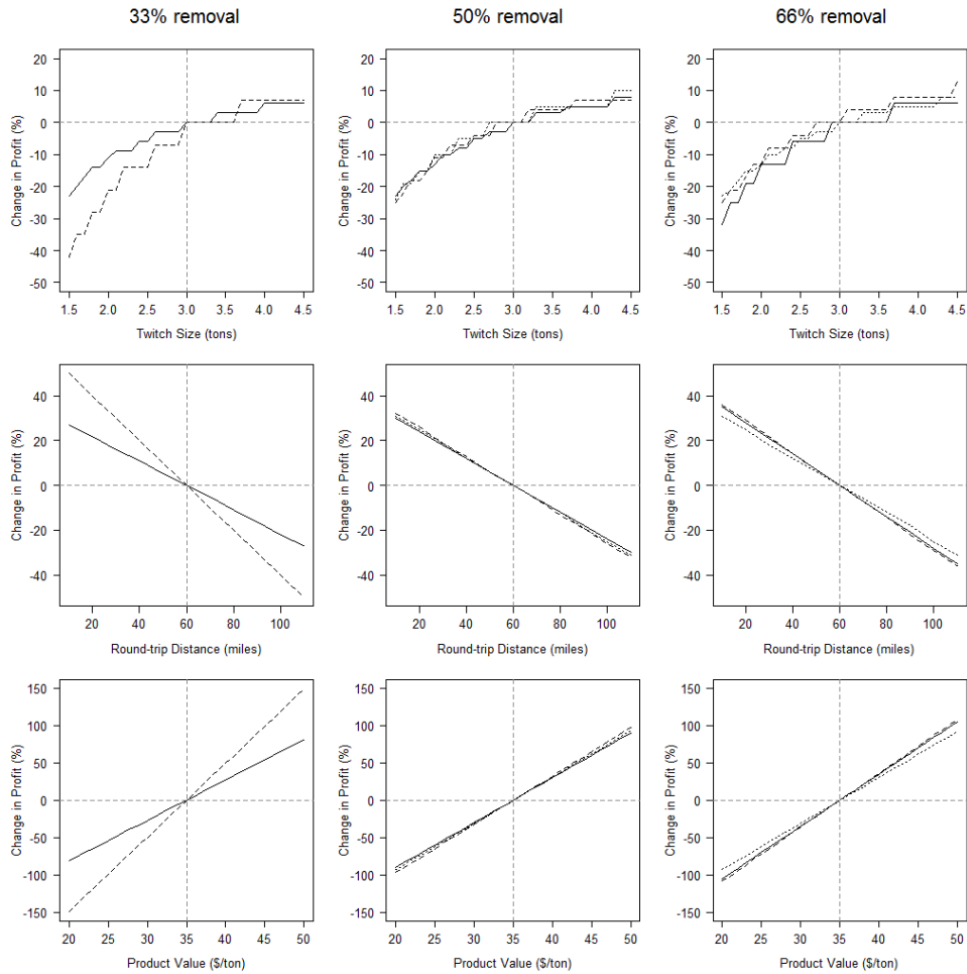


Figure 1: Sensitivity analysis results for three thinning treatments (33%, 50%, 66% removal) at Site A. The top row shows results for changes in twitch size, the middle row shows results for changes in round-trip trucking distance, and the bottom row shows results for changes in product value. The lines in each plot represent the different treatment units and the associated feller-buncher productivity. With the exception of the 33% removal prescription (n=2) all thinning treatments have three observations.

### Site and Operator Comparison

For Site A, biomass harvest costs ranged from \$13.55 USD/ton to \$30.66 USD/ton, with an average of \$20.45 USD/ton (Figure 2). For site B, the harvest costs ranged from \$35.54 USD/ton to \$48.53 USD/ton, with an average of \$42.04 USD/ton. An analysis of variance, followed by Tukey’s HSD pairwise group comparison, showed that there was no difference in unit cost of production between the individual prescriptions at Site A ( $p > 0.929$ ) but between

Site A and Site B ( $p < 0.003$ ). Profit at Site A ranged from \$4.37 USD/ton to \$21.45 USD/ton, with an average of \$14.55 USD/ton (Figure 3). At site B, profit ranged from -\$0.54 USD/ton to -\$13.53 USD/ton, with an average of -\$7.04 USD/ton. An analysis of variance, followed by Tukey's HSD pairwise group comparison, showed that there was no difference in profit between the individual prescriptions at Site A ( $p > 0.929$ ) but between Site A and Site B ( $p < 0.003$ ).

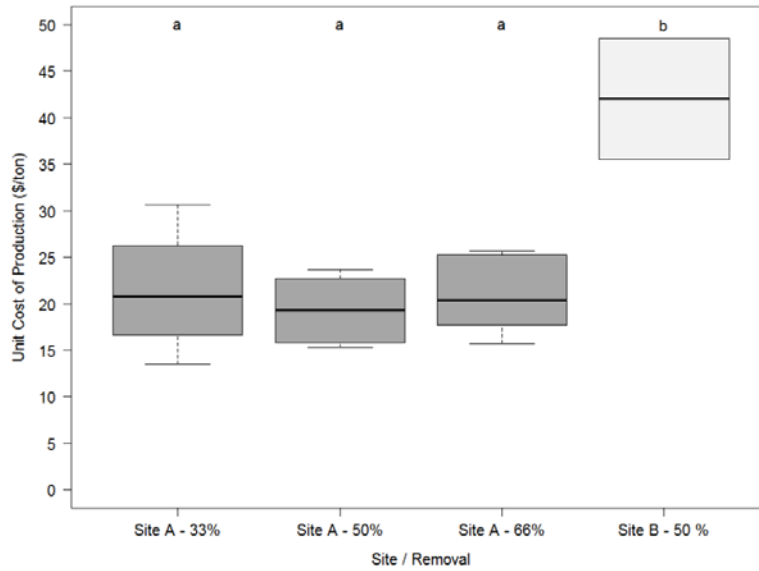


Figure 2: Unit cost of production for three different treatments at Site A and one thinning treatment at Site B.

