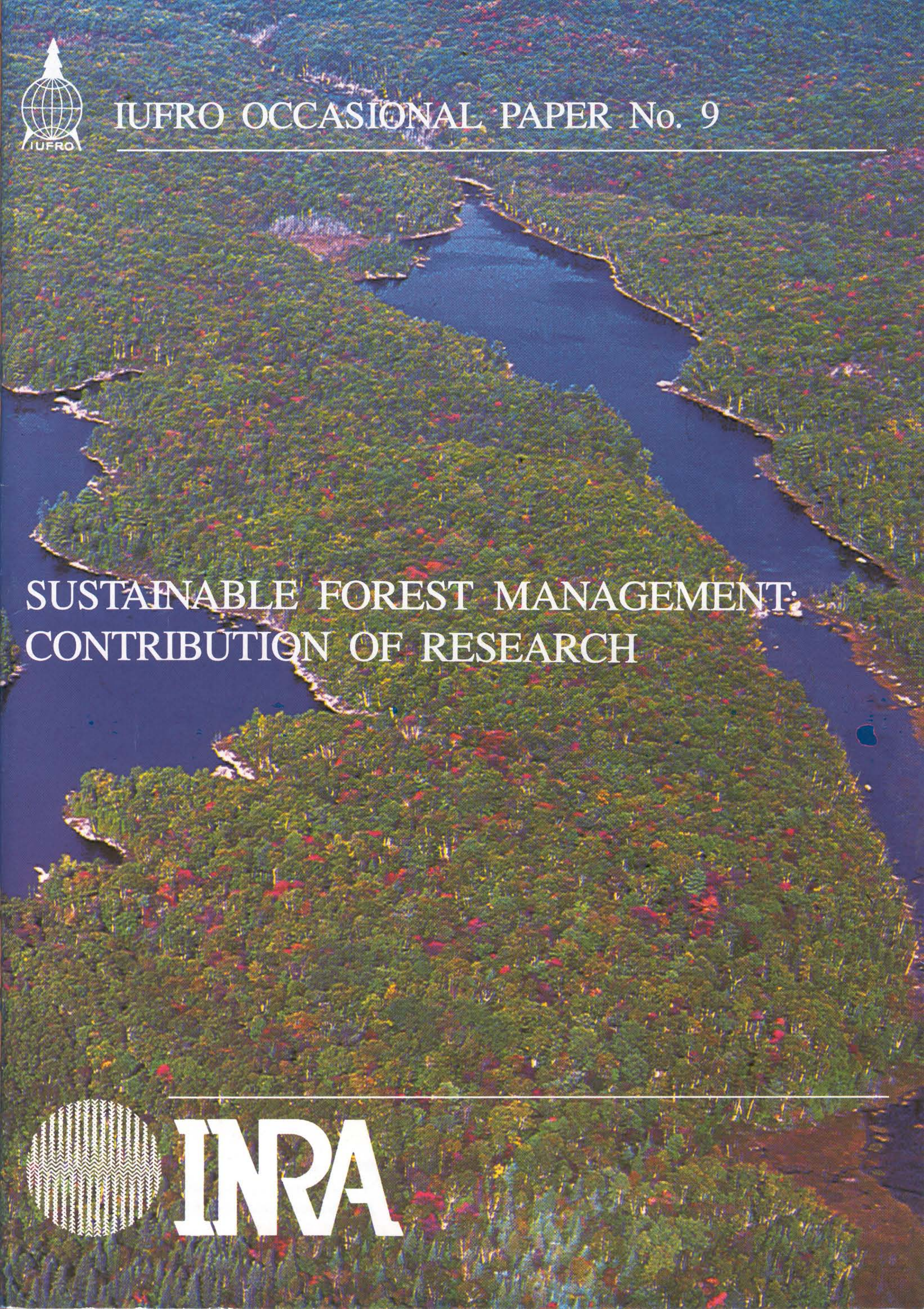

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SUSTAINABLE FOREST MANAGEMENT: CONTRIBUTION OF RESEARCH

INRA

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Facts and Figures on the French Forest

Forest area ▪ France is one of the most forested countries of the European Union, ranking third after Sweden and Finland. French forests cover 14 million hectares, i.e. a quarter of the national territory, and with 136 woody species, these forests are, ecologically, extraordinarily rich.
The French administrative departments with the highest percentages of forested areas are the Landes in the southwest (60.6%), the Var in the southeast (56.5 %), and the Vosges in the northeast (47.8 %).
Overseas, France manages a forested legacy of 8.8 million hectares, 8.3 of which are in French Guiana, which presents enormous biological riches under tropical rain forest conditions.
Within the past 200 years the area of French forests has doubled, and it continues to expand by 30,000 hectare per year. This expansion is due to a long standing afforestation policy and to the abandonment of agricultural land during recent years. In 1994 forests on plains and hills represented 61.7 % of the total forested area; mountain forests 29.6 % and Mediterranean forests 8.7 %.

Broad-leaved / coniferous ▪ In France, two thirds of forests are broad-leaved; the remaining portion is coniferous. Oak and beech are predominant, which is a typical feature of France and of the European temperate zone. In Germany, on the British Isles and in Denmark coniferous forests reach as much as 70 %.

Private / public ▪ Forests are predominantly in private hands: 70% of the forested areas belong to individuals. So-called "public" forests belong to the State (state forests), to territorial communities or public establishments. The 1,500 state forests cover 1.7 million hectares. The other public forests are mainly community forests: 10,000 forest communities own 2.8 million hectares.
Public forests are managed by the Office National des Forêts (ONF) which, in 1966, succeeded to the Administration des Eaux et Forêts. It supervises, maintains, and protects the forested and natural spaces that have been confided to it. The ONF ensures their ecological, economic, touristic, and landscape management.

Timber production ▪ In France, the timber harvest is lower than the biological production of forests. Altogether, forests represent a growing stock of 1.8 billion cubic meters which increases by 75 million cubic meters annually, while only 55 million cubic meters are harvested per year.
According to "Les hommes et la nature" 1996, ONF, 2 avenue de Saint-Mandé 75570 Paris cedex 12.

Biological diversity ▪ The number of species which are linked to the forest environment, or which are omnipresent, is very high; it amounts to about 1,000 species. Only thirty of them are vulnerable or endangered species.
Thirty-two mammalian species are recorded, 6 of them from strict forest environments; 11 of them are considered endangered or vulnerable. The population of ungulae (red deer, roedeer) has considerably increased in the course of the past 20 years; it has doubled for red deer and tripled for roedeer.
Birds represent about fifty species, no matter whether in strict forest environments or not; 8 of them are endangered or vulnerable.

Source for all other paragraphs:
The indicators of Gestion Durable des Forêts Françaises - DERF - 1994.

Some figures about the world's forests

- **Distribution of areas in million hectares**

South America	898
Community of Independent States (CIS)	754
Africa	535
North America	530
Asia	463
Europe	140
Oceania	87

Source: FAO 1990

- **Recent developments of forested areas in million hectares**

Geographical zone	Forested area 1980	%	Forested area 1990	%	Development 1990/1980
Boreal	920	25	920	27	0
Temperate	766	21	777	23	+11
Tropical	1924	54	1753	50	-171
World	**3610**	**100**	**3450**	**100**	**-160**

Source: EEC/FAO 1992

Sustainable Forest Management:
A Strong Demand by Society to the Scientific Community

*"The Masters of Forests [...] shall survey and visit all forests and all woods which they include, and they shall effect the sales as needed, with a view to **continuously maintaining the said forests and woods in good condition**."*

This quote from the Royal Ordonnance on Forests, enacted in Brunoy more than 650 years ago, on 29 May 1346, by Philippe of Valois, appeals to the modesty of many of our contemporaries who have made the question of sustainable forestry a "new paradigm". The above quote shows that history has turned a nose to them.
During the past fifteen years forests have been in the limelight on many occasions, and technical and political conferences about forests have been held at regular intervals. This trend is on the one hand due to people's fear following the forest decline observed in the northern hemisphere during the early 1980s; on the other hand, it is a result of the severe concerns about massive deforestation in the tropics and certain types of forest management practised resulting in enormous clearcuts (in North America, for example). Numerous national, multilateral and global initiatives are currently being developed independently or in competition.

Political stakes, notably the Nord-South relations and multiple pressures exerted by environmentalist non-government organisations (NGOs), are important components, but economic aspects of forests and timber industries are certainly omnipresent as well. In this context, science does not seem to be in a very good position. Although its representatives would have much to say on these issues they often find themselves excluded from discussions. This is due to several reasons. In the many initiatives following the Rio Summit scientists are themselves divided or speak through the voices of "star performers" more concerned with notoriety than with the issues; discussions are frequently dominated by emotion or dogmatism rather than by rigorous argumentation, thereby leaving little room for scientific approaches; and, finally, possible solutions need not always emanate from science.

