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Proceedings

Integrated Management and Dynamics of Forest Defoliating Insects

Edited by:

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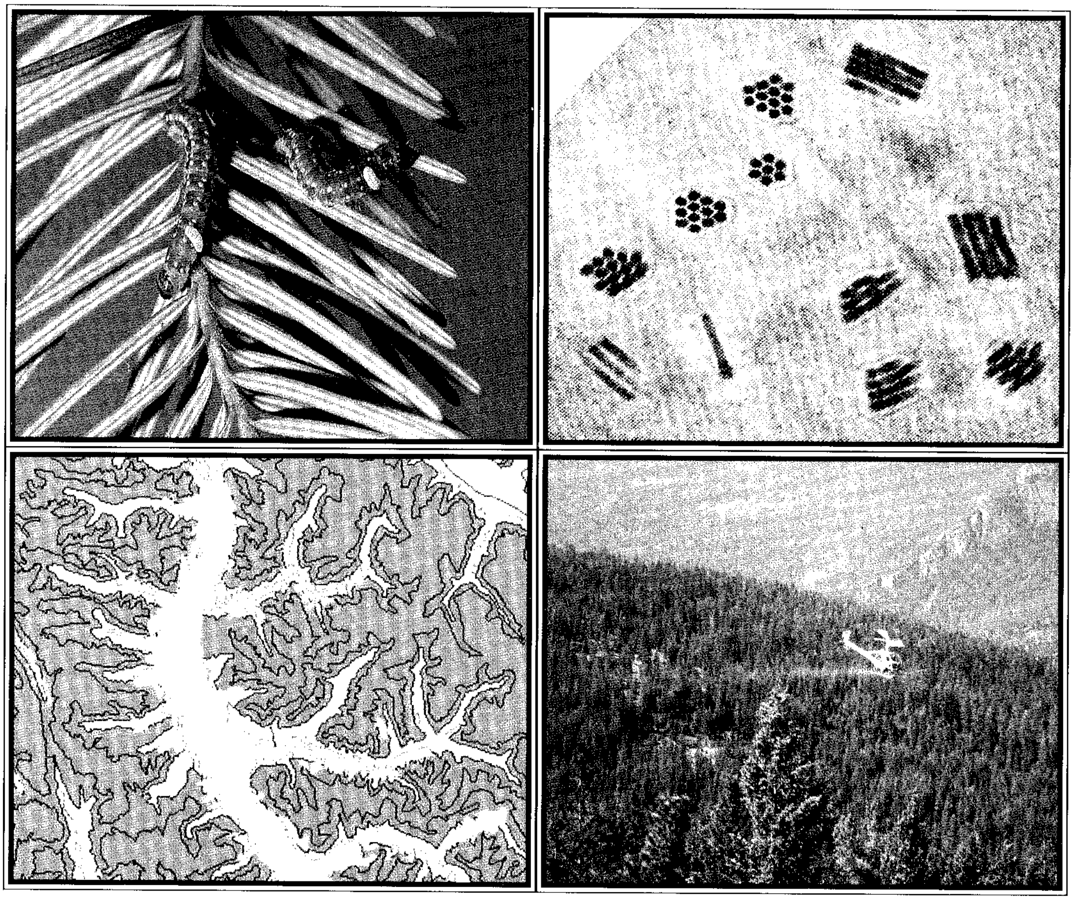
Victoria, British Columbia, Canada
August 15-19, 1999



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The photographs on the cover (from the upper left corner going clockwise) were taken by the following individuals: western spruce budworm larvae with ectoparasites (Imre S. Otvos), Douglas-fir tussock moth nucleopolyhedrosis virus (John C. Cunningham), helicopter spraying of a Douglas-fir tussock moth infestation with OpNPV (Imre S. Otvos), and a map comparing western hemlock looper defoliation to biogeoclimatic zones (Neil Borecky).

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[1] A meeting sponsored by the International Union of Forestry Research Organizations (IUFRO) Working Party S7.03-06, "Integrated Management of Forest Defoliating Insects," and Working Party S7.03.07, "Population Dynamics of Forest Insects."

PREFACE

These proceedings result from a conference, "Integrated Management and Dynamics of Forest Defoliating Insects," held at the University of Victoria, British Columbia, Canada, on August 15-19, 1999. The meeting was a joint meeting of International Union of Forestry Research Organization (IUFRO) working parties 7.03.06, "Integrated Management of Forest Defoliators," and 7.03.07, "Population Dynamics of Forest Insects."

This meeting was the second joint meeting between these two IUFRO working parties and further demonstrated the value of combined meetings between these two groups. The first joint meeting of IUFRO working groups 7.03.06 and 7.03.07 was held in the Slovak Republic in August of 1996. The proceedings of that meeting were published as U.S. Department of Agriculture Forest Service Northeastern Forest Experiment Station General Technical Report NE-247.

The meeting in Victoria was attended by 65 scientists representing 19 countries. A total of 39 oral presentations were given and 11 poster presentations were displayed. The papers presented at the meeting covered a wide spectrum of topics ranging from applied to theoretical areas of focus, but all of these papers addressed some aspect of either the population biology or management of foliage-feeding forest insects. Submittal of a paper for inclusion in these proceedings was optional, thus explaining the smaller number of papers in this volume compared to the total number of presentations.

Holding an international conference such as this required the assistance of numerous individuals and we would like to thank all volunteers from the Pacific Forestry Centre, Natural Resources Canada Canadian Forest Service for their help. Their work on organizing the meeting, registration, and facilitating the field trip was outstanding and made the entire meeting much more valuable for all participants. We also thank the University of Victoria for the use of their meeting facilities. Abbott Laboratories and Phero Tech Inc. both contributed funds for this meeting and we gratefully acknowledge their assistance. The USDA Forest Service Northeastern Research Station and the USDA Forest Service Forest Health Technology Enterprise Team sponsored publication of these proceedings and we thank them for making this volume possible.

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Control of the Most Dangerous Insects of Greek Forests and Plantations

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ABSTRACT Among the considerably large number of insects living in forest ecosystems and plantations of fast growing tree species in Greece, only a few normally constitute a serious danger, and even fewer need to be controlled occasionally. Their control, which can either be carried out from the ground or from the air, includes the use of (1) insecticides that act as inhibitors of cuticle development; (2) preparations based on *B. thurigiensis* used mainly for the control of *Thaumetopoea pityocampa* Schiff, *Stilpnotia salicis* L., *Lymantria dispar* L., and *Laspeyresia splendana* Hbn.; and (3) Diazinon for control of the following wood boring insects in poplar plantations: *Sciapteron tabaniformis* Rott., *Cossus cossus* L., and *Melanophila picta* Pall.. The Greek Forest Service is rather cautious about using insecticides in forest ecosystems and plantations of fast growing trees, especially when these are located near water (e.g., rivers and lakes). In the case of high, productive forests, protection and conservation of ecological stability are the highest priority, even at the expense of maximizing forest production. To the contrary, in recreational forests and parks or areas that attract tourists and in various other plantations, aerial applications are used only when insects tend to cause serious problems, e.g., in order to protect goods received from the forest or in order to preserve forest product quality.

THE LISTS IN Tables 1 and 2 include insects that appear most frequently in Greek forest ecosystems as well as in poplar and cypress plantations and chestnut orchards (Avtzis 1989).

Table 1. Insects that appear most frequently with softwood species of Greek forest ecosystems

Softwoods		
Pine Forests	**Cypress Plantations**	**Fir Forests**
Criocephalus rusticus L.	*Buprestis cupressi* Germ.	*Argyresthia fundella* F. Rösl.
Dioryctria splendidela H.S.	*Phloesinus armatus* Reitt.	*Cryphalus piceae* Ratz.
Evetria buoliana Schiff.	*Phloesinus aubei* Perr.	*Dioryctria abietella* Schiff.
Ips erosus Woll.		*Epinotia subsequana* Haw.
Ips sexdentatus Boern.		*Ernobius kailidisi* Johnson
Monophlebus hellenicus Gen.		*Pityokteines curvidens* Germ.
Myelophilus piniperda L.		*Pityokteines spinidens* Reitt.
Neodiprion sertifer Geoffr.		*Pityokteines vorontzowi* Jacobson
Pissodes notatus F.		*Platypus oxyurus* Duf.
Thaumetopoea pityocampa Schiff.		*Sirex cyaneus* F.
		Trypodendron lineatum Oliv.
		Urocerus gigas L.

Pages 1-5 in Liebhold, A.M.; McManus, M.L.; Otvos, I.S.; Fosbroke, S.L.C., eds. 2001. **Proceedings: integrated management and dynamics of forest defoliating insects**; 1999 August 15-19; Victoria, BC. Gen. Tech. Rep. NE-277. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

Table 2. Insects that appear most frequently with hardwood species of Greek forest ecosystems

Hardwoods	
Poplar Plantations	**Oak and Evergreen Forests**
Agrilus ater L.	*Cerambyx cerdo* L.
Cossus cossus L.	*Coraebus bifasciatus* Ol.
Diaspis pentagona Targ.	*Euproctis chrysorrhoea* L.
Dicranura vinula L.	*Lymantria dispar* L.
Melanophila picta Pall.	*Malacosoma neustria* L.
Melasoma populi L.	*Tortrix viridana* L.
Phloeomyzus passerini Sign.	
Phloeomyzus redelei H.R.S.	
Sciapteron tabaniformis Rott.	
Stilpnotia salicis L.	
Chestnut Orchards	**Elm Trees (along roads)**
Balaninus elephas Gyll.	*Scolytus scotytus* F.
Laspeyresia splendana Hbn.	*Scolytus multistriatus* Marsh.

At this point, it is worth mentioning that these are not the only insects that appear in the forests and plantations of Greece (Kailidis 1986). In addition, the intensity and appearance rate are not the same for all species, and the control of certain harmful insects is not always possible depending on ecological, technical, and funding issues.

All insects listed above can be divided into three groups. The first group consists of only two species: the needle-eating *Thaumetopoea pityocampa* Schiff. (pine processionary caterpillar) and the leaf defoliator *Lymantria dispar* L. (gypsy moth). Rather restricted control measures are applied yearly for both species. The extent of control measures depends mainly on the intensity of the defoliation, on the damage that the defoliation could potentially cause, and on the ability of the Forest Service to cover the financial cost of control.

A second, smaller group includes some insects of poplar plantations and chestnut orchards that are rarely controlled. A third group includes all the remaining insects cited in the lists that are hardly ever controlled.

Materials and Methods

Group A (Yearly Applications)

***Thaumetopoea pityocampa* Schiff. (Pine Processionary Caterpillar).** This needle-eating insect is found throughout Greece and is the most common defoliator of pine forests. These forests cover a total area of 870,486 ha (Ministry of Agriculture 1991); Table 3 lists these forested areas by overstory tree species.

Table 3. Forested area by overstory tree species in Greece

Species	Area
Pinus halepensis and *Pinus brutia*	567,731 ha (65.11%)
Pinus nigra	281,692 ha (32.40%)
Pinus silvestris	20,955 ha (2.40%)
Pinus pinea	108 ha (0.01%)

T. pityocampa attacks all pine species at varying intensities (Avtzis 1983a, 1986; Schopf and Avtzis 1987). It is found nearly everywhere in Greece from sea level to altitudes of 1800 m on Mount Olympus. It does not exist in some areas of Central Greece because of unsuitable weather conditions, nor is it found on some islands of the Aegean Sea, possibly because of geographical isolation (Avtzis 1983b).