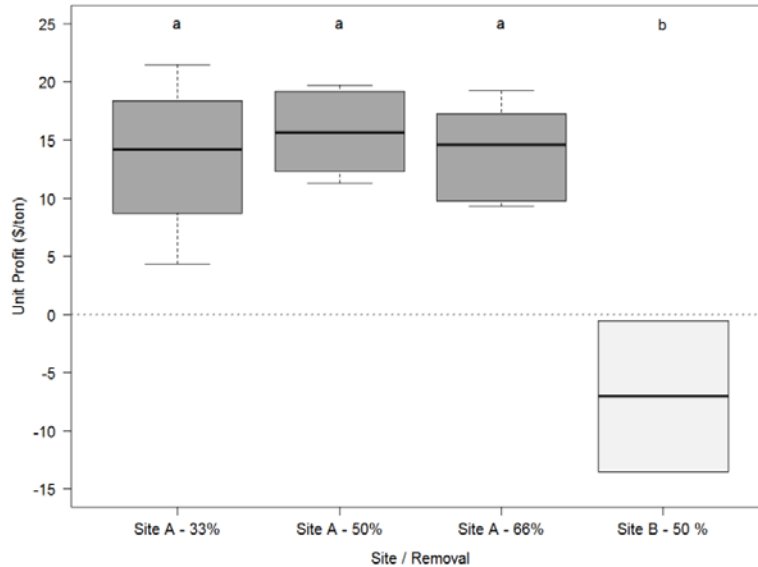


Figure 3: Unit profit for three different treatments at Site A and one thinning treatment at Site B.

#### 4. Discussion

Productivity of harvesting equipment is one factor that can influence the profit that can be achieved. The literature indicates that factors such as tree size, species, twitch size, and skidding distance affect productivity (see Hiesl and Benjamin 2013b). At Site A there was no control over tree size and species. Thus we did not include these two variables in our sensitivity analysis. Further, skidding distance can have a great impact on skidder productivity (Hiesl 2013; Han et al. 2004; Kluender et al. 1997), however, in our study the skidding distance was held constant. We acknowledge that for every 100 ft increase in skidding distance the productivity will decrease by more than 4% (Hiesl 2013) and thus our results would look different with varying skidding distances. Further, a recent study by Hiesl et al. (in review), showed that with an increasing skidding distance it becomes more economical to use a second grapple skidder. Such an addition of a skidder would also change the results.

Twitch size depends on the number of stems, and the average tree size, but also on the loading capacity of the skidder. The individual operator has no influence on the average tree size on a given harvest site, however, he can increase the number of stems in a twitch to increase the twitch size. Our results clearly showed that increasing the twitch size by one ton increases profits by up to 10%. Reducing the twitch size by one ton, however, decreases profits by up to 30%. This exponential behavior is not surprising as the number of twitches does not

decrease by much when increasing the twitch size, but does increase to a large number when decreasing the twitch size. Owing to the calculation of the number of twitches the change in profit follows a sawtooth-pattern. In this case the total volume removed is divided by average twitch size and rounded to the next higher whole number.

Trucking distance has been shown to affect driving speed (Mousavi and Naghdi 2013). Even though a longer trucking distance increase trucking speed, the total time consumption increases as well. Such an increase in time consumption subsequently increases the trucking costs and decreases the profit. It is therefore not surprising to see that the profit increases with decreasing trucking distance and vice versa. In our study, however, we assumed a constant trucking speed and used costs provided by one logging contractor in Maine. In contrast to other states, the availability of trucks in Maine is limited and has been shown to highly influence the non-productive time of chippers (Hutton 2015). These are all factors that need to be considered when applying our results to other regions.

Although not easily influenced, product value is the largest driver in whether or not a profit can be achieved. Our sensitivity analysis results clearly showed that a change of one dollar per ton can cause a 10% change in profit. Such a change in profit might be enough to warrant a longer trucking distance to a mill that pays slightly more for the product.

Results of Hiesl et al. (2015) indicates that the unit cost of production and unit profit of a whole-tree harvesting system operating in small diameter stands are similar across three removal intensities. Their paper further suggests that the unit profit for such a system across three removal intensities is higher than \$4 USD/ton. Data for their study has been collected from one site only and therefore might be overly optimistic. As the CAT 501 feller-buncher is not a commonly used machine in the state of Maine, additional data is limited. In 2013, however, we did a productivity study of such a machine in a stand that is comparable to Site A. The observed productivity of that machine was less than half of what has been observed by Hiesl et al. (2015). This difference lead to a unit cost of production more than twice as high as observed at Site A. Subsequently the unit profit was twice as low, not even breaking even.

A difference in unit cost and profit was expected, however, a difference of such a magnitude was surprising. Equipment operators in harvesters and feller-bunchers have been shown to have a large effect on productivity (Hiesl and Benjamin 2013a; Purfürst and Erler 2011; Kärhä et al. 2004). At Site A the equipment operator had over 30 years of experience working in feller-bunchers, and over two years of experience working in such stand conditions. The operator at Site B had a few years of feller-buncher experience, but only three months of experience in small diameter stands with the CAT 501 feller-buncher. There clearly is a difference in operator experience, which might explain the difference in productivity. This



comparison also shows that choosing the right operator can make a difference between making a profit and reporting a loss.

Results from Site A (Hiesl et al. 2015) show that an economical thinning of small diameter stands with the proposed whole-tree system is achievable. On the other hand, however, we showed that there is the other extreme of reporting a loss when operating in such stands. To fully understand whether or not this harvesting system can economically thin small diameter stands we need to collect data from different harvest sites and different operators.