From perfectly legitimate concerns about the sustainability of important natural resources provided by forests, and about the environmental consequences of their regression or inappropriate management, the discussion has become largely ideological. The new, though little precise concept of sustainable management and/or development, of which biodiversity represents only one of many aspects, has not really made the discussion clearer. In the world of forestry efforts are made to develop one single notion which should be close to "political and technological correctness". However, in practical forestry a highly diverse reality is hiding behind this apparently unifying language; there is sometimes a gap between what is said and what is done.

Similarly, natural forests of tropical countries are frequently confused with natural forests of temperate countries that have been heavily modelled by man or are even artificial.

In any case, all this over-excitement at national and international levels entails important consequences like new regulations or laws, some of them truly pertinent, others being less justified such as, for instance, the community directive on "Habitats" which will be reflected by the network Natura 2000, future eco-certification procedures of forest production that will be a burden for forest owners and industrial competitiveness.

I contend that scientific expertise is more than ever of importance in this field. Let me remind you of the definition of sustainable forest management provided by the Ministerial Conference of Helsinki (1993):

Sustainable forest management means "good management" and utilisation of forests and forested areas in such a way and at such intensity that their biological diversity, productivity and regenerative capacity, their vitality, and their capacity to fulfil, now and for the future, their pertinent ecological, economic and social functions at the local, national and global levels, be maintained, without thereby doing harm to other ecosystems.

When trying to analyse all terms of this (long!) definition, one can easily imagine the large number of dormant scientific questions. It will become clear that sustainable forest management, which, by itself, is integrated in rural space management, requires diverse and solid scientific foundations. The present publication aims primarily at illustrating the scientific contribution of INRA and some of its partner institutes to sustainable management.

It is organized around five major elements of sustainable management:

- Climate and forests;
- Forests and their soils;
- Biodiversity;
- Dynamics of forests and stands;
- Man and his forests.

The volume allowed for this publication required a selection of topics; so we decided to focus on environmental aspects and on the human dimension of research programmes. The reader will thus not find any articles about wood research or development physiology; research activities on topics like forest fires or forest decline, which were developed in a previous publication (INRA Mensuel No 5, 1991, "La forêt et le bois"), have despite their strong environmental connotation not been treated again in this issue. Generally speaking, the present publication about sustainable management tries to describe the ecosystematic approach of research rather than fine studies of mechanisms.

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Forests and Climates

Trees are long-lived organisms and as such are exposed to important climatic fluctuations with all their multiple components such as temperatures, rainfall, increasing CO_2 content, air pollution, storms, ... that can considerably affect stability.
Forests cover surfaces of significant sizes at the local, regional, and global levels and also influence the water regime, local climatic systems, and the carbon cycle, thereby contributing to a sustainable environment.

To illustrate these interrelations, three topics will be discussed: the links between climates and forests at the local, regional, and global levels; the problems due to the impact of elevated atmospheric carbon dioxide concentrations on trees and forests; and, finally, the issue of forests and water, a timely topic of high importance.

1 Interactions between climates and forests at the local, regional, and global levels
(G. Aussenac)

2 Forests faced with increasing atmospheric carbon dioxide
(J.M. Guehl)

3 Forests and water : relations between forest ecosystems and water resources
(G. Aussenac)

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1 Interactions between Climates and Forests at the Local, Regional, and Global Levels

Because of the enormous amounts of biomass and the large dimensions of trees, which constitute the main structural elements of forests, the latter exert a considerable influence on the mass and energy exchanges between the atmosphere and the soil: They intercept solar radiation, curb wind velocity, fix atmospheric carbon dioxide, and evaporate large amounts of water. However, forests do not only influence the climate, they also directly depend on it; they need a minimum temperature, especially during the vegetation period, and a minimum amount of rainfall.

Photo (p. 8): M. Pitsch

Using these factors, it was possible to provide rough descriptions of different types of forests, such as the closed forest of the tropical and equatorial regions which is characterized by permanent rainfall and very high atmospheric humidity; the xerophilous forests[1] of the Mediterranean or Californian climates with very dry summers; or the evergreen conifer forests of the cold temperate regions (Scandinavia, Siberia, Canada).
Despite the incontestable increase in research initiatives that have in recent years been conducted in the tropics, the level of information there is still inferior to the data available on the temperate and cold regions.

The influence forests have on the climate represents a controversial, all but easy subject where experiments are difficult, if not impossible. Several approaches have been made to solve this problem: experimental methods, historical methods, and modelling approaches[2]. Based on the results obtained from these different approaches, one can try to determine the relationships between forest and climate although it has to be noted that numerous uncertainties remain.

Forest - climate interactions
Relationships between forest and climate need to be analyzed using data on mass and energy exchanges and on the quantity of movements between forests and the atmosphere; in essence, one has to begin with a micrometeorological analysis. At this level, prevailing phenomena are relatively well known although they merit further research.

[1] Garrigue, maquis or chaparral.

[2] * The experimental method consists in comparing the climate in forested areas to the outside climate. No parameter except for the influence of the forest cover may disturb the comparison; this is, however, possible only in some rare situations, which eventually restricts the possibilities of exploring diverse examples in consideration of geomorphology and climate.
* The historical method includes a several years' comparative study of the climatic characteristics of forest-covered and exposed (agricultural or other) areas; after that, the modifications of climate characteristics caused by the cutting of the forest are to be observed and measured in comparison with the open area.
* Modelling employed at different scales, especially at the regional and global levels, with numeric models of the functioning of the atmosphere (General Circulation Models) and the biosphere.

With reference to radiation exchanges, the differences between forested and exposed sites can have several different causes: firstly, the differences of albedo[3]; on average, the albedo of forests is lower (0.11) than that of grassland (0.20). Forests therefore represent a more efficient sink of solar radiation than any other type of vegetation. Further, the differences in the radiation exchange between forested and other areas can be a result of differences in the surface temperature of the tree crowns in respect of the importance of evapotranspiration.
Radiative energy (net radiation) is actually divided into two fluxes: the flux of latent heat, which corresponds to evapotranspiration, and the flux of sensible heat (flux of convection) from the forest cover to the atmosphere. The flux of latent heat has two main origins: the transpiration of trees and the evaporation of precipitation intercepted by the forest cover; it is important to remember that about 20 to 50 % of the annual precipitation are intercepted. The interception of precipitation is certainly a considerable loss for forest soils compared to grassland and cultivated land, but on the other hand it provides additional water vapour for the atmosphere above the forests.
Forest cover (i.e. the biomass and air in stands) stocks heat in that trunks, branches and foliage are heated during daytime. As a rule, heat is accumulated in the morning and emitted to the atmosphere in the evening. Surface temperatures more than 8°C higher than those outside the forest cover were measured. The restitution of heat to the atmosphere at the end of the day could be the reason of the increasing convection phenomena and might induce storms in the presence of more humid air above forests.
From the aerodynamic point of view (effect of roughness), vegetative covers are mainly characterized by two parameters: the zero plane displacement (0.8 times the mean height of the vegetation) and the height of roughness, which varies between 1 cm for lawns and 3 m for forests. In general, forest covers slow down the displacement of air masses in the lower strata. This slowdown, which raises the air masses and, consequently, intensifies upward currents, may favour the condensation of water vapour. Apart from these phenomena, when air masses come close to a forest stand, their thermic and hydric characteristics, because of the vertical structure of forests and the evapotranspiration, change according to the displacement. A certain distance from the interior of the stand must be reached in order that a new equilibrium can develop between the characteristics of the considered air mass and the fluxes of water vapour, CO_2, and heat released or fixed by the forest cover; this phenomenon, called "oasis effect", is more significant the more different the hydric and thermic properties of the forested and non-forested areas are.

The study of climates usually involves several different orders of magnitude: the global climate for distances of the order of 1,000 km, regional climates (100 km), local climates (1 to 10 km), and microclimates (10 to 100 m). At each of these levels, the influences of the forest depend on the dimensions of the forest. It is in fact very difficult to determine the minimum dimensions a forest stand must have to exert a significant influence on the climate. Without furnishing proof of their opinion, some authors say that the relevant order of magnitude is from about one hundred ha upward.

Microclimate level

At the microclimate level forests act on solar radiation, precipitation, atmospheric humidity, and temperature, on the wind, and on the evaporating capacity of the air. This means that, even leaving everything else apart, the climate in, and under, a forest cover will always be different from that in exposed locations. This microclimate influences the elementary and overall functioning of forests and conditions the life of trees from their introduction in the form of seeds or plants to the moment when they die or are exploited by the forester. The

[3] The reflected fraction of short-wave solar radiation.

phenomena of flowering, fruiting, germination, photosynthesis, transpiration, and growth are particularly heavily influenced by the microclimate. The role a forest plays varies depending on the species, the type of stand (height, structure, density, etc.), and the climate.