The pine processionary moth has one generation per year, but a small percentage of its pupae exhibits extended diapause. The problems this insect causes can be grouped into three categories: (1) health problems to humans (e.g. eczema, etc.), (2) aesthetic problems (nests in trees, defoliation, etc.), and (3) economic problems due to growth loss resulting from defoliation (Bouchon and Toth 1971).

The control of *T. pityocampa* can be conducted mechanically from the ground by removing and burning overwintering nests. This can be done only in young pine plantations and under particular circumstances. Control of *T. pityocampa* can also be conducted from the ground or from the air using insecticides that (1) act by interfering with chitin deposition (contain inhibitors of cuticle development) and (2) are based on the so called bioinsecticides, such as the preparation that contains *B. thuringiensis* (Avtzis1998).

Mechanical control is conducted during winter before the beginning of the process of pupation into the soil in spring. Control using preparations that influence chitin synthesis or that contain bioinsecticides is conducted primarily during the second and third larval instar stages (October to November).

***Lymantria dispar* L. (Gypsy Moth).** The gypsy moth is a notorious pest in Greece. This extremely polyphagous leaf-eating insect has over 300 different tree species as its host (Coulson and Witter 1984) and causes great damage to poplar plantations, oak forests (1,471,839 ha), and evergreen ecosystems (3,153,882 ha) (Ministry of Agriculture 1991).

In poplar plantations and oak forests, the damage caused by gypsy moth is primarily tree growth loss (Schwenke 1978), and in a few cases, there are problems concerning landscape aesthetics and human health. In evergreen ecosystems, growth loss caused by defoliation is less important. Because these ecosystems occur along the coast and are generally in areas with great touristic interest, the most serious concerns involve aesthetic damage to the landscape and human health.

However, the appearance of *L. dispar* in evergreen ecosystems that consist mainly of *Quercus coccifera* and partly of *Quercus ilex, Phillyrea media, Ceratonia siliqua, Laurus nobilis, Arbutus* sp., and *Pistacia* sp. has both direct and indirect impacts on animal breeding and production. The direct effect involves competition for food between grazing animals (sheep and goats) and *L. dispar*, particularly during heavy defoliation periods. The foliage of those species, especially *Q. coccifera,* is food for both *L. dispar* and grazing animals.

The indirect effect on animals, especially on diary production, involves problems caused by the hairs of gypsy moth caterpillars. During feeding activity and general insect development, part of their hair sticks on the host plant. These hairs can cause stress, uneasiness, and enervation when they pass to the external breathing system of grazing animals, which smell their food before consuming it. As a result there is a reduction in diary production.

The control of gypsy moth is being conducted from the ground or from the air using preparations that (1) act by interfering with chitin deposition (contain inhibitors of cuticle development) and (2) are based on the so called bioinsecticides, such as the preparation that contains *B. thuringiensis* (Avtzis1998). Gypsy moth control is being carried out in the early spring, right after young leaves emerge and during egg hatch.

Group B (Rarely Controlled)

***Stilpnotia salicis* L. (Silk Moth).** This leaf-eating insect has two generations per year and causes serious growth loss, especially following heavy defoliation in poplar plantations (Schwenke 1978). Its control is carried out in early spring, right after young larvae crawl into the crown. Control is conducted either from the ground or by aerial application using the same preparations as described in treating insects in Goup A.

Wood Boring Insects on Polpar Trees. The following wood boring insects mainly affect tree physiology and secondarily devalue the technical features of wood: (1) *Sciapteron tabaniformis* Rott., (2) *Cossus cossus* L., and (3) *Melanophila picta* Pall.. Control of these secondary harmful insects of poplar is conducted in spring during the adult flight and oviposition period. It is accomplished from the ground by totally covering the lower part of the stem with Diazinon 60wp.

***Laspeyresia splendana* Hb.** This insect attacks chestnut seeds and is controlled wherever and whenever it causes serious problems (Dimoulas 1986). Control is conducted in the summer during the adult flight and oviposition period using aerial applications of preparations that block chitin synthesis (contain inhibitors of cuticle development).

As has been pointed out, the Greek Forest Service has been using preparations that block chitin synthesis, Bt productions (Foray 48B), and Diazinon for the control of harmful insects. During the past few years, the following preparations were primarily used: (1) Dimilin 25wp or Alsystin (cuticle development inhibitor group) at a dosage of 250 gr/25 L water/ha, (2) Foray 48B (bioinsecticides group) at a dosage of 1.5L formulation/ha, and (3) Diazinon 60wp (chemical insecticides group) for ground applications at a dosage of 100 gr/100 L water. Aerial spraying was applied mostly with the Polish aircraft PZL-M18 (Dromader), Grumman-GR 164 airplanes, and Augusta Bell helicopters.

Discussion

Greece is located in Southern Europe in the temperate zone. Its Mediterranean climate is favorable for insect population development. Because chemical insecticides are widely used in agriculture, the Greek Forest Service, which manages nearly 60% of Greece's total land area, is particularly cautious about using aerial applications of insecticides in forest ecosystems and plantations.

This cautiousness increased after 1995 when, according to the decision of certain Research Institutes, the Highest Council of the State decided that aerial applications used for the control of *Dacus olaea* and other harmful insects must be restricted for the protection of public health as well as for the preservation of ecological stability. After that decision, Forest Service aerial applications were used only when insect epidemics tended to cause serious problems in recreational forests and parks or in vacation areas and various plantations.

The contrary is true in the case of high, productive forests, where the use of aerial applications with chemical preparations must be the final means when all other applied measures within the framework of integrated pest management (Dent 1991) have failed. In such cases, the protection and conservation of ecological stability are of highest priority, even at the expense of maximizing forest products.

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Coarse-Scale Hazard Rating of Western Hemlock Looper in British Columbia

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ABSTRACT The western hemlock looper (*Lambdina fiscellaria lugubrosa* (Hulst.)) is a serious defoliating pest in western North America. During the 1990-1995 outbreak, this pest was responsible for approximately 63 000 ha of stand mortality in British Columbia. There have been 14 distinct outbreaks, increasing in duration and severity over the past 87 years. Outbreaks tend to occur in Coastal and Interior Western Hemlock biogeoclimatic zones and generally last 2 to 5 years.

A Western Hemlock Looper Hazard Rating System (WHLHRS) is being developed to aid forest managers in dealing with western hemlock looper outbreaks. Province-wide hazard rating has been accomplished at a 2-kilometre grid scale. The hazard-rating values for this grid are based upon the locations of past outbreaks, presence of host forest stands, biogeoclimatic zones, climatic variables, and elevation.

This hazard rating mapping will be useful for future pheromone trap placement, in addition to aiding forest mangers in identifying susceptible forests. The forecasting of defoliation events and the identification of larger scale risk areas are the goals of the WHLHRS. The WHLHRS, as a whole, is anticipated to aid forest managers in dealing with outbreaks of western hemlock looper in an effective fashion through either direct control measures or modified silviculture practices.

OVER THE PAST 87 years, there have been 14 outbreaks of western hemlock looper (WHL) (*Lambdina fiscellaria lugubrosa* (Hulst)) (Lepidoptera: Geometridae) in British Columbia (B.C.), Canada. These outbreaks have increased in size, distribution, and intensity. This insect has been responsible for large areas of severe defoliation and tree mortality in recent years, particularly in the Nelson, Cariboo, and Prince George Forest regions of eastern and central British Columbia. During the last outbreak alone (1990-1995), over 63,000 ha of trees were killed and another 272,000 ha defoliated to varying degrees by the WHL. Outbreaks characteristically begin in old growth western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and remain within the Coastal Western Hemlock and Interior Western Hemlock biogeoclimatic zones (Krajina 1965, Pojar et al. 1987). Outbreaks have occasionally spilled into non-preferred tree species such as western red cedar (*Thuja plicata* Donn), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and western white pine (*Pinus monticola* Dougl.), among others, and their characteristic biogeoclimatic zones (Harris et al. 1982, Parfett et al. 1995).

Logging industry representatives from interior British Columbia indicated their desire for some form of hazard rating system to be developed so that high-risk areas can be identified and monitored. This report outlines some of the major steps in developing a hazard rating system for the western hemlock looper, with the intention of delivering such a system to aid forest managers in their decision-making process.

Pages 6-15 in Liebhold, A.M.; McManus, M.L.; Otvos, I.S.; Fosbroke, S.L.C., eds. 2001. **Proceedings: integrated management and dynamics of forest defoliating insects**; 1999 August 15-19; Victoria, BC. Gen. Tech. Rep. NE-277. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

The creation of the Western Hemlock Looper Hazard Rating System (WHLHRS) is designed to be a multi-stage process. This initial stage involves risk rating the entire Province at a coarse 2-km grid scale. This grid was developed to identify similar traits among regions that have experienced a looper outbreak and to exclude areas that possess no risk for the development of WHL outbreaks. The next stages will involve prediction of the timing and stand-level location of western hemlock looper attacks.

It is hoped that the identification of areas at risk to WHL outbreaks will aid several components of the forestry sector. Forest managers, although they most likely have already identified problem areas prior to this, will now have an accurate definition of areas at risk for looper outbreak. It may also allow for the implementation of preventative silviculture. Following harvesting, areas that are known to harbor looper outbreaks may be re-planted with non-host or less suitable tree species for the looper. The identification of risk areas will also aid in population monitoring of the WHL. Pheromone trapping of adult male looper moths has been conducted in B.C. since 1992. At present, 23 locations selected by Forest Insect Disease Survey (FIDS) rangers based upon their professional and empirical experience are being sampled. In conjunction with the hazard rating mapping, placement of additional traps in the future and continued monitoring of these "sentinel traps" will provide a thorough coverage of at-risk areas. It is expected that a permanent pheromone trap network, supported by other sampling methods, will provide the final basis for outbreak forecasting.

Materials and Methods

Hardware and Software. An extensive Geographic Information System (GIS) is already in place at the Pacific Forestry Centre. Most analysis has occurred using the Environmental System Research Institute's (E.S.R.I.) software program ARC/INFO (version 6.0). Display and map production was performed using ESRI's Arcview (version 3.0a). This software sits on a UNIX network operating on a SUN Sparcstation platform. Data are stored on a RAID system disk

Digital Data. The most extensive portion of this project has been to research and collect digital data. Because the objective of hazard rating has been to define areas with similar physical and climatic parameters where looper outbreaks have occurred (i.e. elevation, temperature, etc.), the acquisition of accurate digital data is essential. Digital data have the potential to contain many sources of error; the details are lengthy and can be best explained by a good GIS textbook. Sources of error include: sampling error, equipment calibration, transformation error, classification error, machine precision, digitizing error, errors of scale, compounding, etc. Two of the main problems in obtaining data for this project were: (1) data availability was limited due to differing scales and / or prescision and (2) lack of existing data. The latter will be discussed at the end of this section.