## 5. References

- Bataineh, M.M., Wagner, R.G. and Weiskittel, A.R. 2013. Long-term response of spruce–fir stands to herbicide and precommercial thinning: observed and projected growth, yield, and financial returns in central Maine, USA. *Canadian Journal of Forest Research* 43(4), pp. 385–395.
- Benjamin, J.G. 2014. Operational & Economic Aspects of Biomass Harvesting: There is No Free Lunch in the Woods. Presentation at New England Society of Foresters 2014 Winter Meeting. Nashua, NH, USA: 25 March 2014.
- Benjamin, J.G., Seymour, R.S., Meacham, E. and Wilson, J.S. 2013. Impact of whole-tree and cut-to-length harvesting on postharvest condition and logging costs for early commercial thinning in Maine. *Northern Journal of Applied Forestry* 30(4), pp. 149–155.
- Han, H.-S., Lee, H.W. and Johnson, L.R. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. *Forest Products Journal* 54(2), pp. 21–27.
- Hiesl, P. 2013. Productivity standards for whole-tree and cut-to-length harvesting systems in Maine. Master Thesis. Orono, ME, USA: University of Maine - School of Forest Resources.
- Hiesl, P. and Benjamin, J.G. 2013a. A multi-stem feller-buncher cycle-time model for partial harvest of small diameter wood stands. *International Journal of Forest Engineering* 24(2), pp. 101–108.
- Hiesl, P. and Benjamin, J.G. 2013b. Applicability of international harvesting equipment productivity studies in Maine, USA: A literature review. *Forests* 4(4), pp. 898–921.
- Hiesl, P., Benjamin, J.G. and Roth, B.E. 2015. Evaluating harvest costs and profit of commercial thinnings in softwood stands in west-central Maine: A Case Study. *The Forestry Chronicle*.
- Hutton, C.J. 2015. Repair and maintenance costs, chipper productivity, and chip quality of biomass supply chains in the Northeastern U.S. Master Thesis. Orono, ME, USA: University of Maine.
- Kärhä, K., Röykkö, E. and Gumse, S.-I. 2004. Productivity and cutting costs of thinning harvesters. *International Journal of Forest Engineering* 15(2), pp. 43–56.

- Kluender, R., Lortz, D., McCoy, W., Stokes, B.J. and Klepac, J. 1997. Productivity of Rubber-tired Skidders in Southern Pine Forests. *Forest Products Journal* 47(11/12), pp. 53–58.
- Mousavi, R. and Naghdi, R. 2013. Time consumption and productivity analysis of timber trucking using two kinds of trucks in northern Iran. *Journal of Forest Science* 59(5), pp. 211–221.
- Newton, M., Cole, E.C., McCormack, M.L. and White, D.E. 1992a. Young Spruce-Fir Forests Released by Herbicides II . Conifer Response to Residual Hardwoods and Overstocking. *Northern Journal of Applied Forestry* 9, pp. 130–135.
- Newton, M., Cole, E.C., White, D.E. and McCormack, M.L. 1992b. Young Spruce-Fir Forests Released by Herbicides I . Response of Hardwoods and Shrubs. *Northern Journal of Applied Forestry* 9, pp. 126–130.
- Olson, M.G., Wagner, R.G. and Brissette, J.C. 2012. Forty years of spruce–fir stand development following herbicide application and precommercial thinning in central Maine, USA. *Canadian Journal of Forest Research* 42(1), pp. 1–11.
- Pitt, D.G. and Lanteigne, L. 2008. Long-term outcome of precommercial thinning in northwestern New Brunswick: growth and yield of balsam fir and red spruce. *Canadian Journal of Forest Research* 38(3), pp. 592–610.
- Purfürst, F.T. and Erler, J. 2011. The human influence on productivity in harvester operations. *International Journal of Forest Engineering* 22(2), pp. 15–22.
- Tian, S. 2002. Effect of Precommercial Thinning on Root Development and Root and Butt Decay Incidence of Red Spruce and Balsam Fir. Orono, ME, USA: University of Maine.
- Zhang, S.Y., Chauret, G., Swift, D.E. and Duchesne, I. 2006. Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. *Canadian Journal of Forest Research* 36(4), pp. 945–952.

# Determining the Impact of Felling Method and Season of Year on Coppice Regeneration

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There is increasing interest in plantations with the objective of producing biomass for energy and fuel. These types of plantations are called Short Rotation Woody Crops (SRWC). Popular SRWC species are Eucalypt (*Eucalyptus spp.*), Cottonwood (*Populus deltoids*) and Black Willow (*Salix spp.*). These species have in common strong growth rates, the ability to coppice and rotations of 2-10 years. SRWC have generated interest for many forest products companies and timber producers and although they might help with the supply for the expected growth on the bioenergy and biofuels market, there are still several concerns about the best way to harvest them maximizing their ability to coppice. SRWC have elevated establishment and maintenance costs if compared to other type of plantations, but due the coppicing ability, the same plantation may be harvested up to 5 times without the need of establishing a new one. Study plots were installed at several locations in Florida, Mississippi and Arkansas, and were cut with a chainsaw and a shear head during summer and winter, to determine the effects of felling method and season on coppice regeneration. Thus, plots were divided in 4 treatments: shear-winter, saw-winter, shear-summer, saw-summer. Harvesting eucalypt and cottonwood trees during winter resulted in better survival rates than harvesting during summer; however, there was no effect of felling method on coppice regeneration. Finally, no statistically significant difference was found on coppice regeneration of black willow when harvesting during winter or summer with a chainsaw or a shear head.