Solar radiation

The forest cover receives a certain amount of energy which is linked to the position of the sun and to the conditions of cloudiness; it is the global radiation (in $W.m^{-2}$), the sum of the direct solar radiation and of the radiation diffused by the atmosphere. Part of it is reflected to the sky; this is the albedo, which varies in accordance with species and forest type, e.g. 0.12 in winter and 0.18 in summer for broadleaved trees and 0.12 for conifers. The density of the forest cover and the orientation of the leaves determine not only the reflection of radiation, but also its penetration in the forest cover. There is in fact interaction; the characteristics of the radiation influence foliar anatomy, morphology and physiology while, on the other hand, the latter modify the quantity and quality of the radiation. The part of the radiation which is not reflected penetrates the forest cover and is either absorbed by the foliage or transmitted to the soil. Absorption is very significant in the case of visible radiation and insignificant for infrared light; briefly, one can say that the light in forests is rich in infrared and poor in ultraviolet radiation. Depending on the amount of radiation penetrating the forest cover that radiation decreases more or less rapidly; the variation can be described by a negative exponential equation. For instance, global radiation under a small oak stand is 20 % of the incident global radiation, as compared to 40 % in a stand of Aleppo pines, 20 % for a *Pinus sylvestris* high forest, 5 % in a beech stand, and 1-2 % in a closed spruce stand. In the two latter cases, quality and amount of the available radiation heavily affect the development of the undergrowth vegetation. The maximum interception of solar radiation takes place at the time of maximum production (maximum current increment) of the stand, i.e. at an age of 50 to 80 years, depending on the species.
If there are gaps in a stand, the available radiation (% of the radiation available in the open land) depends on the relative dimension of the open area, i.e. on the proportion of the diameter of the clearing to the height of the surrounding stand; in the centre of a clearing this would be 13 % for a proportion of 1 and 50 % for a proportion of 2. In the case of forest strips the available radiation depends again on their relative dimensions, but also on their orientation.
In general, it must be noted that other climatic features, such as temperature, wind, or evapotraspiration, will correspond to a given light intensity, which means that even considering only the relative light intensity will permit the definition of a particular microclimate more or less close to the outside climate.

Temperature

The temperature of the air in and under forest covers varies according to the solar radiation, which represents the principal source of heat for the vegetation, the top layer of the soil, and the air. During the night, temperatures depend on the significance of the energy losses suffered by the vegetative surfaces, on the canopy structures, and on the atmospheric conditions (air humidity and wind velocity). Like above bare soil, temperatures vary also in forests between night and day; however, the thermic profile of forest stands is somehow disturbed as the vegetative biomasses (leaves, branches, trunks), which absorb and emit the radiation, are distributed in variable density depending on the respective type of stand. As a rule, the crowns absorb part of the global radiation during daytime and warm the ambiant air, from where the maximum temperatures at their level come. During the night, temperatures drop more the less the vegetative surface is shielded from the atmosphere. Temperatures are therefore lowest in the upper part of the crown, while at the level of the underwood the decline in temperature is moderated by the crowns. In short, one can say that the climate under the vegetative cover is buffered and that the daily and seasonal thermic variations are moderate compared to the outside: maxima are lower and minima higher. These thermic effects are also perceptible in forest soils, which in winter are warmer, and in summer cooler, than soils of exposed areas. In concrete terms, the moderating effect of the crown cover on the forest microclimate limits both frost damage of seeds and young plants in spring and extreme rises in temperature (70°C) on the soil surface of clear cuttings in summer.

Silvicultural interventions (thinnings, clearings, belts, shelterwood felling) or wind breakage[4] interfere with these effects of the forest cover in that they make the thermic climate more like that of open areas. It has been recognized, however, that clearings of a diameter of less than three times the height of the ambient stand have a moderating effect (4 to 5°C more) on the severity of late frosts and can be profitably used for the silviculture of certain sensitive species. It is estimated that for diameters exceeding 6 times the height of the neighbouring stand the climate of the clearing will be very similar to that of the open land.

Shelterwood fellings are efficient means against late frosts, but they also represent important covers providing a low relative light intensity (15% to 20%) which severely affects the growth of seeds and young trees.

With respect to seed cuttings traditionally used for natural stand regeneration, no precise information is available, but with reference to some fragmentary results it can be assumed that, as they increase the radiation losses, openings of the canopy also increase the risk of frost damage to seeds, especially in situations where the silviculturist conserves, or can dispose of, a very small number of seed trees only.

The effects of forest strips are similar to those of shelterbelts used in agriculture, i.e. a slightly increased risk of frost connected with the deceleration of the wind velocity, which favours the stratification of the cold air, and the limited accumulation of heat among forested belts.

Atmospheric humidity

The absolute atmospheric humidity ($kg.m^{-3}$) in forests does not differ considerably from that observed in the open land; in contrast, the relative atmospheric humidity is generally higher considering the lower temperatures in forests. In clearings, thinnings and forest belts the relative humidity has been observed to be between that of clear cuttings and closed stands.

Photo (p.11): D. Feuillas

Wind

Forests exert a considerable influence on the wind. The latter, in turn, represents a determining factor for the life of forests through the variations in temperature and humidity it can cause, and also through its direct mechanical and physiological action on transpiration and photosynthesis. At low velocity, the wind favours transpiration in that it reduces the resistance to the transfer in the boundary layer surrounding the leaves. By accelerating convective exchanges it influences also the temperature of the foliage. The reaction of the forest species to increased wind velocity varies, but above 15 $m.s^{-1}$ there is usually a reduction of transpiration and photosynthesis in connection with a closing of the foliar stomata to regulate gas exchange.

[4] Trees thrown over by the wind.

The influence of the forest on the wind is more marked the more closed and stratified a forest cover is and the higher its trees are. Usually a reduction of 80 % of the wind velocity is observed in forest stands.
Stand thinnings and gaps "shrink" the cover, thus favouring the penetration of wind and turbulences, which can cause significant windthrow where the remaining trees were not able to colonize the opened space and to develop a root system adapted to the new conditions of aeration. It is generally observed that, at equal velocity, wind has a more devastating effect when it blows in a direction which is uncommon in the respective region. This is due to the fact that, in the course of their development, trees progressively adjust their entire aboveground and root architecture to the constraints imposed on them by the winds blowing from the most frequent direction. It is usually assumed that the reduction of wind velocity in clearings, forest belts (15 - 50 % depending on their dimensions) and shelterbelts improves the microclimatic conditions (evapotranspiration) and favours plant growth.

Precipitations and evapotranspiration
Precipitations are heavily influenced by forest cover. On an annual scale, between 20 and 50 % of the incident precipitations are intercepted (depending on stand type and climate), which explains to a large extent (40 % of the annual total) the high amount of evapotranspiration in forest stands compared to other vegetative covers. Altogether, the strong evapotranspiration of forests increases their energy consumption, which, in the course of the day, leads to temperatures above forest covers being generally lower than temperatures above other cultivated land.

Photo (p. 11): Measurement of transpiration. Photo: M. Pitsch

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Canopy openings (thinnings, clearings, belts, clear cuttings) reduce both the interception of precipitations and the transpiration and thereby increase the humidity of the soil, which has a favourable effect on tree growth. In certain low-permeability soils the excess of water may unfavourably influence the growth of seeds, and even trees, if the water remains on the surface and is present during the vegetation period.

To conclude, one can say that at the plot level microclimatic conditions are heavily influenced by the respective stand dimensions. In some cases foresters can profitably use these phenomena by modulating covers in such a way that microclimatic conditions favourable for the growth of seeds and plants are created. It is today well established from experiments that, while they are young, most forest species grow best at a relative light intensity of approximately 45 to 55 %. In fact, this level of light intensity defines climatic (thermic and hydric) features which have a highly favourable effect on the photosynthetic activity (limited hydric constraints) and growth of very young trees (5 - 10 years). With growing age this level of light intensity sooner or later becomes insufficient for the trees (depending on the species) and must be raised to 100 % to allow optimum growth.

Local and regional levels
It is difficult to determine the influences of forests at the local level as this would require the long-term use of well distributed and tight meteorological data networks, which, in fact, are not available. Moreover, controlled experiments necessitate such far-reaching interventions in

respect of the forest canopy, and in topographically and geographically comparable situations, that they have been conducted very rarely.
Altogether, it appears that the lower temperatures and the more elevated atmospheric humidity above a forest stand compared to the adjacent agricultural area cause an increase in precipitations in the area not covered by trees and located leeward of the forest stand. Such a result was clearly illustrated in the Landes, in France (Project HAPEX-MOBILHY) for an area of 100 km side length which was 40 % covered with trees or other woody plants. In the chalky Champagne, a study based on the regional pluviometric network seems to confirm a possible moderating effect on the decrease of precipitations in summer through the afforestation of *Pinus sylvestris* stands. Although these results are based on insufficient data, they are consistent with what is indicated by the analyses of mass and energy exchanges of forest covers and also by the results of studies based on models. At the moment it is, however, difficult to present exact figures of the pluviometric surplus, although annual increases of 1 to 2 % are frequently given in the expert literature.
Outside large forest stands of several thousand hectares belonging to one single tenant, we are confronted with the problem of the "bocage" landscape type. Although no figures are available, it can be assumed that in this case, compared to completely deforested, notably agricultural zones, there must be a climatic, and in particular a thermic, effect linked to the strong evapotranspiration of tree groups, hedges, and small forest stands consuming the advective energy from the neighbouring agricultural areas. However, it is difficult to furnish a direct proof of this effect.