Data Summary.

(1) Western Hemlock Looper Defoliation data (1911 to 1995)
(2) Grid Location of Mature Hemlock Stands in B.C. based upon Forest Inventory Planning Files (1996)
(3) Biogeoclimatic Zones (Ministry of Environment Lands and Parks)
(4) Digital Elevation Model (DEM) of British Columbia (USGS)
(5) Ecodistricts of Canada (CanSIS 1995)

(6) Precipitation by Ecodistrict (CanSIS 1995, Environment Canada 1961 to 1990 Climate Normals, Polestar Geomatics)
(7) Temperature by Ecodistrict (CanSIS 1995, Environment Canada 1961 to 1990 Climate Normals, Polestar Geomatics)

The WHL defoliation data were previously produced by a number of sources and based upon annual FIDS reports. WHL defoliation data were recorded during aerial surveys in late summer after insect feeding was completed. Defoliation surveys from fixed-wing aircraft were accomplished by sketching defoliated areas onto 1:100,000 or 1:250,000 scale maps, with an estimated 200- to 300-m positional accuracy for the defoliated polygons (Bob Erickson NRCAN-CFS-Pacific, personal communication). The former FIDS rangers digitized and classified defoliation areas from annual aerial survey maps since 1985 by defoliation severity. In addition, we digitized previous years' sketch maps and interpreted descriptive reports of early outbreaks into a digital representation (Parfett et al. 1985). The construction of this database was part of a prior project.

Point locations of mature hemlock stands were taken from the database component of Forest Inventory Planning (FIP) files that contain information on forest cover in ASCII text format. Mature hemlock is defined as any stand that has an age class of six and above (i.e. all stands older than 120 years). This age class was chosen based on the FIDS rangers' experience and empirical observations of WHL outbreaks. These points, representing the centroid of forest-stand polygons, are referenced in UTM coordinates to the lower left hand corner of a 2-km by 2-km grid coverage of British Columbia. Attribute information includes: stand area, composition, age class, road access, UTM zone, and percent hemlock in each stand. This point information was in a comma-delimited format. It was imported, projected, and joined in ARC/INFO as an Arc coverage. Multiple stands within the same grid were combined and stand area, age class, and percent hemlock were averaged using an area-weighted function. In addition, 1,000 m was added to the easting and the northing to place the point in the middle of the grid. This data is intended for use at a scale of 1:20,000.

Biogeoclimatic data have been made available for electronic use by the British Columbia Ministry of Forests. These data have been referenced to varying scales at different locations; specific details are available at:

ftp.env.gov.bc.ca/dist/arcwhse/wildlife/qbec_bc_meta.txt

The DEM data have a 1,000-m precision and are based upon the USGS DEM of North America. Because we were limited to our coarsest data scale, we declined to use a more detailed DEM.

Obtaining accurate and precise climate models for B.C. was the single most constraining task during the course of this project. Several groups are in the midst of creating Canadian climate models. Two of the more promising models are being constructed by D.W. McKenney of the Canadian Forestry Service in Sault Ste. Marie, Canada, and Christopher Daly of Oregon State University, U.S.A.. The decision was made to use Ecodistrict normals in the analysis. The production of these data was commissioned by Agriculture and Agrifood Canada and is readily available over the Internet via: http://res.agr.ca/CANSIS/NSDB/ECOSTRAT/DISTRICT/climate.html (Note: This website address is case sensitive). These data are an average of the 1961 to 1990 climate data in each ecodististrict. The downside of these data is that these normals are aggregated into large areas. The positive aspect is that ecodistrict data does have the advantage of its unique classifications. In either case, the availability of decent climate data has been a major limiting factor. As a result of this, climate data were weighted considerably less than was originally planned.

Process. The rationale and theory behind the WHLHRS is that it's necessary to find areas bearing common characteristics to regions that have experienced past WHL outbreaks. This entails comparing each areas's parameters to WHL outbreak area parameters and determining the specific characteristics (if any) that exist during outbreaks (i.e., if the majority of outbreaks occurs between 500 and 600 m in elevation, then all areas between 500 and 600 m in elevation share this common characteristic with outbreaks). These common characteristics are mapped and added together to determine locations across the Province that share the same specific charcteristics as regions where WHL outbreaks have occurred. This process involves six steps:

(1) Data research and gathering. In this initial stage we examined what data might pertain to outbreaks, as well as determined the availability.
(2) Overlaying each separate parameter (DEM, Climate Data, Biogeoclimatic Zones) with WHL outbreaks.
(3) Analysis and identification of parameters common to outbreak areas. Each parameter was examined by range (e.g., elevation of 0 to 200 m, 200 to 400 m, etc.) for the WHL outbreak area. This was then compared to the WHL total outbreak area.
(4) Rasterization of the parameters is a fairly simple process. The transformation from polygons to raster data format in ArcInfo was performed using the percentages as grid values. For example, if 60% of the area where outbreaks have occurred lay within 500 to 1,000 m of elevation, the resulting grid value for those areas was 6. Areas below 1% were given a value of 0.
(5) Weighting of the parameters was performed using two methods. First, the FIDS rangers were given a survey that requested they rank the parameters in order of importance based upon their experience when considering areas at risk for WHL outbreak. The results of this survey largely ended up being a collaborative consensus among the rangers, giving a fairly uniform ranking system.

The final global weighting, based upon the rangers' ranking of importance of the eight factors, is tempered by the accuracy of the data. Parameters are also weighted locally by the distribution of past defoliation through the range of the data. Parameter suitability for hazard assessment is evaluated by whether or not there was a difference in the distribution between defoliated and undefoliated hemlock stands for each parameter. Distributions that are identical between defoliated and undefoliated stands are excluded from this analysis. The following figures were derived by overlaying defoliated and undefoliated hemlock stands with the individual parameters and comparing their distributions. Ideally, defoliated stands will possess a different distribution than undefoliated stands if a particular parameter is to be of any use in the analysis.

It is apparent that the distribution of defoliated stands when considering elevation is much more clustered than the undefoliated stands, although it tends to follow a similar trend (Fig. 1).

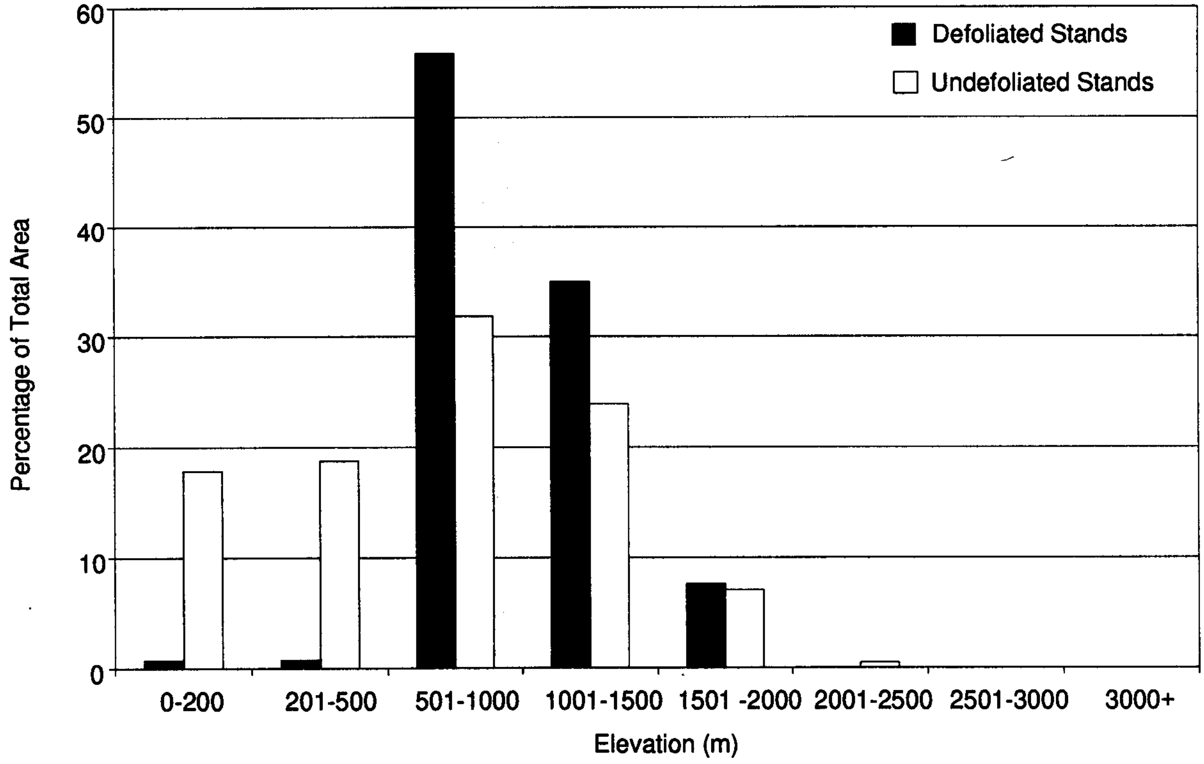

Figure 1. The distribution of undefoliated and WHL-defoliated mature hemlock stands by elevation in British Columbia.

In general, the majority of the defoliated stands were within the 500 to 1,500 m elevation range, whereas the undefoliated stands tended to be more normally distributed. The main drawback of using coarse-scale DEM data is that it does not account for detailed topography. This can be misleading, for example, where an area of high relief along the coast of B.C. has the same elevation as the valley floors of the interior. The fact that the low relief of the valley floors has harbored the majority of the attacks (Erickson 1984) is ignored in this situation. The DEM data is given the least amount of weight with regard to the final hazard model. The primary use of this data was to remove unreasonable areas from the analysis, such as high altitude regions.

Most of the defoliation occurred within ecodisticts receiving, on average, between 36 and 46 cm of precipitation in June (Fig. 2). Once again, this differed greatly from the distribution of the undefoliated hemlock stands, making this a potentially useful parameter in identifying areas prone to outbreaks.

Significant differences in the distribution of defoliated versus undefoliated stands also occurred for the biogeoclimatic zones and the rest of the climate data (minimum, maximum, and average temperatures for June and July as well as precipitation for those months).