## 1. Introduction

The increasing necessity of finding new alternatives to produce fuel and energy has never been so evident in the United States. Issues like the increasing population, dependence on foreign oil, and the declining availability of fossil fuels have made renewable energy sources, such as biomass, become a plausible and promising option to address these issues. Moreover, researchers and politicians have developed some ideas, where a major part of the nation's energy needs will be sourced from renewable fuels (25x'25 Alliance). Several states in the U.S.

are joining alliances to replace 25% of their fuel consumption by some type of clean energy. As a result, a great amount of biomass will be required to produce clean energy and accomplish the goals. A considerable amount of that biomass will be allocated to woody biomass from harvest and forest products mill residues, but also from new plantations intended to supply new biofuel and bioenergy mills.

Recently, several companies and institutions have ventured into the short rotation woody crops (SRWC) supply system. According to the U.S. Department of Energy (2011), a SRWC is an intensively-managed plantation of a fast-growing tree species that produces large amount of biomass over a short period of time, usually less than 10 years, that can be shortened to as little as 3 years when coppiced, depending on the species and production method. The characteristics that define the SRWC are the ability to coppice, rotations between 2 and 10 years, and an impressive fast growth. It is also important to highlight that SRWC generally have very high costs. Tuskan (1998) specifies that SRWC involve appropriate site selection, use of improved clonal planting, extensive weed control, fertilization as required, pest control, and efficient harvesting and post-harvest processing. For this reason, to maximize the utilization of the plantation through the coppicing ability is fundamental. The coppicing ability is the ability that a tree has to regenerate new stems from the stump, after the harvest is performed. Popular SRWC species are Cottonwood (*Populus deltoids*), Black Willow (*Salix* spp.), and Eucalypt (*Eucalyptus* spp). The United States Department of Energy (2011) states that poplar, southern pine, willow, and eucalypt, are the most likely woody energy crop species to be developed for bioenergy production today.

Although the establishment of SRWC plantations is becoming popular in the SE region, the biofuel and bioenergy markets are not yet completely developed. In countries and regions where a bioenergy market is already established, the development and use of machinery specialized to harvest SRWC is very common. However, in the U.S. the absence of a solid bioenergy market has discouraged the development of a system specialized in harvesting SRWC plantations, thus making the investment on a foreign machine not feasible. The utilization of smaller equipment, with low capital and maintenance cost, such as a skid steer with a shear head, may be a temporary option, while specialized machinery is being developed. However, this equipment may cause damage to the stump's structure and bark, which could cause possible effects on coppice regeneration.

On the other hand, little is known about the optimal harvest scheduling in SRWC in the Southeast. The effect of the season of the harvest has always been a subject of interest. Theories state that harvesting during summer could damage the stump, preventing coppice, and thus limiting the harvest to the winter season.

It is evident that further research in SRWC harvesting techniques and machinery is needed. This study will compare the effects of harvesting SRWC plantations in the Southeast region with a small shear-head and with a chainsaw (simulating a circular saw-head), and also examine the potential difference in coppice response between harvesting during winter and summer seasons.

## 2. Materials and Methods

Six sites (Table 1) were selected to determine the effect of the felling method and the season of year on coppice regeneration. Three sites located in Florida were planted with Eucalypt (two with clonal *E. urograndis* and one with *E. grandis* from seedlings). Two sites, in Arkansas and Mississippi, were planted with clonal Cottonwood (*Populus deltoides*), and one in Mississippi was planted with clonal Black Willow (*Salix* spp.).

**Table 6: Description of the sites harvested during the project.**

Site	Location	Specie	Age at harvest	Avg. DBH (inch)	Plantation spacing (trees/ac)	Trees Felled
Evans	Florida	<i>E. urograndis</i>	2	4.8	728	828
Bates	Florida	<i>E. urograndis</i>	2	4.6	1,282	867
Lykes	Florida	<i>E. grandis</i>	8	7.4	Unknown	105
Estes	Arkansas	<i>P. deltoides</i>	3	1.7	Unknown	803
Admire – C	Mississippi	<i>P. deltoides</i>	5	4.7	1,720	301
Admire – W	Mississippi	<i>S. nigra</i>	5	3.0	1,720	583

Two felling methods were compared to determine the different effects they may have on coppice regeneration. They were a small shear-head, attached to a skid steer, and a chainsaw (to simulate the effect of a circular saw-head). The harvests took place at each study site in two different seasons of year: summer and winter. A randomized block design was the experimental design used to install the treatments at each study site, which were composed by a study plot divided into four treatments: summer/saw harvest, summer/shear harvest, winter/saw harvest, and winter/shear harvest. The study plots in all sites were ~1 acre in size.

### **3. Harvesting Methodology**

The layout or design of the plantations was fundamental to the selection of the harvesting treatment. The ideal methodology was the completely randomized design, randomly cutting each tree, and controlling the effect of extraneous variables. However, due to physical and spatial limitations, and to facilitate the felling operation, it was not possible to implement the random design. As a consequence, alternating the felling equipment between rows, harvesting one row with the chainsaw and the adjacent row with the shear-head was the selected experimental design. At the Evans and Lykes study sites, alternating the felling equipment was not possible due the layout of the plantation; consequently, instead of alternating the equipment every row, it was alternated every 5 rows, thus creating blocks of 5 rows for each equipment.

After completion of the harvest at each site, an evaluation of damage caused to the stump and stump bark was performed. Five bark damage classes were specified, each representing the percentage of the bark of the stump that resulted damaged: 0 (0%), 1 (1-25%), 2 (26-50%), 3 (51-75%), and 4 (>75%). The types of harvest damage observed on stumps were: barber chair, missing chunk(s), fiber pull, split, and shattered stump. Different from the bark damage, the harvest damage was caused to the structural part of the stump, or to the wood, and not to the exterior part. Additionally, the diameter of the stump's cut surface (DGL) was measured for each stump, to account for the effect that diameter may have on the coppice regeneration.