Global level

At the global level the impacts of forests on the climate, and in particular on precipitation, cannot be measured and must be evaluated by means of modelling. This approach has been used in the Amazon Basin where the tested hypothesis was the total deforestation of a 5 million km² forest stand. The result of the simulation was that such deforestation would cause a significant increase in the temperature of the air (in the order of 1 - 3°C) and a decrease in the evapotranspiration (reduction of intercepted precipitation and transpiration). Moreover, due to the diminution of water vapour emitted into the atmosphere, the models also predict a substantial reduction (26 %) of precipitation.

Conclusion

The impacts of forests on the climate are particularly marked at the level of plots, i.e. at the microclimatic level; it has been possible to establish and quantify those influences sufficiently in relation to the architectural characteristics of forest covers. Those influences are now so well known that they can be used by foresters to improve the growth conditions of seeds and trees and to modify the natural development of stands to their benefit. It is incontestable that an important part of forestry technique is connected with the microclimate. At the local and regional levels, it is much less easy to establish the influence of forests; except for major modifications that concern several hundred thousand hectares it is difficult to identify climatic changes.

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For further reading

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2 Forests Faced with Increasing Atmospheric Carbon Dioxide

The increasing atmospheric CO_2 concentrations, which are essentially linked to the use of fossil fuels by man, represent a major component of global environmental and climatic changes, the risks of which are now largely measured by the international community*.
Plants are in fact exposed to atmospheric CO_2 concentrations, and to increased rates of such concentrations, which have never before occurred in their recent evolutionary history. The accumulation of CO_2 and other greenhouse gases might also induce a global warming of 2 to 4°C at the earth's surface and effect changes in the precipitation regime.
In view of these changes the question arises as to what are the implications for forest ecosystems, which represent 26 % of the surface of the continents and almost half of the surface of the total vegetative covers of the earth.

Photo (p.13): R. Canta

See also "The Productivity of European Forests is Increasing: A Fact of Considerable Consequence", on page 65.

Forest ecosystems must be considered from two points of view:
- First, they are an essential component of the global carbon cycle that constitute an important carbon reservoir, are extremely mobile, and interfere heavily with the atmospheric CO_2 reservoir. Depending on the conditions of the environment (temperature, drought), a forest ecosystem can either represent an overall carbon sink by assimilating important amounts of atmospheric CO_2 or, by contrast, constitute a "source" of CO_2 towards the atmosphere.

Which of the two are our forest ecosystems today: Are they "sinks" or "sources" of CO_2? And what will they be in the coming decades? Could a generalized reforestation policy enable us to limit the increase of atmospheric CO_2 through increased carbon sequestration in the biomass and the soils?
- Secondly, forest ecosystems must also be seen as biological systems which respond to the increasing atmospheric CO_2 content and to climatic changes which modify their functioning, productivity, structure, and potential geographic species distribution.

The longevity of trees is a major issue to be considered in the analysis of these answers. The time frame of the current environmental changes corresponds to the average lifetime of trees. It is the young trees of today that will be exposed to the elevated CO_2 concentrations and the modified environmental conditions of coming decades. In addition, the high speed of climatic

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* Atmospheric CO_2 concentration has increased more or less exponentially from a value of 270-280 ppm (parts per million) at the beginning of the past century to the present level of 360 ppm. Simulations based on the most realistic scenarios of CO_2 emissions to the atmosphere predict a doubling of CO_2 concentration until the middle of the next century compared to the preindustrial level. The retrospective measurement of CO_2 concentrations, which has become possible through the analysis of micro-air bubbles from polar ice indicates that in areas which are not subject to human influence, the atmospheric CO_2 concentration has fluctuated between 200 and 280 ppm in the course of the past 200,000 years.

changes and the increasing human influence on the environment will rule out a long-term response by genetic adaptation or migration of species like those in the order of millenia, linked to alternations of glacial and interglacial periods. The risks of dysfunction and gradual dying of forests might therefore increase. In the field of forestry, it is more than anywhere else essential to anticipate environmental changes by appropriate species selection and adaptation of silvicultural rules. Our forests managers are perfectly aware of that necessity (Mortier 1995).
Research can assist in decision-making by describing the inter-specific variability of the influence of increased atmospheric CO_2 on growth. Will the main species of the French forest react differently to the increase in atmospheric CO_2? It will also be crucial to improve our understanding, and elaborate models, describing interactions between increasing atmospheric CO_2 concentrations and other environmental factors such as temperature, drought, and nutrient supply.

The description of cooperative research work in which our department participated[1] will refer to cumulative knowledge, but also to the many questions that remain in respect of these two aspects.

The role of forest ecosystems in the global carbon cycle and the increase of atmospheric CO_2

Increasing atmospheric CO_2 and the carbon "sink" linked to terrestrial ecosystems
Since the beginning of the industrial era about 235 Gt[2] of carbon have been emitted into the atmosphere through the use of fossil fuels (coal, petrol, gas). Another 165 Gt of carbon have been injected into the atmosphere as a result of deforestations which caused combustion or accelerated oxidation of the organic matter contained in biomass or soils. The increase of the atmospheric CO_2 concentration observed during the same period corresponds to the accumulation of approximately 170 Gt of carbon in the atmosphere, an amount considerably lower than the integrated value of emissions (235 Gt + 165 Gt).
The present rates of carbon emission (in the form of CO_2) to the atmosphere are evaluated at 5.4 Gt (fossil fuels) and about 2.0 Gt (deforestation, mainly in the tropics) annually. The annual increase of the atmospheric CO_2 concentration is 1.5 ppm, which corresponds to an increase in the total mass of atmospheric C by 3.4 billion tons.
So the atmospheric carbon budget indicates that, in their entirety, oceans and biosphere constitute a carbon "sink" which presently absorbs almost 4 Gt of carbon per year. Thanks to detailed analyses and modelling of spatio-temporal variations (at the global level) of the concentration (Figure 1) and, in particular, of the isotope composition (proportions $^{13}C/^{12}C$) of the atmospheric CO_2, the important contribution (in the order of 2 Gt p.a.) of the terrestrial biosphere to this effect, and especially the role of forests, are today well established [3].

CO_2 concentration (ppmv)

[1] National or international (AGROTECH-INRA programme; the French group "Forêts Tempérées" of the International Geosphere-Biosphere Programme; community programmes).
[2] 1 Gt = 1 giga-ton = 1 billion tons.
[3] Vegetative covers are characterized by an important isotopic discrimination relative to $^{13}CO_2$ in photosynthesis, while that discrimination is insignificant in the case of CO_2 entering the oceans. The spatiotemporal analysis of the atmospheric isotopic signal points out the existence of a large C sink in the terrestrial biosphere at the temperate latitudes of the northern hemisphere.

Figure 1 ◆ Time-course of the atmospheric CO_2 concentration at the observatory of Mauna Loa, Hawaii. The decreasing parts of the curve (summer in the northern hemisphere) result from the absorption of CO_2 by vegetative-cover photosynthesis and from the dissolution of CO_2 in the oceans (data according to Keeling and Whorf, 1994).

Photo (p.14): CO_2 measurements in an open-top chamber.
Photo: Christophe Rose

That such a sink exists now is probably linked to two factors. The first one is the extension of forest areas observed in industrialized countries, mainly in the temperate zone of the northern hemisphere (in France, forest areas have practically doubled since the beginning of the 19th century). This causes important carbon immobilization, especially in the form of wood. The second factor is the stimulation of the photosynthetic activity and productivity of vegetation covers, which is related to the increase in the atmospheric CO_2 concentration (this is sometimes called CO_2 "fertilisation"; for the process, see below) and, in a geographically more heterogeneous way, to an increase in soil fertility through man-made emissions of nitrogenated compounds (see also the article on productivity trends in European forests).

Carbon fluxes and reservoirs in forest ecosystems
Compared to the size of carbon reservoirs of terrestrial ecosystems and atmosphere, and particularly compared to the velocity of changes in the atmospheric reservoir, terrestrial biosphere and atmosphere mutually exchange enormous amounts of carbon per year (Figure 2).

Figure 2 ◆ Reservoirs (in billions of tons) and fluxes (in billions of tons p.a.) of carbon at the global level. The net fluxes between atmosphere and terrestrial biosphere or oceans are presented in broken lines; their estimation is independent of the estimation of unidirectional fluxes.