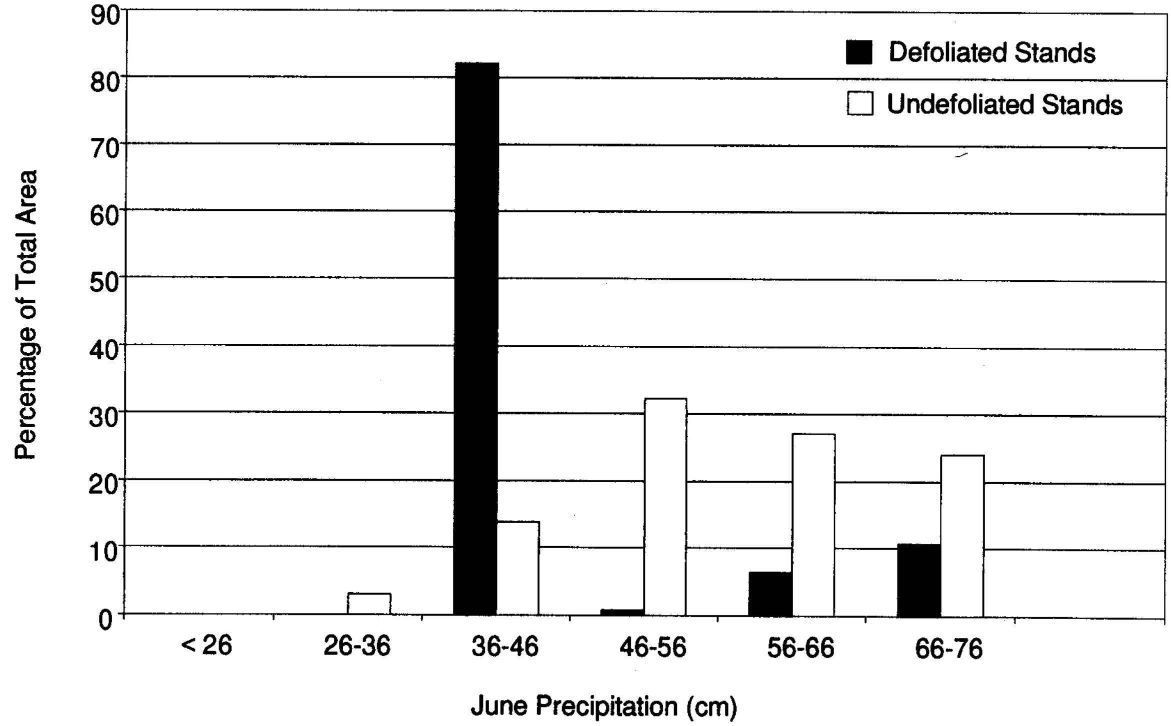

Figure 2. The distribution of undefoliated and WHL-defoliated mature hemlock stands by average June precipitation in British Columbia.

In addition to the DEM, biogeoclimatic data, and climate data, various stand characteristics were explored and were found to have differing distributions between defoliated and undefoliated stands. Given the looper's preference for mature growth hemlock, stands that were younger than 120 years were excluded from the analysis, but other characteristics, such as percent hemlock and stand size, were examined. Looper attacks are not limited to mature hemlock; however, because we are using point-source forest cover data for the entire Province, it is impossible to include all forest stands in the analysis. Actual stand preference will be examined in the next phase of analysis, utilizing more detailed forest cover data within smaller test regions.

We can see that stand areas of defoliated and undefoliated hemlocks did not differ in distribution (Fig. 3). It is evident that this lack of distinction renders stand size ineffective as a characteristic for defining areas at risk from defoliation at this scale. Overall stand hemlock content presented similar results, indicating that stand characteristics are not a factor in determining outbreaks, and that the presence of host trees is the only stand requirement.

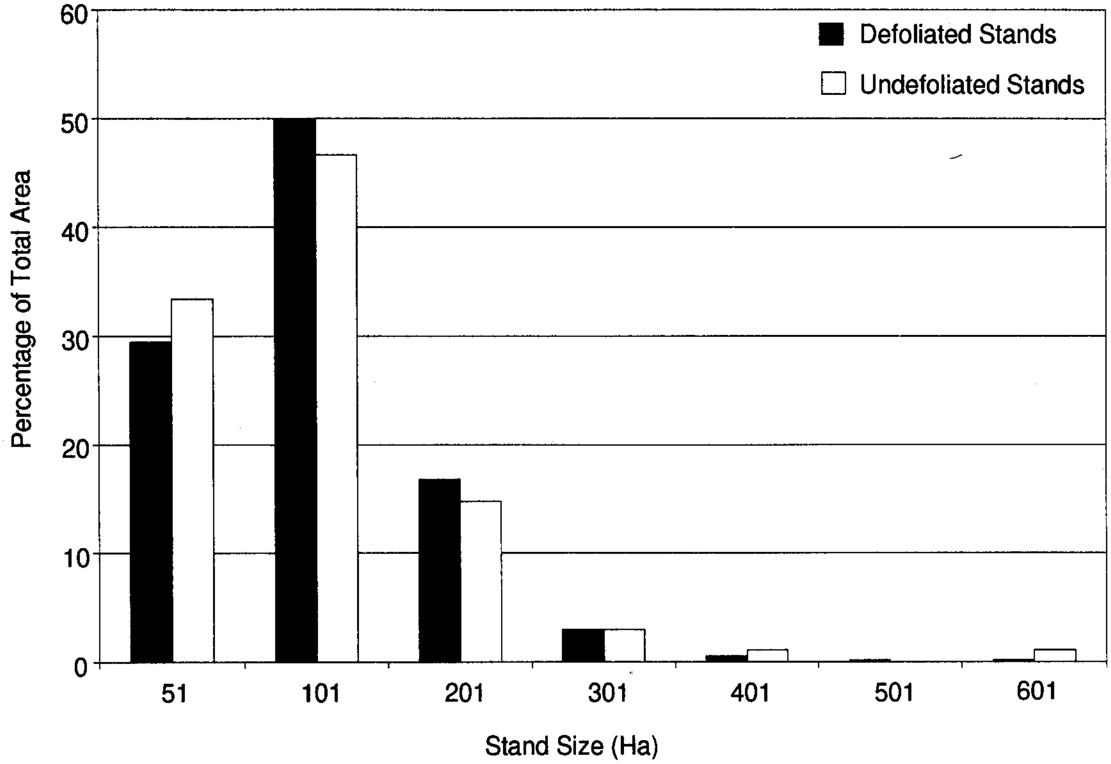

Figure 3. The distribution of undefoliated and WHL-defoliated mature hemlock stands by stand size in British Columbia.

Once the final parameters were chosen, the weighting scheme was applied to the individual parameters. Grid values were multiplied by the weight given to each parameter (Table 1). The proximity to past outbreaks was considered the most important factor at this scale, as outbreaks tend to occur within the same areas, provided the stands are not killed during the course of defoliation or through some other form of disturbance. Past hazard rating models only considered this factor in a vector-based hazard rating system. We feel that the addition of other variables improves the scope and coverage of this system.

Table 1. Weighting scheme for final parameters

Parameter	Weighting
Proximity to past outbreak	20
Location of Mature Hemlock	10
Biogeoclimatic Zones	3[a]
Climate factors	0.25[a,b]
DEM	1

[a] These weightings were multiplied by the existing grid value to give a higher number, whereas the first two parameters were binary, either receiving the weighted amount or zero

[b] The climate factors (Average June and July Precipitation, Average June and July Temperature, and Minimum and Maximum Temperature for June and July) were all added

(6) For the final hazard grid production, several weighting schemes were considered. Many models consider a multiplicative function, whereby all parameters are multiplied by one another. This type of model tends to emphasise interactions among parameters; the obvious result is that the whole is greater than the sum of the parts. The data available to the WHLHRS is somewhat non specific. Climate data is aggregated to an average of values over each ecodistrict. We felt that an additive model would be less misleading, particularly given the spatial area where specific interactions are unknown given the present data coverage. As a result, the parameters were added to one another to arrive at a summed grid. The areas that are most in common with the outbreak areas have increasingly higher numbers. The areas most at risk have experienced past outbreaks.

Once this final hazard-rating grid had been calculated, it was multiplied by a binary grid to exclude regions that are unlikely to harbor looper outbreaks. As previously mentioned, such regions include high elevations such as mountain tops, non-host biogeoclimatic zones, etc. It was hoped that one could exclude regions that have been logged of mature trees, but this data was unavailable for inclusion on a province-wide level. A negative impact of its inclusion would be that the hazard rating would exclude areas that may benefit from silviculture planning. The final raster layer has a resolution of 2,000 m. The majority of the data was able to be converted to raster with a 1,000-m resolution; however, the mature hemlock data had been located to the aforementioned 2-km grid, hence the resolution limitation.

Results and Discussion

The final raster grid gives hazard scale values from 0 to 72. Cell locations were rated as minimal, low, medium or high with regard to WHL outbreak hazard. This was an arbitrary classification, although there was some rationale used in determining bin values. There are numerous ways of devising classification schemes; however, it may be preferable for forest managers to use their own judgement when aggregating values into bins, based upon their own objectives. For the purposes of this report, a minimum was established for low risk areas; cells had to have experienced defoliation in the past, or they must possess many of the same qualities as areas that have been defoliated. Due to the spatial aggregation of the climate data, histogram analysis identified several natural breaks in the distribution of the cell values. For the purposes of display, these breaks were used to classify cell values. The data was classified as follows: < 20 = minimal risk, 20-27 = low risk, 28-36 = medium risk, and 36+ = high risk. The final hazard rating analysis was then plotted using an HP DesignJet 755CM plotter.

Figure 4 gives an overview of the areas at risk in British Columbia, projected in Lambert conformal conic, using a NAD27 datum and a Clarke1866 spheroid. The inset area detailed is the Nelson Forest Region. The highest risk areas conform to locations where defoliation has occurred in the past, as one would expect based upon the weighting system. Medium and lower risk regions are located near the high risk regions and typically include areas that have mature hemlock and/or a susceptible biogeoclimatic zone in combination with climate variables similar to previously defoliated regions. Limitations with the present hazard-rating mapping include being constrained by the lack of specific data for the entire province as well as its limited operational use. A more accurate climate model is imperative to refining the hazard rating. Climate data have been given relatively low weighting and it is also prohibitive when considering a multiplicative model. A more refined DEM and contours would also improve the accuracy of the mapping. The present mapping provides decision support when considering the placement of pheromone trapping. It also provides a good reference for generalized risk regions.

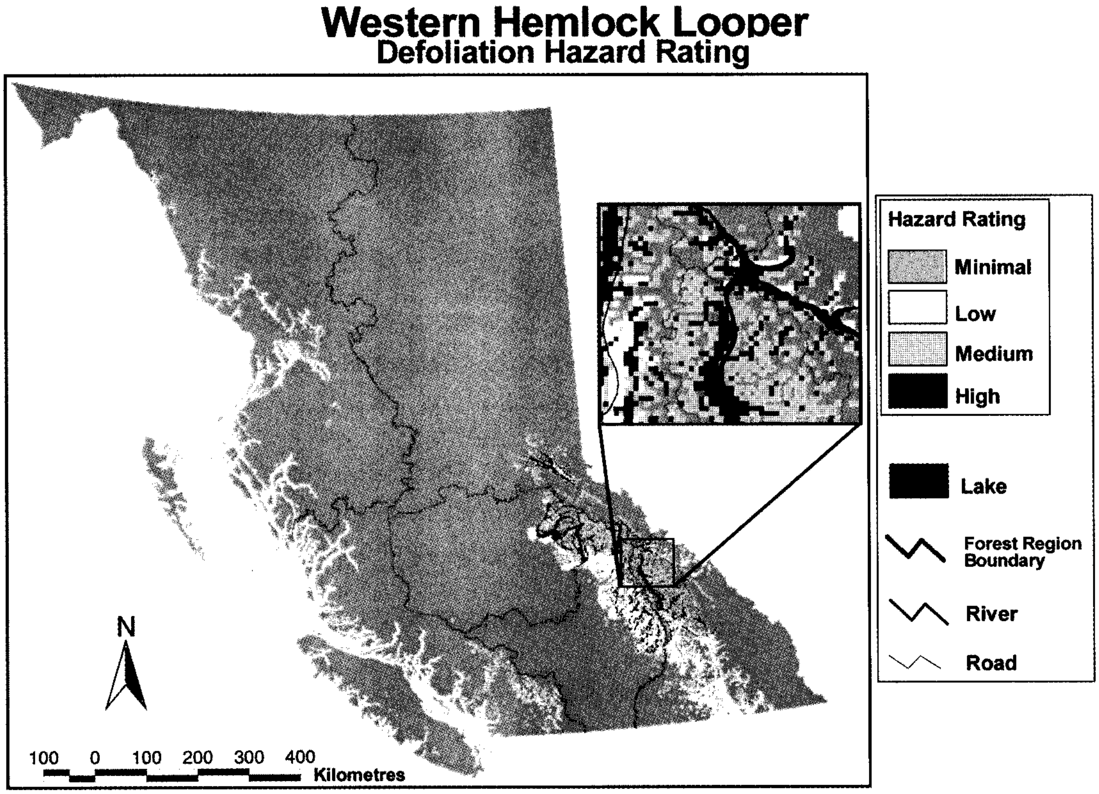

Figure 4. Coarse-scale hazard rating for the Province of British Columbia, Canada.