#### **Coppice Evaluation**

The field evaluation of the coppice response occurred 5 months after the winter harvest and 6 months after the summer harvest. For the coppice evaluation, each stump was individually analyzed. If the stump presented regeneration of new sprouts, it was recorded as a live stump. However, if it had no new stems it was recorded as a "dead" stump. The number of new stems regenerated was counted at each stump.

#### **Data Analysis**

The Generalized Linear Mixed Model (GLMM) analysis was used to compare the coppicing response of the stumps and to determine the effects that the independent variables (felling equipment, harvest season, and bark and stump damage) have on the dependent

variable (coppice response), which was classified as the coppicing ability (or stump survival) and the number of new stems regenerated per stump. Additionally, stumps' DGL and skidder damage (when existing) were considered, since they could be related to coppicing ability of the cut trees.

Although each stump was individually evaluated, due the experimental design, the harvesting methodology, and the layout of the study plots, a random effect of rows nested into plot was accounted for the Evans and Lykes sites, while a random effect of rows was accounted for all the other sites. As a consequence, plots (for Evans and Lykes) and rows (for the other sites) were considered as the experimental unit, and not the stump. Each study site was individually analyzed, with the utilization of a full model (Table 2).

**Table 2: Models used to determine the felling techniques on coppice regeneration.**

Site	#	Model
Evans	1	$CR \sim FM/S + Dam + FM: Dam + DGL + HD + SD + (1   Plot/Row)$
	2	$NS \sim FM/S + Dam + FM: Dam + DGL + HD + SD + (1   Plot/Row)$
Lykes	3	$CR \sim FM + Dam + FM: Dam + DGL + HD + SD + (1   Plot/Row)$
	4	$NS \sim FM + Dam + FM: Dam + DGL + HD + SD + (1   Plot/Row)$
Estes	5	$CR \sim FM/S + Dam + FM: Dam + DGL + HD + (1   Row)$
	6	$NS \sim FM/S + Dam + FM: Dam + DGL + HD + (1   Row)$
Admire	7	$CR \sim FM/S + Dam + FM: Dam + DGL + HD + (1   Row)$
	8	$NS \sim FM/S + Dam + FM: Dam + DGL + HD + (1   Row)$

*CR*=Coppice regeneration  
*S*=Season (winter and summer)  
*FM*=Felling Method (shear and chainsaw)  
*Dam*=Bark Damage Class

*DGL*=Diameter at Ground Level (inch)  
*HD*=Harvest Damage Type  
*SD*=Skidder Damage  
*NS*=Number of New Sprouts  
: = Interaction between

#### 4. Results and Discussions

After the coppice evaluation, it was decided that, due technical issues Bates and Lykes study sites would not be included on the analysis. Also, although the effect of season on

coppice regeneration was calculated for all study sites, and the results are reported, the experimental design of the plots was not the ideal. Hence, it can be inferred that the results presented for the effects of season on coppice regeneration can be suggested but not considered definitive. The significance of the factors were determined at  $\alpha = 0.05$ . Additionally, an ANOVA was performed for each model to determine their significance, at  $\alpha = 0.05$ .

### Effects of felling method and season on eucalypt coppice regeneration

At Evans site, a significant season effect was observed (p-value: 0.00398), in which 96% of the trees felled during winter regenerated coppice, while only 79% of the trees felled during summer regenerated new sprouts (Figure 1). No significant difference was observed between felling with the shear head or chainsaw.

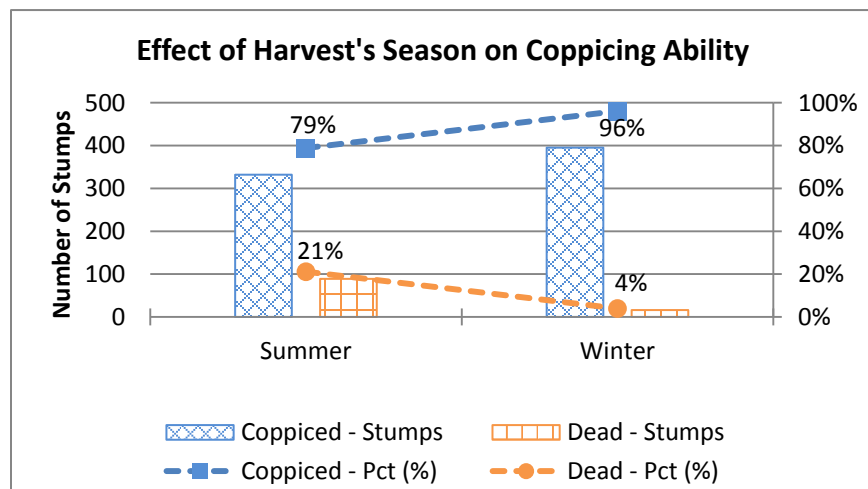


Figure 1: Effect of season on stump survival of eucalypt harvested at Evans.

### Other factors affecting coppice regeneration of eucalypt

Higher damage on the bark of the stump resulted statistically significant (p-value: 0.00419), negatively affecting the ability to coppice of eucalypt at Evans site. In total, 55 trees felled were classified under the bark damage class 0 and 52 (95%) of those trees successfully regenerated coppice; on the other hand, 151 of trees felled were classified under the bark damage class 4 and only 125 (83%) of those trees were successful in regenerating coppice.

The number of sprouts regenerated per stump resulted significantly affected by the DGL at the Evans site (p-value: 7.42-7). Stumps with larger diameters generally regenerated a larger



number of sprouts (Figure 2). Smaller stumps, with DGL range between 0 – 2 inches, regenerated an average of 3 sprouts per stump, and larger stumps, with DGL on the range between 8 – 10 inches, averaged 6.7 sprouts per stump regenerated.