Atmosphere	750 Gt (+3.4 Gt p.a.)
Deforestation	2 Gt
	5.4 Gt
Photosynthesis	100 Gt
Respiration	50 Gt
	2 Gt
Decomposition	50 Gt
Terrestrial biomass	610 Gt
Organic matter of soil and litter	1,560 Gt
Oceans	90 Gt
	90 Gt
	2 Gt
Fossil fuels	5,000 - 10,000 Gt

The annual flux of atmospheric CO_2 which is sequestrated through photosynthesis represents approximately 100 Gt of C. It is almost completely (but for 2 Gt) compensated by a CO_2 flux in the inverse direction corresponding to the respiration of plants (about 50 Gt p.a.) and microorganisms of the soil (bacteria, fungi, etc.) which decompose litter and soil organic matter (again about 50 Gt p.a.). Considering these figures it is obvious that even a slight variation of these fluxes in one direction would considerably influence their net budget and, consequently, the increase rate of the atmospheric CO_2 concentration. A crucial effect in this context is the marked stimulation of respiratory processes as a result of the rise in temperature.

At the level of different ecosystems making up the terrestrial vegetation cover, in particular forest ecosystems (tropical moist forests, temperate forests, boreal forests), our knowledge about the functioning of carbon is still very incomplete. However, this sort of data is extremely important to be able to predict carbon exchanges between terrestrial ecosystems and atmosphere.

In the course of the past years remarkable methodological developments have been realized in the fields of micro-meteorology (eddy correlation technique) and regarding the isotope budget of carbon fluxes. As a result, it has become possible to directly evaluate CO_2 fluxes at the interface of ecosystem and atmosphere and at the infra-ecosystem level with a time resolution of less than a day. The application of these methods together with the study of the key physiological and edaphic processes allows advances in the analysis of the carbon functioning of forest ecosystems. In the framework of national and international cooperative work our laboratory is interested in a wide range of forest ecosystems[4]. We try to analyze and elaborate models of the different components (photosynthesis, respiration of trees and soil, recycling of CO_2 of respiratory origin through photosynthesis, etc.) of net CO_2 fluxes between various ecosystems and the atmosphere. The final objective is to be able to predict the global changes of these fluxes and of the carbon reservoirs immobilized in biomass and soils by means of simulation through mathematical models and spatial integration.

A high and probably lasting level of atmospheric CO_2 concentrations

Without alternative energy solutions, the major part of the fossil fuels that are still available will probably be exhausted within the next few decades. According to that scenario total emissions would correspond to an amount of carbon exceeding by far the current atmospheric reservoir (Figure 2). Even in the most optimistic hypotheses of reforestation programmes, which assume an increase in the carbon immobilization per unit area (increasing net productivity of ecosystems), terrestrial ecosystems will altogether not be able to absorb and immobilize such quantities of carbon over the long term. For some time only absorption by oceans will be able to help reduce the atmospheric CO_2 reservoir and that effect will take several thousand years. It is highly probable that many future generations of trees will be exposed to atmospheric CO_2 concentrations exceeding twice the preindustrial level.

Impacts of the elevated atmospheric CO_2 concentration on trees and forest stands

[4] In cooperation with the Laboratory of Vegetation Ecology of the University of Orsay and the INRA Laboratories of Ecophysiology, Forest Nutrition, and Bioclimatology in Bordeaux our laboratory participates in several international projects about a series of different forest ecosystems which cover a very large latitudinal gradient in boreal, temperate and tropical zones:
- The project EUROFLUX ("Long-term carbon dioxide and water vapor fluxes of European forests and interactions with the climate system"), which is part of the programme ENVIRONNEMENT of the European Union. The French partners are particularly interested in the beech forest of Lorraine and the pine wood of the Landes, in the east and south-west of France, respectively.
- The North-American project BOREAS ("Boreal ecosystem-atmosphere study") in which several European teams participate.
- In close cooperation with the INRA forest research unit at Kourou we are also developing a programme on the carbon function of the tropical moist forest of French Guiana in which also the University of Salt Lake City (Utah, USA) participates.

Basic processes and implementing approach

Atmospheric CO_2 concentation affects the functioning of plants of the metabolic type C_3[5] (to which all trees belong) by two direct effects:

- a reduction in stomatal conductance (a parameter which describes the degree of opening of the stomata) which reduces at the same time the transpiration flux of water vapour escaping from leaves and the diffusional flux of CO_2 into leaves;
- a stimulation of photosynthesis which, despite the inhibiting effect on the stomatal conductance, is induced by an increase of the CO_2 concentration inside leaves.

These effects are greatly dependent on species and on the environmental and nutrient status; in some cases they may not occur at all.

In recent years our research unit has focused mainly on the analysis of growth and its physiological determinants (photosynthesis, sugar concentrations of different tissues, etc.) and on drought tolerance[6]. At the experimental level, the approach consists in growing young plants either under present-day conditions of CO_2 (360 ppm) or at a concentration of approximately twice the present concentration (700 ppm) (Figure 3).

Figure 3 ◆ Inside view of air-conditioned and CO_2-regulated mini-glasshouse; maritime pine and pedunculate oak.
Photo (p. 16): C. Picon

The growth of trees and stands

Results obtained from different species indicate an average increase of 46 % of biomass growth with a doubling of the CO_2 concentration, with inter-specific differences. The stimulating effect of CO_2 on growth is less marked under limiting nutrient or water conditions, which mostly apply to forests, than under optimum conditions.

A novel result of our studies is that we were able to show an effect of CO_2 on the morphogenesis (accelerated shoot formation, higher average number of shoots and leaves per shoot, increase in the mean size of leaves [Figure 4]) for sessile and pedunculate oak. These observations suggest that changes in growth behaviour depend rather on a plant's capacity for carbon utilization than on its capacity for C acquisition through photosynthesis. In fact, the latter depends largely on the growth-rate of the plant.

Are inter-specific differences in growth stimulation by the increase of CO_2 linked to differences in the plasticity of morphogenetic processes in view of the increase in CO_2 and *in fine* to the growth type (determined or undetermined, monocyclic or polycyclic growth)[7]?

In terms of stand dynamics results allow one to **predict an acceleration of the initial growth the most important result of which could be a reduction of the time necessary for canopy closure.** This issue has important implications for the functions of stands and ecosystems and leads to the assumption that it will be necessary in the future to modify the management rules of stands (e.g. earlier thinnings). However, the results obtained thus far do not at all allow one

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[5] In the case of these plants the first molecule formed after the reduction of CO_2 contains three C atoms, while in the case of C_4 plants (such as maize), this molecule has four C atoms. The photosynthesis of plants of the metabolic type C_4 is practically not affected by the increase in the atmospheric CO_2 concentration; it appears, however, that the effect of stomatal closure might exist.

[6] These studies complement the work on carbon metabolism conducted by the research unit Écophysiologie Cellulaire of the University Henri Poincaré Nancy I.

[7] This hypothesis will be tested in cooperation with the Laboratoire d'Écologie Végétale of the University of Orsay, using a selection of the main European forest species.

to anticipate the modifications of the stand practice after the canopy closure, which is the most important phase in respect of wood production. The planned experiments with dense closed covers of young trees (aged up to 4 or 5 years) growing under conditions of interspecific competition should offer valuable information in this respect.

Transpiration and drought tolerance

The interactions between the increase in atmospheric CO_2 and drought tolerance are essential in the context of global changes.

The following questions will be discussed:

◆ Does partial stomatal closure, such as induced by the increase in CO_2, really reduce water losses and improve the water regime of trees? Does this effect vary depending on species? Is it possible that compensation effects linked to the integration of processes at the level of crown covers (canopy structure and amount of foliage, microclimate) occur?

◆ Can positive effects of the increase in CO_2 on stomatal regulation and water-use efficiency (ratio photosynthesis / transpiration) be counterbalanced by secondary effects (for instance, effects connected with a changed carbon allocation in the plant) affecting other aspects of drought tolerance such as the structure of xylem conduits which determines the efficiency of the water transfer in the tree, its osmoregulation, or the mycorrhizal status of its roots?[8]

These studies are conducted on maritime pine, a species which "avoids" drought and whose stomata are characterized by a great sensitivity to water stress, and on sessile, pedunculate and, at certain points, cork oak, "tolerant" species with a lower stomatal sensitivity. In these two groups of species, adaptation to drought is effected by different mechanisms. It might therefore also be differently affected by the increase in atmospheric CO_2. This hypothesis is confirmed by results concerning the stomatal function in relation to drought. In pine, the stomatal sensitivity to drought does not change, while in pedunculate oak it rises. It still needs to be determined whether these differing responses can be extrapolated to all "avoiding" and "tolerant" species; and an analysis including all components of drought tolerance has to be elaborated.

Figure 4 ◆ Effects of a doubling of atmospheric CO_2 on seeds of pedunculate oak: 700 ppm left, 350 ppm on the right-hand side.