Although stand-level mapping was not within the scope of the initial province-wide hazard assessment, this will become the focus of the next stage of hazard and risk rating. Future refinement will focus upon specific stand attributes, drawing upon nearby climate station data, and site-specific information and data (pheromone trap counts, defoliation history, etc.) to use risk rating at the stand level.

Conclusion

Efforts in the coming months will be concentrated on the creation of a more detailed stand-level risk assessment rating. Many components are required to realize such a system and research into these components is continuing. Various models that incorporate local weather conditions, three-tree beating data on looper larval density (used as a proxy measure of population until pheromone trapping follows one cycle), biogeoclimatic zones, and tree stand characteristics will be evaluated. Current pheromone trap locations will be examined and moved if necessary after the stands most likely to suffer looper attacks have been clearly identified. The aim of creating a forecasting system to predict western hemlock looper outbreaks is an attainable goal.

The WHLHRS hinges on accurate data for its operation; however, the acquisition of accurate data requires time. Data availability is often limited by technology, storage space, and fiscal constraints. Essential to this process is a need to know how the data are being used. By identifying the end product, pheromone trapping can proceed in areas identified as having a high risk of future defoliation, and the present pheromone trap system can be expanded as trap catches rise. Climate data from these trapping sites can be used in conjunction with defoliation history and stand health to forecast the probability of future outbreaks and subsequent stand mortality. In addition to this, more accurate climate models and DEMs may be employed in the near future and used to refine existing hazard rating maps. It is anticipated that such a system will aid forest managers in dealing with western hemlock looper outbreaks in an effective fashion, both through direct and indirect pest management methods, depending on the value of the threatened stands.

Acknowledgments

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Effects of Gypsy Moth Defoliation on Tree Growth – Preliminary Models for Effects of Cumulative Defoliation on Individual Host Tree Radial Increment

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ABSTRACT Two hundred and one stands in the Ridge and Valley physiographic province of central Pennsylvania (USA) were followed from 1978 to 1985 and approximately one third of these stands were followed until 1995. Individual trees on three 0.10-acre (0.040 ha) plots per stand were visited each year. These stands experienced two major defoliation episodes by the gypsy moth (*Lymantria dispar* L.), first from 1981 to 1982 and again from 1986 to 1987; some trees and stands also experienced significant defoliation in the early 1990s. In 1995, increment core samples were collected from plot trees based on a matrix of species, stand defoliation history, and crown class (dominance). In this paper, we consider only core samples from the red oak and white oak species groups. We first examine the relationship between the sample population and the earlier classification of the forested area where the research sites are located. Results indicated that using these data, models can be developed across the site classification scheme. We then consider the appropriateness of developing a single model for both species groups. Finally, we consider a cumulative effects model with the data organized by severity of defoliation to individual trees over three years (current and the past two years' defoliation). Results provide reasonable individual tree growth effects for the species under consideration. In a forest model that uses individual tree lists to simulate forest stands, these growth effects models can be linked to population dynamics models for the gypsy moth to obtain a dynamic model for an individual stand or larger forested areas.

GYPSY MOTH (*LYMANTRIA dispar* L.) is a non-native pest in North America. After it was introduced through an accidental release in the Boston area in 1869 (Liebhold et al. 1989), it has been slowly spreading, generally moving west and south. Because the adult female does not fly more than a few feet, if at all, the population spread has been quite slow and central Pennsylvania was not generally infested until the 1980s. The data used in this study are all taken from the study area originally set up by David Gansner and Owen Herrick in 1978 (USDA Forest Service Cooperative Study 4820-FS-NE-4201-35). The objectives of the original study were to monitor gypsy moth impacts in forest stands and evaluate and refine stand hazard rating procedures that predict tree mortality and value loss following a gypsy moth outbreak (Gansner and Herrick 1984, Herrick and Gansner 1986, Gansner 1987, Herrick and Gansner 1987a). As gypsy moth first invades a new area, populations can reach outbreak proportions in just two or three years, as happened in central Pennsylvania. Gypsy moth populations were first seen in 1979, and by 1980, considerable defoliation was recorded on many of the study plots. The cooperative study ended in 1984, but by then the USDA Forest Service State and Private Forestry – Forest Pest Management staff had agreed to continue the monitoring project for several years (Gypsy moth hazard rating pilot project field guide – 1983, Jesus A. Cota and Frank J. Kenny, unpublished). In 1986, the new Forest

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Pages 16-30 in Liebhold, A.M.; McManus, M.L.; Otvos, I.S.; Fosbroke, S.L.C., eds. 2001. **Proceedings: integrated management and dynamics of forest defoliating insects**; 1999 August 15-19; Victoria, BC. Gen. Tech. Rep. NE-277. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

Service gypsy moth research project RWU-NE-4507, Silvicultural Options for the Gypsy Moth, in Morgantown, WV, agreed to continue following approximately one third of the study plots. Due to limitations in available support, 75 of the original 201 stands (225 plots) were selected to be maintained.

Data collection continued following the previous standards, but tree vigor (health) ratings were added to the data set. These plots were visited annually from their establishment in 1978 until 1992 and again in 1995; although field data was collected in 1985, we do not have these data to include in our analyses. Gypsy moth defoliation continued through the 1980s and to a lesser degree in the early 1990s; however, heavy mortality in the early 1980s reduced vulnerability of many of the residual stands. The influx of natural enemies may have also reduced the severity of defoliation impacts from subsequent outbreaks in many of the stands that were severely affected by the initial outbreaks. While considerable attention has been given to defoliation effects on tree mortality (Gottschalk et al. 1998) and stand composition (Feicht et al. 1993), to date these data have not been used to investigate the effects on tree growth.

Location and Description of the Study Site

Originally, three plots were established in each of 201 stands in the Ridge and Valley physiographic province of central Pennsylvania. The stands are all located from Nittany Mountain, just northeast of State College, PA south and east to just northwest of Harrisburg, PA; all are located west of the Susquehanna River. Stands were located on ridge tops or generally dry, upper slopes that were dominated by oak species. Plots were permanently marked and described for future relocation. The 0.1-acre circular plots were laid out 300 feet apart in an equilateral triangle. Physiographic features were recorded for each plot and all trees 3 inches in diameter at breast height (dbh) were permanently marked with paint.

Due to limitations in available support, 75 stands (225 plots) of the original 201 stands were selected to be maintained beyond 1985. The original stands were classified using methods for rating stand susceptibility to defoliation and vulnerability to mortality following defoliation that were developed by Gansner and Herrick (Gansner and Herrick 1985, Herrick and Gansner 1987b). The original distribution of stands was 24, 40, and 35 percent in the high, moderate, and low defoliation classes, respectively. Approximately one third of the 75-stand subset was drawn from each of the three defoliation classes. Since the subset was selected in 1986, some stands were protected from imminent defoliation in the early 1990s by spraying and a few were sufficiently affected that they were incorporated into salvage sales. These stands have been dropped from the data set for this study. At present, there are 22, 19, and 22 stands, respectively, in the high, moderate, and low defoliation classes.

The Data

For this study, we used the final defoliation classification of stands to stratify data collection. Approximately one third of the sample trees were to come from each of three defoliation classes (high, moderate, and low), three tree dominance classes (dominant/codominant, intermediate, and suppressed), and three species groups (red oak group, white oak group, and other species). A total of 477 trees was sampled by extracting two increment cores per tree at breast height and coring as close as possible to pith. Table 1 displays the tree counts by species and species group for the 303 oaks sampled using this stratification. In addition, 174 non-oak trees were sampled for dendrochronological growth analysis, but the majority of these were red maple (71 trees); it has been discovered that the diameter growth pattern of this species is not conducive to analysis using increment cores.

Table 1. The number of oak trees sampled by species and species group in each defoliation and dominance class

Species Alpa Code	Species Numeric Code	Species Common Name	Defoliation Class (No. Trees Sampled) High	Moderate	Low
WO	802	White Oak	4-0-0[a]	1-1-1	6-5-5
CO	832	Chestnut Oak	17-19-16	18-16-16	11-22-13
White Oak Group			21-19-16	19-17-17	17-27-18
RO	833	Red Oak	13-7-5	18-16-8	16-20-8
BO	837	Black Oak	6-7-2	1-2-1	3-3-1
SO	806	Scarlet Oak	6-2-1	1-3-1	1-0-0
Red Oak Group			25-16-8	20-21-10	20-3-9

[a] The sequence a-b-c gives the counts for the three dominance classes: a = dominant/codominant, b = intermediate, c = suppressed.

Atlhough a well-distributed sampling plan was carried out, for this study we used only those oak samples that had two cores per tree and were found to be consistently dated using the Cofecha program from the International Tree Ring Society's (ITRDB) Program Library (Grissino-Mayer et al. 1997). Those samples are summarized in Table 2. We are in the process of re-dating, re-measuring, and analyzing the remaining data to increase the strength of the analysis that we present here. The increment cores were mounted, dried, and sanded. After manual dating of each sample, ring width was measured using a digital micrometer equipped with a microscope. The ring-width series measured from two cores per tree constitutes the basic raw data. For this preliminary analysis, we considered the data for five species of interest: northern red oak (*Quercus rubra*), white oak (*Q. alba*), chestnut oak (*Q. prinus*), scarlet oak (*Q. coccinea*), and black oak (*Q. velutina*).