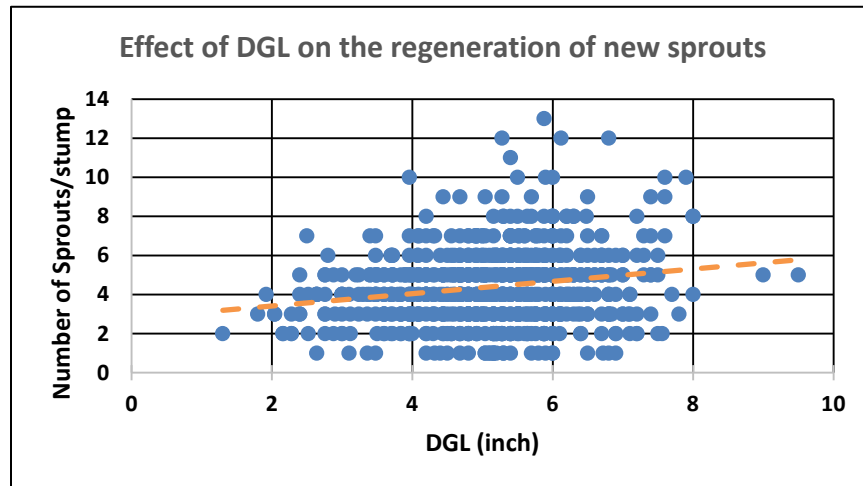


Figure 2: Scatter plot of the effect of DGL on the number of sprouts per stump on Evans.

### Effects of felling method and season on cottonwood coppice regeneration

The season variable was the only significant variable on the stumps' survival at the Estes site (p-value: 0.000372), where 98% of trees harvested during the winter were successful in regenerating coppice, while only 49% of trees harvested during summer regenerated coppice (Figure 3).

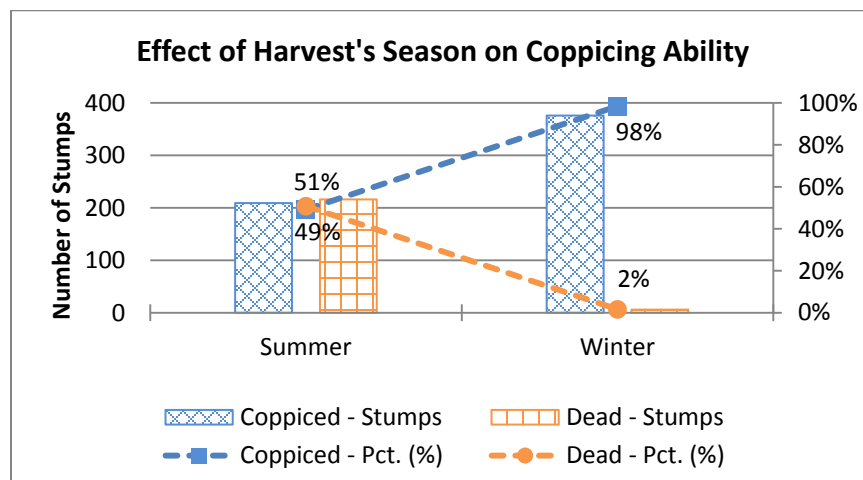


Figure 3: Effect of harvest season on the survival of cottonwood stumps at Estes.

On the other hand, the felling equipment had a significant effect on the number of new sprouts per stump of felled cottonwood at the Admire site (p-value: 0.0350). On average, stumps cut with the shear head regenerated 5.7 sprouts, while stumps cut with the chainsaw regenerated 4.7 sprouts.

### Other factors affecting coppice regeneration of cottonwood

The DGL of the stumps had a significant effect on the stump survival of trees cut at Admire. Stumps with larger DGL showed better survival rates than the stumps with a smaller DGL.

The DGL of the stumps also had a significant effect on the number of new sprouts, both in the Admire (p-value: 0.0001) and Estes (p-value: 0.0001) study sites. At the Admire study site, it was observed that stumps with a larger DGL regenerated more sprouts, when compared to stumps with a smaller DGL (Figure 4). On average, stumps with lower DGL regenerated 2.7 sprouts, while the stumps with larger DGL regenerated an average of 8.5 sprouts. The results were similar at Estes, where stumps with a smaller DGL regenerated less sprouts than stumps with a larger DGL. On average, the stumps with DGL between 0 and 2 inches regenerated 1.4 sprouts, while the stumps with larger DGL regenerated up to 12.6 sprouts.

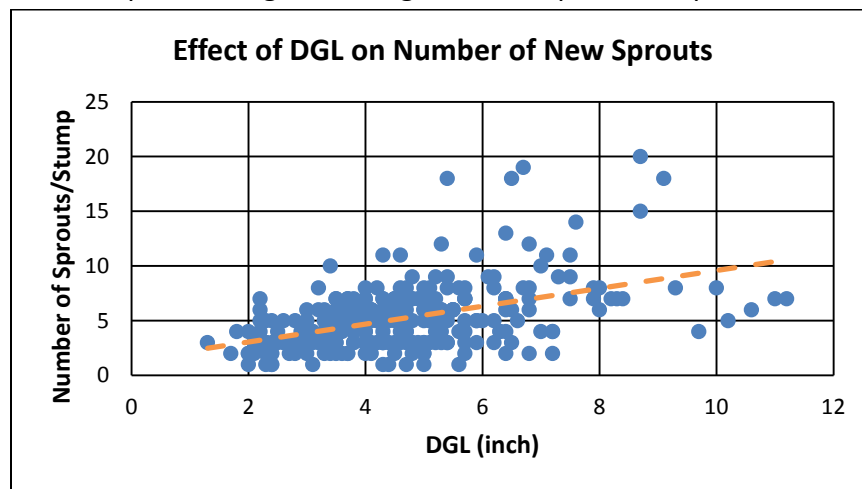


Figure 4: Scatter plot for the effect of the stump DGL on the number of new sprouts per stump at Admire.