Photo (p. 17): P. Vivin

Conclusions

Through the increasing amounts of carbon they immobilize, terrestrial and particularly forest ecosystems play an important part in attenuating the man-made increase of atmospheric CO_2. However, it is not certain if this effect will remain effective in future decades. In any case, if anthropogenic CO_2 emissions remain high, forest ecosystems will not be able to avoid a considerable, and long-term, increase of the atmospheric CO_2 concentration.

In view of future impacts of elevated atmospheric CO_2 on trees and forest stands it is necessary to continue research on the interspecific variability of possible changes regarding growth behaviour, drought tolerance, and resistance to other environmental stresses. We will have to determine the morphogenetic and physiological features which permit the classification of species into different functional groups for each of the characteristics under consideration.

[8] Collaboration with the research team Microbiologie Forestière of Nancy.

A second main direction of research on which we will concentrate during the next years concerns the integrated responses of trees at the ecosystem level (plant/atmosphere, plant/soil and also plant/plant relationships). For that purpose, carbon-nitrogen-water interactions will be analyzed at different levels of functional integration (cell, plant, ecosystem) in reconstructed mini-ecosystems. The analysis of C, N, and H_2O fluxes at those levels will mainly be based on methods using stable isotopes. We will concentrate particularly on changes in the carbon inputs into the soil (exudations, mortality of fine roots, litter, etc.) and on consequences for the acquisition of mineral resources.

Finally, one has to take into account the effects elevated atmospheric CO_2 has on the biochemical composition and quality of wood.

The construction of large CO_2-conditioned glasshouses near Nancy, where the outside climate will be reproduced, is an important asset for advances in these research directions.

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3 Forests and Water : Relations between Forest Ecosystems and Water Resources

Through their influence on the hydrologic cycle, forests influence the water resources of catchment areas both quantitatively and qualitatively. The role of forests in hydrology cannot be considered in isolation; their influence depends on the soil and climate conditions, on the precipitation regime and the amount of precipitation as well as on the evaporating capacity of the air. In fact, amount and distribution of precipitation are the decisive factors which, together with temperature, regulate the life of forests and the types to which they belong. It is estimated that, altogether, forested areas receive twice as much water as other types of soil cover.

Photo (p.18): S. Levoye - INSTITUT POUR LE DÉVELOPPEMENT FORESTIER (IDF)

This large number of components and the resulting difficulties in clearly identifying the role of forests explain why in the course of the past century controversies have developed regarding that issue in Europe and North America. Despite insufficient experimental data the idea that forests improve our water resources and have a moderating effect on high-water has taken possession of many forest managers. Although the important advances in forest hydrology during the past twenty-five years have improved our knowledge in that field, contradictory results and difficulties in the measuring of certain variables remain and complicate an indisputable interpretation of how forests influence water resources.

The influence of forests on the amount of precipitation and on the precipitation regime

Experiments conducted at the end of the past century, notably in Nancy (France) have substantiated the idea that forests considerably (18 %) increase precipitation at the regional level. In reality, the influence forests have on the amount of precipitation falling on a specific region is difficult to determine due to the complex relations between, on the one hand, forested and non-forested sites and, on the other, oceanic and continental surfaces. In addition, comparisons must be conducted under similar topographic and geographic conditions to be valid, a provision which is difficult to satisfy. With reference to experiments conducted in Nancy, the differences in altitude and regarding the exposure to the dominant winds are sufficient to explain the precipitation surplus measured in the Forest of Haye as compared to the agricultural zones east of Nancy.

It appears now that the effects of forests concern more particularly the convective storms during summertime.

At present, no reliable data are available on the minimum dimensions a forest stand must have so that it exerts a significant influence on the energy and hydric budgets of the ambient atmosphere. It is assumed that coherent stands of several hundred hectares are necessary. The effect of numerous small stands separated by non-forested areas is even less known. Despite such uncertainties a surplus in the order of 1 to 2 % of the annual precipitation of large forested areas as compared to agricultural zones is now assumed for the **temperate regions**.

With reference to **tropical moist forests**, which are affected by large-scale deforestations, several studies have been conducted; for instance, a potential reduction of the precipitation in the north (Sudanese area) of the Ivory Coast was associated with a reduction of the evapotranspiration as a result of the diminution of forest-covered areas in the southern part of that country (closed rain forest). The changes caused by brush fires and the introduction of annual cultures on vast surfaces lead to a reduction of the amounts of water vapour emitted into the atmosphere as compared to closed forest stands, which have a high transpiration potential and a high capacity of intercepting precipitations. Also, the absence of active vegetation (bare or fallow soil) results in important amounts of caloric energy being injected into the atmosphere, which increases the temperatures of air and soil and affects the mechanisms of cloud formation. Finally, the result would be a lower amount of precipitation in areas at a certain distance from the sea; but these are indirect "proofs" which do not guarantee that such decreases in precipitation were really due to that process.

In Amazonia, the possible effects of total deforestation (pastures on degraded soils) on the precipitation of that region have been studied by means of simulation using a numeric model of the functioning of the atmosphere and the biosphere. The results of that simulation indicate that a reduction of evapotranspiration is connected with rises of the temperatures of air and soil by approximately 1 to 3°C in the case of deforestation and with a decrease of the annual precipitations of about 26 %, coupled with an extension of the dry season. This study is based on the extreme case of the total deforestation of an immense geographic zone and absolute absence of reafforestation (degraded soils and low and interrupted vegetation cover), but despite a reduction, the mean precipitation prognosticated by the model would remain high (1,821 mm) and therefore might allow the restoration of a forest vegetation which, floristically, would without doubt differ from the original vegetation, but which would be capable of having an important evapotranspiration. It is important to remember that the model refers to the entire Amazon Basin. An extrapolation of the results to more limited areas must therefore be envisaged with caution.

The hydrologic cycle of forests

The influence of forests on precipitation

The liquid or solid precipitations that fall on forest covers are designated for diverse fates. Part of them is intercepted by the vegetative surfaces which constitute the forest ecosystem (main stand, understorey, shrub layer, herbaceous layer, litter). The rest reaches the ground either directly by throughfall, or by stemflow. Part of the water which reaches the ground can flow off from the surface. The remaining part is infiltrated in the soil, where, depending on the characteristics of inclination, structure, and texture, it can circulate by subsurface flow. The surplus water percolates and feeds the groundwater and the rivers. In the soil, water is absorbed by the plant roots and returns to the atmosphere by means of transpiration; it is also directly evaporated from the soil and inert vegetation surfaces.

The interception of precipitation by the forest cover represents a major component of the influence forests exert on the water cycle. In the case of closed-canopy stands it constitutes an important part of the annual precipitation: 25 to 50 % in conifer stands and 15 to 30 % in deciduous forests. In tropical forests, and particularly in forests of the tropical moist zone, the percentages of interception are variable and often lower than in the temperate region. The interception which, as a relative value, decreases with the amount of precipitation, depends on the intensity of the rainfall, on its persistent or intermittent character, and on the evaporating capacity of the air. If the same amount of water falls on a stand, interception will be stronger in the case of short intermittent showers than in the case of heavy continuous rainfall. This is due to the fact that during the interruptions the intercepted water evaporates rapidly so that

the cover is again capable of taking up precipitation. As the maximum precipitation storing capacity of the cover is low and does not exceed 3 mm, the reservoir function of forest stands is less marked where precipitations are persistent and very heavy.
Interception increases with growing **age and density of stands**: In beech, for instance, the annual interception reaches 20 % at the age of 50 and increases to 25 % at 120 years; in the case of Douglas fir, which has a very big crown, the interception is very high (35 %) already when the trees are only 15 years old. Openings of the cover caused by thinning reduce the interception, which, however, would not be of the same proportion: If, for example, half of the trees of a Douglas fir stand are removed, this will cause only a 17 % reduction of the interception because the opening of the cover facilitates the moistening of the crowns and allows a more rapid evapotranspiration of the intercepted water. The major part of the intercepted water is evaporated. While the evapotranspiration of water intercepted by grassland leads to a reduction of the transpiration corresponding to 100 % of the interception, it is assumed that, in temperate climates, the total loss amounts to 80-85 % of the water intercepted by forest covers.
In regions characterized by **frequent fog,** such as coastal or mountainous regions, forests are able to condensate by 30 to 50 % more than the open land. In certain cases (California, Hawaii, Czechoslovakia) there are no losses through interception as a result of fog condensation. The condensation of fog thus has a stronger influence on the water balance of mountain forests than it has on open land.
Apart from fog, the **formation of dew** is observed during the night when the temperature of the air drops below the temperature of the dew point. Forests profit from dew if the condensed water comes from the atmospheric air mass, but in many cases the dew appears to originate at least partly from the water of the ecosystem. It is assumed that on a horizontal surface the maximum height of dew which can form at temperatures between 0 and 20°C is in the order of 0.07 $mm.h^{-1}$; the height of the water at the end of the night is between 0.2 and 0.5 mm. Dew is therefore only a minor component of the hydrologic cycle.
The forest cover has a strong impact on the distribution and accumulation of **snow**, which, due to its lightness, is very sensitive to the roughness of the substrate on which it falls. While for rain it is the surface tension which determines interception, the fixing of the flakes is a result of their physical state. Conifers with dense covers, such as fir, spruce or Douglas fir, intercept most, while the interception of broad-leaved trees is much less significant. Some species or ecotypes of boreal altitude or regions have developed crown column forms which intercept small quantities of snow. The consequences of snow stored on crowns are controversial as it is difficult to evaluate the losses through evaporation. In forests, the snowmelt takes longer than on bare land; this extends the period of snow cover, which may persist up to 3 weeks longer in forests than on open land. The establishment of this phenomenon enhanced the development of management techniques permitting to control the duration of the snow cover and to improve the distribution of the water available underneath.