Table 2. The number of trees used in this study by species in each defoliation and dominance class (the comments on the sample size are based on the ITRDB standard of 10 trees to construct a species chronology)

Species Alpa Code	Species Numeric Code	Species Common Name	Defoliation Class (No. Trees Sampled[a]) High	Moderate	Low
WO	802	White Oak	5 (I)	0	14 (MS)
CO	832	Chestnut Oak	34 (S)	39 (S)	33 (S)
RO	833	Northern Red Oak	17 (MS)	23 (S)	29 (S)
BO	837	Black Oak	3 (I)	1 (I)	3 (I)
SO	806	Scarlet Oak	6 (I)	3 (I)	3 (I)

[a] I = Insufficient sample size
S = Sufficient sample size
MS = Moderately sufficient sample size

The available data (number of sampled trees) for each species is given in Table 2. Based on the rule of thumb set forth by the International Tree Ring Data Bank, a minimum of 10 trees was required to build a species chronology. Therefore, the comment regarding the sample size (number of trees per species) is based on this standard. Except for chestnut oak and northern red oak, the other tree species did not have sufficient samples to carry out a more elaborate statistical analysis. We plan to complete those analyses following reprocessing of the field samples.

Tree-Ring Data Quality Control

Before tree ring chronologies were developed, the quality of the measured tree-ring series was tested using the Cofecha program of Holmes (Holmes et al. 1986) from the ITRDB Program Library (Grissino-Mayer et al. 1997). The program checked for cross-dating errors, measurement errors, and other ring width irregularities that might limit the usability of the ring-width time series for tree ring analysis. Based on the output from the Cofecha program, cores with no measurement or dating errors were used in further analysis. Cores with dating or measurement problems were removed from the data set. This resulted in a reduction of the sample size (number of trees/species). In light of the common characteristics of the species, two species groups were created:

(1) Red oak group (Species Group I): contains all data for northern red oak, scarlet oak, and black oak.
(2) White oak group (Species Group II): contains all data for white oak and chestnut oak.

Three chronologies (standard, residual, and arstan) were developed using the ARSTAN program (Holmes et al. 1986); due to negligible differences in these chronologies, we chose to use the standard chronology as a response variable in the analysis of growth in relation to defoliation. All subsequent statistical analyses showed nearly identical results for all chronologies. A standard chronology is most commonly used in tree ring research.

Methods

A ring width produced in a particular year is a function (product) of several interrelated biological, physical, stand, and climatic factors. Since our main objective was to understand or evaluate the effect of defoliation on growth, it was necessary to use a growth response variable that reflected the effect of defoliation; hence, factors that affected the width of an annual ring produced in a given year that were not related to defoliation (e.g., dbh and biological persistence) were removed from the ring-width series.

After the quality check, the ring-width series of each remaining core (for both species groups) was standardized (Fritts 1976, Cook 1985) to remove long-term trends in growth associated with tree age, size, and stand dynamics. The need for standardization prior to creating a stand-average ring chronology is discussed in detail in Fritts (1976) and Cook (1987). Because the ring-width series were rarely more than 100 years long, negative exponential or linear regression curves were used to detrend the series.

After the growth curve was estimated for each series, each value of the series was then divided by the corresponding value of the growth curve. The resulting ratio was a series without trend or long waves. This process transformed the ring-width values to tree-ring indices that exhibited a mean of 1 and a variance that was independent of tree age, position within the trunk, and mean growth of the tree. This kind of transformation is called detrending, or standardization, and its purpose is to remove long-term trend or low frequency variance from the tree-ring series.

Mathematically, let R_t be the ring width (mm) for year t and G_t be the fitted ring width (mm) from the detrending model for year t. Then

$$I_t = \frac{R_t}{G_t}$$

is a unitless tree-ring index for year t. In this step, R_t for each core is transformed into I_t. The resulting index series (I_t), also called the "filtered" or "smoothed" series for each core, is a series "free" of long-term trend or low frequency variance. If $I_t > 1$, then growth in year t is above average, and if $I_t < 1$, then growth in year t is below average.

An additional source of variation in ring-width series arises from the persistence of various effects into subsequent years through variation in food reserves and preconditioning of growth. That is, tree ring series invariably possess some degree of serial persistence or autocorrelation that is principally due to physiological preconditioning within the tree. Therefore, the information contained in a given ring width is somewhat determined by past tree growth and vigor. The autocorrelation structure of tree ring indices can be adequately modeled as an autoregressive process. The magnitude of autocorrelation can be assessed by calculating autocorrelation and partial correlation functions. The general autoregressive (AR) process of order P has the form:

$$I_t = \left(\sum_{i=1}^{P} \phi_i I_{t-i} \right) + e_t$$

where:

I_t is the observed process for year t, e.g., ring index for year t

ϕ_i is the autoregressive coefficient of the AR (P) process, i years past

e_t is an unobserved error that does not contain any autocorrelation

Programs like ARSTAN use such time series techniques to model and transform each filtered series to a residual series statistically equivalent to white noise. That is, due to the existence of autocorrelation in the indices, the ring-width index of each year for each core is autoregressed by the index of the previous year. The residuals of the autoregression model are used as response variables for further statistical analysis. However, the analyses performed using these pre-whitened chronologies provided similar results as those using the standard chronologies in this study.

Results

Chronology Comparison. After the species groupings were performed, the data were analyzed in ARSTAN to create standard chronologies for each defoliation rating: high, moderate, and low. Figure 1 compares the standard chronology for high, low, and moderately rated stands in Species Group I. Figure 2 depicts the same information as in Figure 1 but for Species Group II. In both figures, there was no apparent difference in chronologies due to defoliation rating (high, moderate, and low). To confirm this visual comparison of chronologies, a two-way analysis of variance was performed to detect any statistical significance. The analysis was conducted using year and the ratings (high, moderate, and low) as treatment groups and standard chronology as the response variable.

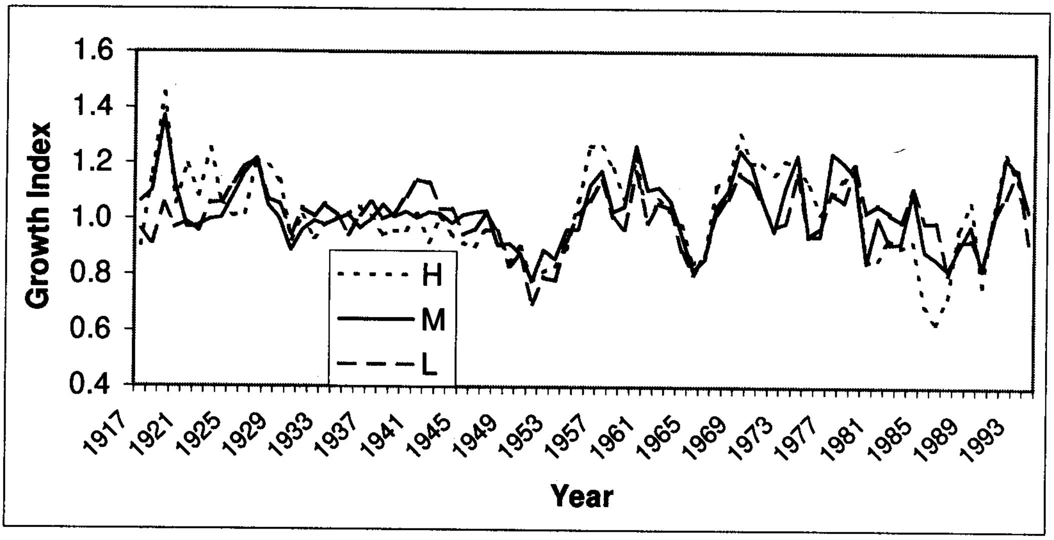

Figure 1. Standard chronologies for Species Group I (red oak group) in the high (H), moderate (M), and low (L) defoliation classes.

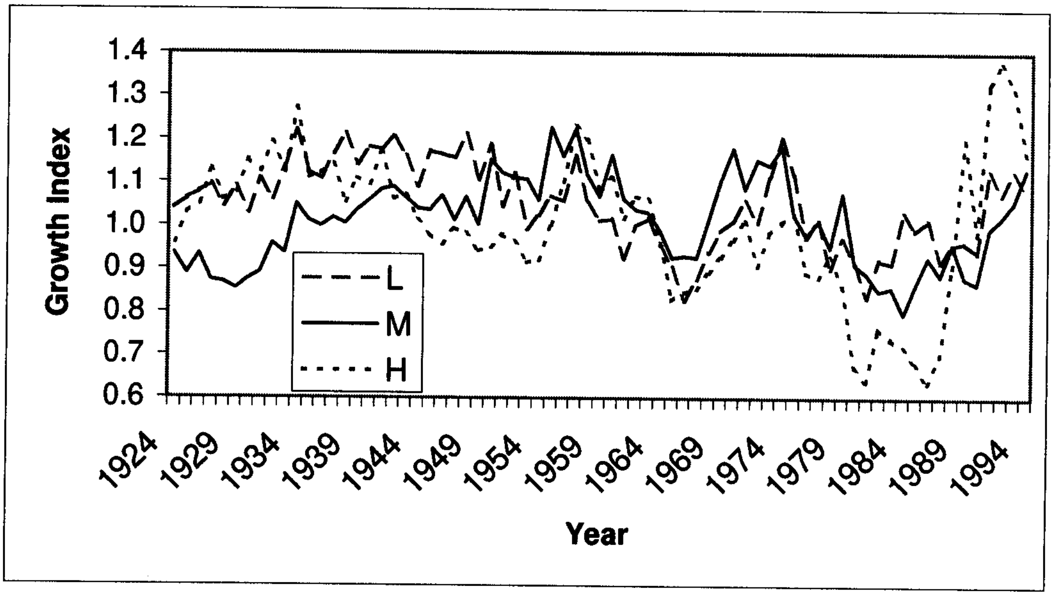

Figure 2. Standard chronologies for Species Group II (white oak group) in the high (H), moderate (M), and low (L) defoliation classes.

Analysis of variance was used to investigate the differences among standard chronologies within the original defoliation classification. Tables 3 and 4 show the results of the ANOVA. The response variable in this analysis was the standard chronology index and the independent variables were year and defoliation class.

Table 3. Summary statistics and a two-factor analysis of variance comparing standard chronologies in the high, moderate, and low defoliation classes for Species Group I (red oak group)

SUMMARY

Defoliation Class	*Sample Size*	Sum	Average	Variance
High	78	79.827	1.023423	0.02347
Moderate	78	79.745	1.022372	0.014467
Low	78	78.673	1.008628	0.010654

ANOVA

Source of Variation	***SS***	df	***MS***	***F***	P-value	F crit
Year	2.921063	77	0.037936	7.120945	4.3E-25	1.371692
Class	0.010631	2	0.005315	0.99776	0.371075	3.054765
Error	0.820414	154	0.005327			

Table 4. Summary statistics and a two-factor analysis of variance comparing standard chronologies in the high, moderate, and low defoliation classes for Species Group II (white oak group)

SUMMARY

Defoliation Class	Sample Size	Sum	Average	Variance
Low	71	74.656	1.051493	0.009523
Moderate	71	71.848	1.011944	0.010379
High	71	71.173	1.002437	0.025733

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Year	1.940603	70	0.027723	3.095365	6.79E-09	1.392513
Class	0.096112	2	0.048056	5.365612	0.005685	3.060762
Error	1.253876	140	0.008956			

These results indicated that for both species groups, there were no significant differences among the standard chronologies due to differences in defoliation classification of the stands. Because the P value for the white oak group was low, we re-analyzed just the data where defoliation data existed to confirm the fact that the between-class differences were not significant. The result was not significant over the shortened range ($F_{2,32} = 1.01896$, $P = 0.37238$). Thus, it was reasonable to combine tree ring series from these classes in further analysis.