## **Effect of felling method and harvest season on coppice regeneration of black willow**

It was observed that the average number of sprouts regenerated per stump was higher when the harvest was performed during summer than when performed during winter (p-value: 0.0001). Stumps cut during summer averaged 6.2 sprouts per stump while stumps cut during winter average 4.5 sprouts per stump.

## **Other factors affecting coppice regeneration of black willow**

The DGL was determined to have an effect on the coppice regeneration of black willow, both in the stump survival (p-value: 0.0188) and in the number of sprouts regenerated per stump (0.0001). The stumps with the lowest DGL class had lower survival rates when compared to the higher DGL classes.

The DGL of the black willow stumps also had a significant effect on the number of new sprouts per stump. A positive linear relation was observed between the DGL and the number of sprouts per stump, where stumps with larger DGL, generally regenerated a larger number of sprouts.

## **5. Discussion**

The key outcome of this study was to determine if the felling equipment and the season of year could have an impact on the coppicing ability of the stumps of eucalypt, cottonwood and black willow; however, additional variables were present at the time of the harvest and could not be left out, broadening the scope of the study. It has been proved with many tree species that factors as species, tree diameter, bark damage, and harvest damage may have impacts on the regeneration of coppice (De Souza et al., 1991; Ducrey and Turrel, 1992; Hytonen, 1994, 1996, 2001; Simões et al., 1972; Strong and Zavitovski, 1983).

## **Effect of harvest season on coppice regeneration**

Eucalypt and cottonwood trees presented better survival rates when the harvest was performed during winter. This pattern was expected to be observed on cottonwood and black willow trees, which are deciduous genera, however it was not expected on the eucalypt, since it is an evergreen genus without a clear dormancy phase, capable of producing sprouts when

felled at any time of the year (Ceulemans et al., 1996). The lower survival rate observed on the cottonwood harvested during summer may be explained with the fact that the carbohydrate reserve on the root system is lower after the onset of shoot growth during the first part of the growing season (Ceulemans et al., 1996; Strong and Zavitovski, 1983). On the other hand, the higher survival rate observed on the eucalypt harvested during winter may be explained with the fact that the period of rain in south Florida occurs during summer, and although eucalypt is an evergreen species, it may store higher levels of carbohydrates during the drought period, maximizing the regeneration of coppice if harvest occurs during winter.

Although harvest season did not affect the survival of black willow stumps, a significant effect was observed on the number of sprouts per stump. Stumps cut during summer season regenerated, on average, more sprouts than stumps cut during winter. This pattern was not expected, however it seems to match the results of other studies (Steinbeck, 1978; Hytönen, 1994). According to Hytönen, 1996, the reasons for differences in coppicing due to timing of the cutting are not fully understood, since the number of sprouts regenerated varies, presenting better results either during summer or winter.

#### Effect of the felling method on coppice regeneration

There were no differences observed on stump survival of eucalypt, cottonwood nor black willow when harvesting with a shear head or a chainsaw, which was expected, since previous and similar studies showed similar results (Simões et al. 1972; Hytönen, 1994; Crist et al., 1983). However, the effect observed on the number of sprouts regenerated per stump on the cottonwood site Admire, proved that stumps cut with the shear head regenerated, on average, more sprouts than stumps cut with the chainsaw, which also coincided with Hytönen (1994) results, where leaving a rougher cutting surface resulted in higher number of sprouts regenerated. Nonetheless, the DGL of sheared stumps resulted slightly larger than the sawed stumps, which can also explain the higher average number of sprouts.

#### Other factors affecting coppice regeneration

It was observed that DGL had a positive linear relationship with the average number of sprouts regenerated in all sites. Stumps with larger DGL averaged more sprouts than stumps with smaller DGL. This result was expected, since the stumps with larger DGL, theoretically, have more buds on their surface, which can develop to form new stems to replace the material removed or damaged during the harvest.

The DGL also showed significance on the survival of black willow and cottonwood stumps at the Admire study site. In this case, stumps with larger DGL presented better survival than the smaller stumps. A result that sounds pertinent, since stumps with larger DGL probably have a larger root system, which can capture higher amount of nutrients and water, suppressing the growth or regeneration of new sprouts by the stumps with smaller DGL.

It was also noted that bark damage caused a significant effect on the survival of eucalypt stumps at Evans site. A negative linear relationship was observed, where the more severe the bark damage to the stump was, the lower the survival rate resulted. This is probably because the axillary buds that regenerate sprouts in eucalypt trees are located under the bark, and damaging the bark may damage or expose those buds, affecting the coppice regeneration (Ceulemans et al. 1996; Opie et al., 1984).

## **6. Conclusions**

Despite analyzing the effects of season on coppice, operational harvesting restrictions affected the experimental design. For this reason, the results presented should not be considered as definitive, and further research is recommended to determine the effect of season on coppice regeneration.

### **Stump Survival**

The results showed a season effect on the eucalypt and cottonwood trees, restricting the harvest of these species to the winter season. Nonetheless, it was not fully understood why the seasonality was observed on the eucalypt. Perhaps the precipitation may be the answer, but further research and study is recommended to determine the best harvesting schedule of eucalypt in South Florida. Additionally, the coppice regeneration of eucalypt in a different region of the United States, with a precipitation regime evenly distributed through the year, may not result affected during any season, since, as already mentioned, it is an evergreen specie and could regenerate coppice regardless of the season.

The utilization of the shear head attached to a skid steer proved to be a good option while waiting for the development of machinery specialized on harvesting SRWC. Since no difference was found on coppice regeneration between harvesting with a chainsaw and a shear head, the use a shear head (which results in lower capital and maintenance costs) instead of a circular saw feller-buncher or a chainsaw (which imply higher danger and lower productivity) is highly recommended.