The influence of forests on water and soils
Apart from the phenomena of evaporation, water which reaches the ground can be diverted by surface flow, subsurface flow, infiltration and storage in the soil, and groundwater run-off.

Photo (p. 21): A. Campana

The surface run-off depends on the amount of precipitation, on the topography of the land, and on the infiltration capacity of the soil.

Subsurface flow corresponds to a lateral movement of water in the upper soil layers. How important that part is depends essentially on the structure (permeability) of the soil; impermeable horizons of low depth favour this type of water movement which can sometimes represent up to 80 % of the total flow.

The **infiltration capacity** ($mm.h^{-1}$) is a dynamic property; it is high at the beginning of a shower and then progressively decreases (increasing size of the soil colloids, which leads to a reduction of the pore size; flow of fine particles in the pores). The infiltration capacity of forest soils is usually higher than that of bare soils because, on the one hand, the forest litter reduces the mechanical effect of the water drops, which tends to destroy the surface soil structure by favouring the slacking (blockage of the pores by the fine particles), and, on the other hand, the activities of the different living organisms (microorganisms, animals, roots) increase the porosity and stabilize the structure of the soil. The infiltration capacity can be reduced by logging activities or fires. It is assumed that it increases from bare soil to → cultures → grassland → forests. Forest humus has high permeability which, however, varies significantly with the initial moisture content. For instance, after long periods of drought the raw humus types of conifer stands are very hydrophobic and constitute an impermeable layer for the first precipitations; under humid conditions, they retain large amounts of water, while the mull of broad-leaved forests intercepts much less.

In the soil, the maximum amount of water ($mm.m^{-1}$ of the soil) that is available for transpiration depends on the texture and depth of the soil (75 mm for sands and 170 mm for argillaceous silt). In fact, the more the available reserve is exhausted, the more difficult it is for the trees to extract water from the soil and from the time when 60 % of the available reserve have been used up they reduce their transpiration. The depth up to which water is extracted corresponds to the rooting depth, excepting the capillary activity which is difficult to quantify. At the beginning, water is almost exclusively extracted from the surface layers; with growing scorch, the trees progressively consume water also from lower reserves.

The magnitude of flood depends mainly on climate conditions and geomorphological characteristics, but compared to bare soils, which have a low infiltration capacity and therefore support surface run-off, forests control the force of floods and delay the moment of their occurrence. The influence of the forest cover (interception and high water infiltration capacity of the soil) remains very limited when flooding is a result of subsurface flow and when the storage capacity of the drainage basin has been largely exceeded after prolonged precipitations. The most significant effect of forests is probably their erosion-controlling capacity and, therefore, their capacity to reduce the amount of sediments which increase volume and force of flooding. A slightly peculiar case concerns interrupted arboreal covers like the landscape type of the "bocages" in north-western France. Studies carried out in the Bretagne show that in landscapes of that type flood events are on average one or two times less heavy than on bare land; however, there remain numerous uncertainties linked to the climate conditions favouring floods.

Evapotranspiration of forests

Evapotranspiration represents the water consumption of a forest cover and consists in the transpiration of water by plants and the evaporation of water from the soil and of the rain water intercepted by the leaves which, e.g. for a *Pinus sylvestris* stand, is 54.1 %, 6.5 % and 39.4 %, respectively, of the total annual evapotranspiration. Evapotranspiration depends on various climate factors: solar radiation, temperature, air humidity, and wind velocity. In the case of "rough" forest covers (conifer forests), where the phenomena of turbulent exchange are highly effective (connection between cover and atmosphere), the amount of transpiration and the saturation deficit of the air are closely correlated. In contrast, solar radiation seems to be dominant in the case of broad-leaved forests (decoupling).

The direct estimation of forest evapotranspiration is particularly difficult because of the dimensions, the longevity, and the deep rooting of trees. Evapotranspiration can either be determined directly on the basis of microclimatic profiles above the cover, or indirectly using the general equation of the water budget at plot level and at the level of the catchment areas. The amount of the surplus water which runs off can thus be calculated from the difference between precipitations and evapotranspiration or measured at the level of the streams coming from the catchment areas.

Influence of the stand density

Under given soil and climate conditions evapotranspiration reaches a maximum (and, thus, the run-off a minimum) when the canopy is closed; in that case interception and transpiration are also at a maximum. Complete or partial removal of forest cover leads to a reduction of evapotranspiration, which results in a higher water content of the soil and, depending on the circumstances, also in increased run-off. The increase of the run-off in catchment areas depends on the amount of precipitation: For example, in regions of the USA with precipitations between 1,200 and 2,300 mm, the increase of the run-off caused by a clearcut varies from 130 mm to 460 mm; in regions with lower precipitation (between 530 mm and 710 mm), run-off would increase by no more than 25 to 75 mm. Finally, in zones with less than 480 mm of precipitation, the run-off would not increase at all. In Lorraine, a reduction of the evapotranspiration of 29 % was observed after a clearcut. The duration of the period of elevated run-off depends on the initial increment after the cutting as well as on type and importance of the latter and of the rate of regeneration of the cover. In contrast to total or partial cuttings, thinnings have a much more transitory effect as the cover quickly closes again and the roots of the trees recolonize the available soil within a short time. In a 19-year old Douglas fir stand in Lorraine it was observed that the effect of strong thinning (50 % of the basal area[1]) would disappear after a period of 5 years.

Species- and age-related influences of forest stands

It is reasonable to distinguish between the total evapotranspiration of stands and the transpiration of the trees of individual species. Depending on whether we deal with densely or thinly stocked species, the undergrowth will be more or less developed. In the first case the transpiration of the trees represents practically the entire evapotranspiration of the stand, while in the second case the role of the undergrowth will be of greater significance, e.g. in maritime pine in the Landes. The transpiration of trees of that species is closely correlated to the degree of opening of the stomata, to the foliar characteristics, and the saturation deficit of the air; the transpiration of the herbaceous undergrowth is closely linked to the solar radiation received by the foliage and altogether represents 25 % of the total evapotranspiration when the soil is well supplied with water, while under conditions of drought it exceeds that of the trees.

In Lorraine the comparison of evapotranspiration of 4 stands during the vegetation period leads to the following classification in decreasing order: beech (*Fagus silvatica* L.), giant fir (*Abies grandis*), Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* Karst.). It can generally be assumed that, during the vegetation season, hardwood stands evapotranspirate equal or even higher amounts than conifer stands. The converse is true for the period of late autumn-winter and early spring because at that time the interception is much higher in conifers and the transpiration capacity of deciduous trees is reduced. The stands show significant age-related modifications regarding their biomass and structure. In general, the herbaceous and shrub layers are important at the beginning of the life of stands; they decrease when the main storey closes and eventually increase again when the stand becomes older and

[1] Cumulated surface/ha of the trunk sections of trees (section of 1.30 m).

sparser. These transformations cause variations of the evapotranpiration which are the result of changes in the transpiration of water by plants, the evapotranspiration of water from the soil, and the interception. The evapotranspiration of the stands is maximum and, thus, the run-off minimum, when the stands are about 40 to 60 years old.

Photo (p.23) - Measurement of the transpiration of a stand. Photo: H. Cochard

The evapotranspiration of forests compared to that of grassland

The evapotranspiration of forests is higher than that of formations of low height, such as grassland. Depending on the case, the proportion of the evapotranspiration of grassland/forests varies between 0.9 in moist climate and 0.7 in climates with significant water deficits. When the hydric deficit increases, forests consume considerably more water than the grassland, as their deeper rooting enables them to completely exploit the hydric reserves of the soil. However, under conditions of extreme drought their more efficient rooting system is no longer an advantage because the small amounts of precipitation cannot profoundly supply the soil with water again.