Growth In Relation To Defoliation. Individual tree defoliation data was only available from 1978 to 1992. The pattern of average defoliation over time is depicted in Figures 3 and 4 for Species Group I and II, respectively. The figures indicate that defoliation varied in a haphazard manner with no clear and detectable cyclic trend. A meaningful statistical comparison of the defoliation data among the different classes could not be made due to (1) small sample size (14 observations) and (2) the fact that the assumption of homogeneity of variance was violated (see Table 5).

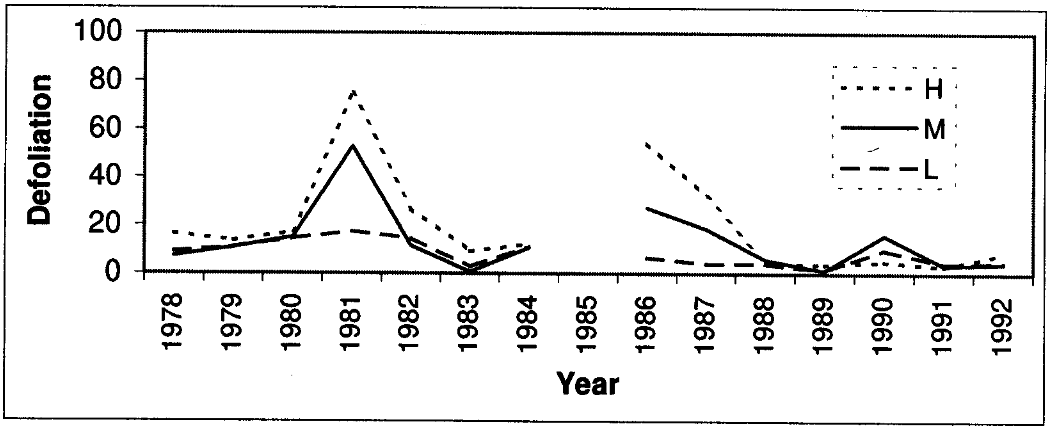

Figure 3. Pattern of average defoliation over time for Species Group I (red oak group) at high (H), moderate (M), and low (L) defoliation sites.

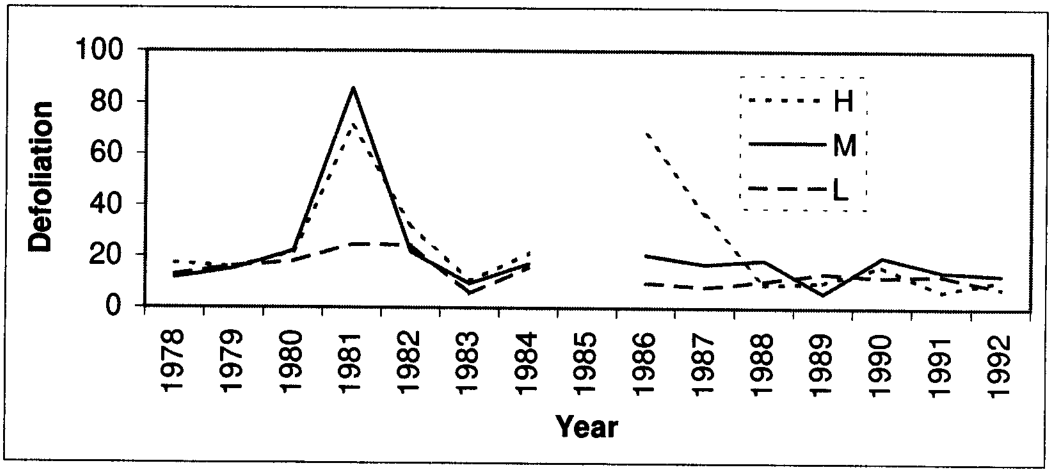

Figure 4. Pattern of average defoliation over time for Species Group II (white oak group) at high (H), moderate (M), and low (L) defoliation sites.

Table 5. Summary statistics (sample size, total, average, and sample variance) of defoliation data by defoliation class for both species groups (red oak and white oak) showing a clear trend in average defoliation and considerable differences in variance

SUMMARY: Red Oak Group				
Defoliation Class	Sample Size	Sum	Average	Variance
High	14	271.6667	19.40476	660.3022
Moderate	14	185.1429	13.22449	182.941
Low	14	110.4348	7.888199	27.62417
SUMMARY: White Oak Group				
Defoliation Class	Sample Size	Sum	Average	Variance
High	14	357.1429	25.5102	333.3931
Moderate	14	268.5714	19.18367	341.1976
Low	14	208	14.85714	37.20879

There was a considerable difference in variability of the defoliation data in stands rated high, moderate, and low, as was expected from the original classification scheme. The summary in Table 5 indicates that variability appeared to increase with the defoliation rating of the stand. It also shows a clear pattern in average defoliation (Fig. 5) where stands rated high had the highest average defoliation, followed by stands rated moderate and low.

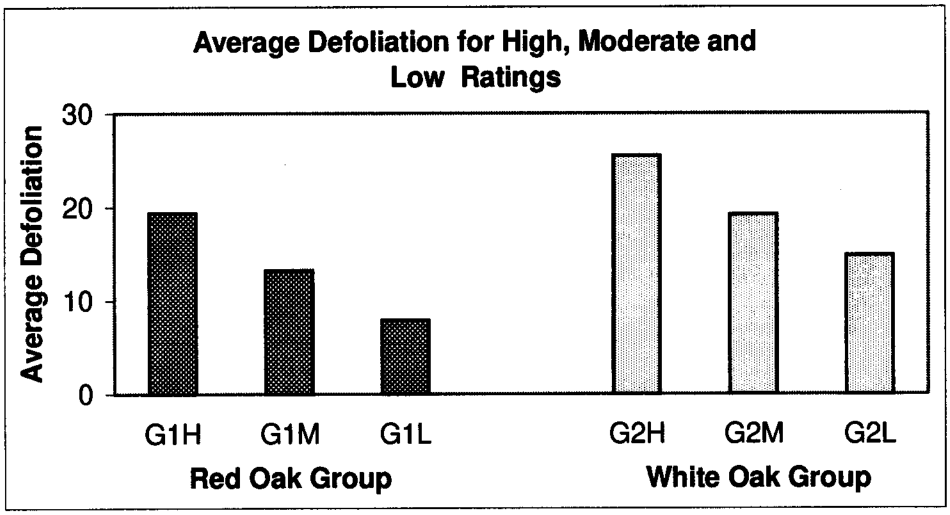

Figure 5. Trend of average defoliation with respect to defoliation classifications for both species groups, indicating a decreasing trend in average defoliation across these classes. (G1 = Species Group I, G2 = Species Group II, H=high, M=moderate, and L=low).

A comparison of chronologies for the period where defoliation data was available (1978 to 1992) showed that the standard chronology for stands classified as high tended to be lower than those of the other stands (Fig. 6 and 7).

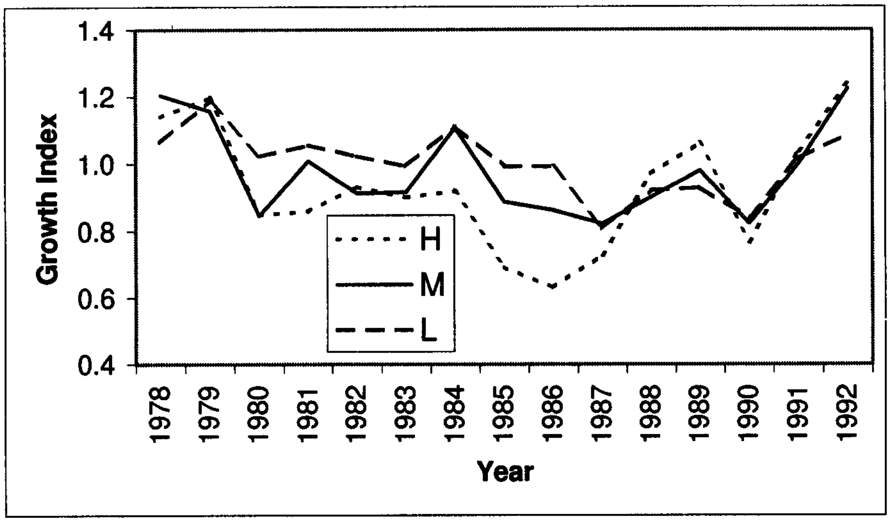

Figure 6. Pattern of the standard chronology for those years when defoliation data were available for Species Group I (red oak group) at high (H), moderate (M), and low (L) defoliation ratings; this shows that the chronology for stands rated high is well below the chronologies for stands rated moderate and low for most of the period.

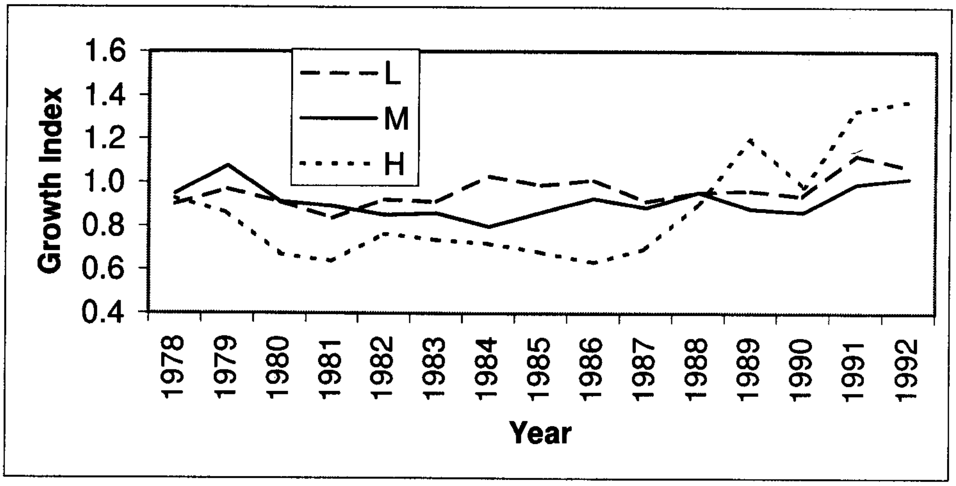

Figure 7. Pattern of the standard chronology for those years when defoliation data were available for Species Group II (white oak group) at high (H), moderate (M), and low (L) defoliation ratings; this shows that the chronology for stands rated high is well below the chronologies for stands rated moderate and low for most of the period.

After recognizing that the effects of defoliation on growth (standard chronologies) between the species groups were similar, we combined the samples and restructured our analysis to investigate the differences among the defoliation histories of these data. We reorganized the sample data into five defoliation severity groups:

(1) At least 2 years of 90+% defoliation (Group 1 or G1)
(2) At least 2 years of 80+% defoliation (Group 2 or G2)
(3) At least 2 years of 70+% defoliation (Group 3 or G3)
(4) At least 2 years of 50+% defoliation (Group 4 or G4)
(5) All remaining samples

The defoliation pattern among these groups and the effects on growth can be seen in Figures 8 and 9, respectively.