## Number of sprouts per stump

Although the number of sprouts regenerated per stump was studied, it is very important to deepen the study on the importance of this factor. It was found that depending on the species, the number of sprouts per stump was affected by DGL, felling method, and harvest season. However, the DGL of the stump was consistent in showing statistically significant effect on the number of sprouts for all the species. In all cases, stumps with larger DGL regenerated more sprouts per stump, which is pertinent due the higher number of shoot buds present on larger stumps.

Nonetheless, the importance of the number of sprouts regenerated per stump is not yet clear. There is no certainty about the benefits of having several sprouts per stump, instead of having a unique sprout. Perhaps having a single sprout regenerated per stump may be more desirable, depending on the goal of implementing a coppice plantation. In addition, there is knowledge of occurrence of self-pruning after a determined time after the harvest, in which the coppiced stumps will automatically eliminate the smaller stems, maintaining only the dominants or one single main stem.

In conclusion, the season effect observed on the stump survival of eucalypt and cottonwood may imply an economic impact on the SRWC supply, restricting the harvest to the winter harvest. However, the utilization of the shear head can be recommended as a possible felling method to harvest SRWC, since it does not have an effect on the survival of the stumps; which could reduce the costs of actual harvests operations used at SRWC plantations.

## 7. Literature Cited

- 25'x25': America's Energy Future. <http://www.25by25.org/>
- Ceulemans, R., McDonald, A. J. S., Pereira, J. S. 1996. "A Comparison among Eucalypt, Poplar and Willow Characteristics with Particular Reference to a Coppice, Growth-modelling Approach." *Biomass and Bioenergy*. Vol. 11(2/3): 215-231.
- Crist, J. B., Mattson, J. A., Winsauer, S. A. 1983. Effect of Severing Method and Stump Height on Coppice Growth. Web page: <http://www.treesearch.fs.fed.us/pubs/18839>. Revised on 04/28/2014.
- Ducrey, M., Turrel, M. 1992. "Influence of Cutting Methods and Dates on Stump Sprouting in Holm oak (*Quercus ilex* L.) Coppice." *Ann. Sci. For.* Vol. 49: 449-464.
- Hytönen, J. 1994. "Effect of Cutting Season, Stump Height and Harvest Damage on Coppicing and Biomass Production of Willow and Birch." *Biomass and Bioenergy*. Vol. 6(5): 349-357.
- Hytönen, J. 1996. "Biomass Production and Nutrition of Short-Rotation Plantations." The Finish Forest Research Institute. Research Papers 586: 61 pp.

- Hytönen, J., Issakainen, J. 2001. "Effect of Repeated Harvesting on Biomass Production and Sprouting of *Betula pubescens*." *Biomass and Bioenergy*. Vol. 20: 237-245.
- Opie, J. E., Curtin, R. A., Incoll, W. D. 1984. "Stand Management". In: W.E. Hillis and A. G. Brown (Eds.), *Eucalypts for Wood Production*. CSIRO/Academic Press, Melbourne, Australia. Chapter 9, 179-197 pp.
- Simões, J. W., Pereira, R. A. G., Tanaka, O. K., Pompeu, R. M. 1972. "Efeitos da Ferramenta de Corte sobre a Regeneração do Eucalipto." *Revista IPEF*. Vol. 4: 3-10.
- Steinbeck, K. 1978. "Intensively Managed Short-Rotation Coppice Forests." In: E. T. Choong and J. L. Chambers (Eds.), *Energy and the Southern Forest*. Louisiana State University, Baton Rouge, Louisiana. 123-129 pp.
- Strong, T. F., Zavitovski, J. 1983. "Effect of Harvesting Season on Hybrid Poplar Coppicing." In: E. A. Hansen (Ed.), *Intensive Plantation Culture: 12 years Research*. USDA Forest Service. Gen. Tech. Rep. NC-91: 54-57
- U.S. Department of Energy. 2011. "U.S. Billion Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. R.D. Perlack and B. J. Stokes (Eds.), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN.

## **Elevation error of LiDAR-derived DEM in the complex terrain and vegetation condition of eastern deciduous forest**

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Airborne light detection and ranging (LiDAR) data are invaluable for natural resource applications due to quick and accurate data collection over large landscapes. LiDAR data are most often used to model surface terrain features to create a digital elevation model (DEM), which can be used in many fields, land management, and research. However, it is well noted that DEM vertical error is not uniformly distributed throughout landscapes and can be affected by DEM interpolation method, topographic slope, and presence of vegetation. Many studies have evaluated one of these aspects of DEM error; however, we proposed a study to evaluate vertical error in an understudied most error prone area. We quantified error in a dense deciduous forest with multiple vegetation layers and steep slopes ranging from 0 to 100%. The dense vegetation and steep slopes also provide a challenge to obtaining reference measurements, as GPS accuracy is very low under these conditions. Thus, we proposed a new method of evaluating DEM error using reference features, identifiable within LiDAR data, while averaging elevation errors around a central reference point to evaluate the error of a whole surface rather than point errors. We compared errors from different slope classes and slope variability (ruggedness) classes as well as compared DEMs derived from low-density, high density, and combined LiDAR datasets and DEMs derived from four different interpolations methods. We found no difference between LiDAR datasets and interpolation methods; however, we did find that error increases as slope and ruggedness increases, with slope contributing more to error than ruggedness. Average errors from this study ranged from 73.4 – 73.8 cm and when classified by slope and ruggedness class ranged from 23.2 – 145.5 cm. As expected because of the complex terrain and vegetation conditions, our errors were much higher than other studies. However, these errors must be taken into consideration when using DEMs for deriving topographic and forest metrics. We suggest further research to improve algorithms used to classify LiDAR points into ground and non-ground points because we expect this misclassification is the largest source of LiDAR-derived DEM elevation error.