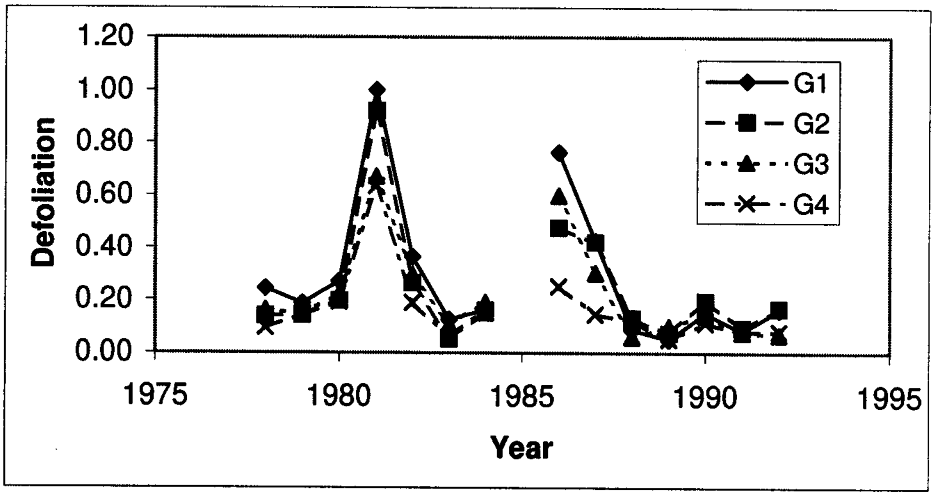

Figure 8. Defoliation data (proportion of crown defoliated) by defoliation severity group.

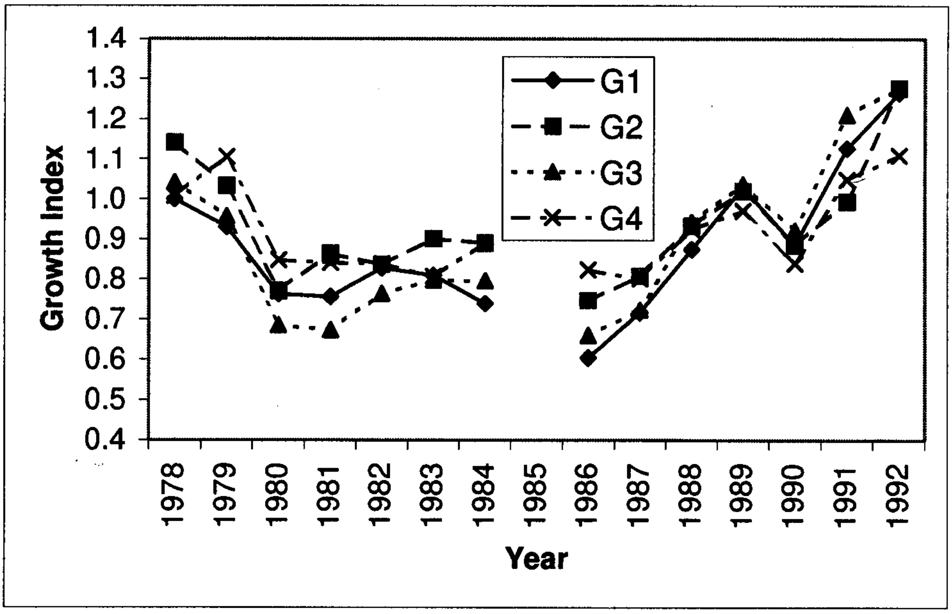

Figure 9. Growth index data by defoliation severity group.

A review of these data revealed the expected differences in defoliation among groups while the differences among series growth indices showed a consistency that suggested that there was not a significant difference among these groups. Analysis of variance supported this fact (Table 6).

Table 6. Analysis of variance for grouped series differences

SUMMARY

Defolation Severity Group	Sample Size	Sum	Average	Variance
Group 1	14	12.33	0.880714	0.031293
Group 2	14	13.104	0.936	0.021365
Group 3	14	12.487	0.891929	0.039022
Group 4	14	12.86	0.918571	0.012165

ANOVA

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Groups	0.0265	3	0.008833	0.340245	0.796298	2.782599
Within Groups	1.349987	52	0.025961			
Total	1.376487	55				

The results in Table 6 suggested that we could combine and analyze the data in a single defoliation effects model. We then constructed cumulative defoliation effects models of the form $G_t = F(defol_t + defol_{t-1} + defol_{t-2})$, where G_t is the growth index for year t as a function of the current and past two years of defoliation. Defoliation was expressed as a proportion of the crown defoliated (between 0.0 and 1.0) for each year so the cumulative defoliation value can be between 0.0 and 3.0. This can be seen in Figure 10.

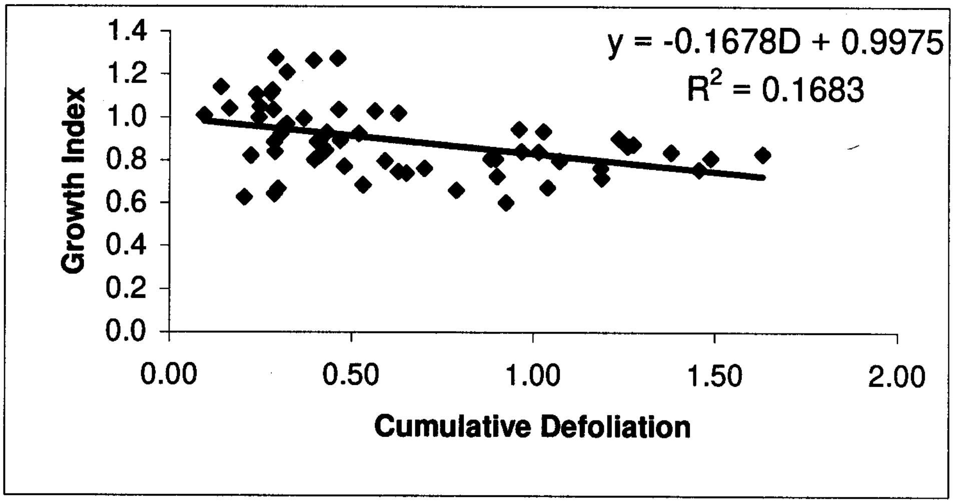

Figure 10. Growth index as a function of cumulative defoliation over the current and past two years. Cumulative defoliation values range between 0.0 and 3.0 as the sum of three proportions.

This showed a clear decrease from the norm ($G_t = 1$) for the standard chronology. Testing this model using linear regression produced a very reasonable, as well as highly significant, trend and intercept, as can be seen in Table 7.

Table 7. Regression results for current growth index as a function of the current and the past two years' defoliation

Regression Statistics					
Multiple R	0.410244				
R^2	0.1683				
Adjusted R^2	0.15396				
Standard Error	0.15034				
Observations	60				
ANOVA					
	df	SS	MS	F	Significance F
Regression	1	0.265274	0.265274	11.73669	0.001132
Residual	58	1.310922	0.022602		
Total	59	1.576195			
	Coefficients	Standard Error	t Stat	P-value	
Intercept	0.997489	0.036316	27.46695	6.16E-35	
D	-0.16779	0.048977	-3.42589	0.001132	

First note that the intercept was quite near 1.0, which implies that the model predicts a neutral effect (no growth impact) for either very light defoliation or as defoliation decreases. Following the development of this cumulative effects model, we considered the possible effects of having no defoliation data for these trees in 1985. After reviewing Figure 8, we considered using an estimated value of 20 percent for the average in each defoliation class. Using these data proved to change the model only slightly. The regression results are presented in Table 8 and Figure 11 provides the fitted curve.

Table 8. Regression results for current growth index as a function of the current and the past two years' defoliation after assuming defoliation in 1985 averaged 20 percent

Regression Statistics	
Multiple R	0.510936
R^2	0.261056
Adjusted R^2	0.248315
Standard Error	0.141709
Observations	60

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.411475	0.411475	20.49036	3.03E-05
Residual	58	1.16472	0.020081		
Total	59	1.576195			

	Coefficients	Standard Error	t Stat	P-value
Intercept	1.029956	0.035483	29.02697	3.1E-36
D	-0.20642	0.045601	-4.52663	3.03E-05

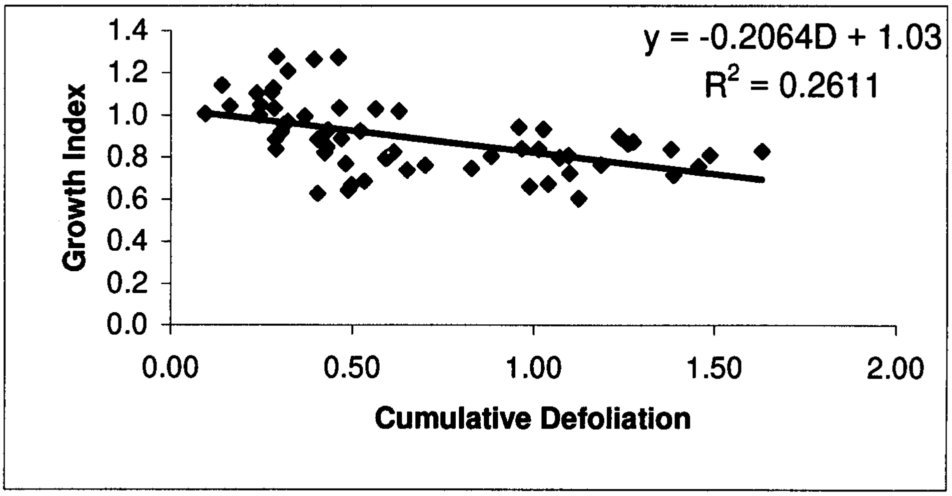

Figure 11. Growth index as a function of cumulative defoliation after substituting 20 percent for missing defoliation data in 1985. Cumulative defoliation values range between 0.0 and 3.0 as the sum of three proportions.

Discussion and Conclusions

The models that were derived from these data are quite reasonable considering the range of data. We would expect that either of these models would provide an acceptable means to predict the effects of defoliation outbreaks on oak species. Because we are able to remeasure and verify the quality from the remaining samples, we expect to strengthen these models as well as investigate the possible interactions of growth effects associated with site conditions and tree vigor or health that may adversely affect growth more strongly during outbreaks. The current models available for predicting individual tree loss from defoliation (Colbert and Sheehan 1995) within the gypsy moth life system model (GMLSM) were developed by fitting data published earlier by Campbell and Garlo (1982) and Baker (1941). The models developed for the GMLSM indicate a maximum decrease in growth of approximately 40 percent, whereas these models predict slightly less for the range of data averages in the aggregate chronologies. However, at the extreme of individual tree defoliation, these models would predict more growth loss.

These models are the first that we are aware of that were derived directly from field data where both defoliation and growth data were available for individual trees. Muzika and Liebhold (1999) provided estimates for individual host species, including those in the red oak and white oak groups considered here. Their analyses indicated that both current and the previous year's defoliation affected growth. They did not consider lag beyond one year nor did they construct a cumulative effects model. Their approach did provide different weights (separate coefficients) for the current and previous year's defoliation.

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