The influence of forests on water quality

The influence of forests on water quality of brooks and rivers is difficult to define as other factors are involved as well, especially the soil type and atmospheric inputs. However, it seems that, compared to grassland and broad-leaved forest species, conifers produce a more acidifying litter and, through their persisting and usually more important foliar surfaces, constitute a more efficient sink for atmospheric pollutants (in particular nitrogen and sulphur). In this context it has to be underlined that forests sequestrate the nitrogen inputs in their biomass and that forest strips along brooks and rivers obviously reduce the nitrate content of alluvial layers. In several studies differences were observed regarding the chemical composition of waters running off from catchment areas covered with grassland, broad-leaved forest stands, or conifer stands. These differences are associated with the more significant chemical erosion in the conifers, particularly in spruce. It is now assumed that on chemically poor soils massive afforestation with coniferous species and intensive silviculture (important exportation of mineral elements) can cause an acidification of the water that has a negative effect on certain species such as salmon.

Conclusion

The influences of forests on the water resources are complex and diverse because they depend on climate, soil conditions, and human activities. It can, however, be stated that the evapotranspiration capacity of closed-cover forests is higher than that of the other vegetation formations and that for this reason, and due to the high precipitation absorption capacity of their soils, they represent a determining factor in the distribution of run-offs to the rivers. Reducing the size or coherence of forest covers by cuts (thinnings or clearcuts) modifies the water consumption and, thus, the water yield in catchment areas. For broad-leaved and conifer stands, the differences in water consumption are less marked than we thought and, depending on the respective stand type, may even be inverted. With respect to water quality, conifers apparently cause a stronger chemical erosion than broadleaved trees or grassland and increase the acidity of the water running off in the catchment areas. In conclusion, one can say that despite recent progress numerous uncertainties remain in respect of the hydric and hydrologic functioning of forest stands and catchment areas which require further research.

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For further reading

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Forests and Their Soils

The soils of forest ecosystems constitute a particularly important component where major physical and biological processes occur, among them the carbon cycle and the nutrient cycle both of which are closely linked to the turnover of organic matter. Research work conducted as a consequence of novel forest damage observed in the early eighties showed that knowledge of the function of soils in relation to their own characteristic properties, the practiced silvicultural method, and anthropogenic factors (nitrogen depositions, acid depositions, ...) was essential to understand the stability or instability of forest ecosystems. To ensure a sufficient nutrient supply of trees, from the seedlings to the adult plants, and in physical and biological ways (symbiotic microorganisms of the rhizosphere), is another aspect of that stability.

To guarantee soil fertility and the nutrient supply of trees and stands over the long term therefore represents one of the pillars of sustainable forest management and is a major subject for scientists. The item is even more pertinent in the context of a changing climate or more intensive silviculture (more productive varieties) the consequences of which we should try to foresee.

Photo (p. 24/25): Aleppo pine : © R. Schiano - CEMAGREF

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1 How sustainable is soil fertility? (J. Ranger)

2 Assuring sufficient nutrient supply for trees - a basic condition of sustainable forests (J. Garbaye, M. Bonneau)

1 How Sustainable Is Soil Fertility?

The concern about maintaining, or even improving the level of forest soil fertility is not new, as from the end of the 19th century onward, Grandeau (1879), Sabatier (1890), and Henry (1908) already worried about this issue. However, this parameter did not so much attract the attention of foresters as that of agriculturists.
This is due to a number of reasons, and probably the legendary frugality of forest stands, the longevity and robustness of the species, and the relatively extensive exploitation of the resource contributed to the differentiated view of that parameter, which in fact appears a bit contradictory in a country having a long silvicultural tradition.
More intensive silviculture makes us now very seriously pose the question of sustainability of such management.

Sustainable management can be realized only when all key parameters regarding the functioning of ecosystems are known. These parameters include the factors of sustained production which, however, are not the only ones to be considered as the entire variety of ecosystem functions has to be taken into account, in particular those that concern the conservation of the environment (quality of soils, surface waters, biological diversity, landscape, etc.).
In this article, sustainable management will be discussed exclusively from the point of view of "soil fertility".
The question which needs to be answered refers to the renewable character of the resource "soil". It appears that it was only in the recent past, as a consequence of the novel forest damage of the eighties, that people became aware of the fact that the soil does not represent a renewable resource. Whatever type of management, or even "non-management", is practiced: the soil will continue its evolution and thereby sooner or later lose its initial fertility.
These losses accelerate with growing demands on the ecosystem or if external stresses occur suddenly (diffuse and *a fortiori* elevated pollution, for instance). The development of vegetation, the drainage of diluted solutions, harvesting, and regeneration cause elemental or even material losses (erosion) that are irreversible. How significant these losses are depends on the intensity of the stresses on the ecosystems and the loss of fertility, though unavoidable, usually causes only a slow decline of the production capacity which is certainly more marked when the initial reserves of the soil are limited.
Sustainable management will thus consist in reducing such losses as far as possible or in compensating for them. In this context, the classical rules of agronomy apply to forestry.
Managers will certainly wish to maintain the production of the system; this is not necessarily synonymous with maintaining the fertility of the soil which, in this context, is considered an absolute criterion. In fact, it is possible to substitute existing species by new, less demanding ones which even under lower conditions of fertility produce equal, or higher, amounts of biomass.
The strategy will be first to discuss the procedure in a context of extensive forestry, with the management being adjusted to the environmental conditions; the pressure of intensification will then have to be discussed according to the different parameters, necessarily including the environment.

Photo (p.26): M. Pitsch

The concept of soil fertility

The concept of fertility should be precisely defined so that criteria taking into account fertility can be identified on the basis of impact studies of various silvicultural practices in accordance with the respective environmental conditions.

The "inherent" fertility of a soil depends on a series of physical, physico-chemical, chemical, and biological factors that determine the capacity of the soil to sustain a production. These diverse components will be treated separately for didactic reasons only; in reality, they are in strong interaction.

The definition rests on the assumption that only the soil changes while, for instance, climate conditions are stable, which is not entirely true. Soil fertility is a potential resource to be used in a specific way by the respective vegetational stand. The role of the silviculturist has to be considered, too; in the past, plantations with often allochthonous species, silvicultural treatments favouring one particular species, or litter removal were practiced in forests for the benefit of cultivated lands.

This article will concentrate especially on the soil parameter of "mineral fertility", which has two components:

- present fertility;
- medium- and long-term fertility.

Present fertility represents static data determined on the basis of soil analyses. Long-term fertility data are dynamic and correspond to the flux of elements slowly set free as a result of the weathering of soil minerals in the course of the neutralization of delivered or internally generated acidity (withdrawal of cations, nitrification, oxidation processes). This flux will recharge the "available pool" of the soil.

This applies to all elements, including nitrogen, which, in ecosystems without nitrogen-fixing agents, behaves very much like the other elements although it does not occur in the parent rock.

Methods

- **Present fertility**: The methods used to determine the fractions of elements available for the vegetation consider the exchangeable elements (cations of the type Ca, Mg, K,...) and phosphorus called assimilable, i.e. extracted by relatively soft reagents which set free the unstable portion of the organic and mineral components, and the mineral nitrogen produced at the moment or cumulated for the annual period of vegetation.

For these methods components are extracted whose physico-chemical characteristics are "well" known and which supposedly can be utilized by plants. There is a wide nuance between these two terms and, depending on the soil type, the actual availability for the vegetation can vary widely. Diagnoses of the present state of soil fertility can be made by reference.

The potential described by these analyses remains highly different from the real environment from where plants draw their nutrients. In fact, soil solution even around roots is a diluted milieu with an ionic strength much lower than that used in the classical analyses. Its physico-chemical equilibrium with the solid soil phase will indicate inter-element ratios considerably different from those obtained with concentrated solutions; it appears that the methods used to determine the present soil fertility, though largely applied, are not completely satisfactory and that it would be interesting to test other methods which come closer to the real nutritional conditions at the interface of soil and plant.

◆ **Medium- and long-term mineral fertility**: The flux of weathered soil minerals is a parameter much more difficult to measure than the present fertility; it is, however, the only one suitable to characterize the resilience[1] of extensive systems, where it compensates to a high degree the depletion of existing reserves by cultures.
Many indirect approaches have been made to quantify this parameter:
- nutrient budgets using the age of the soil and an initial reference and assuming the linearity of the phenomenon;
- ecosystem budgets with all terms known except for the weathering flux of soil minerals and assuming the stability of the system;
- experimentation under controlled conditions and attempts of extrapolation to natural conditions.
The information derived from ecosystem budgets provides a means to determine the order of magnitude of the weathering flux of soil minerals which is necessary to maintain the status of the system. This approach, however, does not identify the exact origin of the elements; in particular, the portion representing the weathering flux may originate from a desaturation of the absorbing soil complex or from a destabilization of the organic matter. In terms of soil functions, the difference between these origins is very important as desaturation affects the equilibrium of the system, which may within a short time cause a reduction of the pH value and an aluminisation of the absorbing complex, with all possible consequences for the biology and the production of the ecosystem. On the other hand, when the cation losses are compensated by the weathering flux, the buffering capacity of the soil, and thus its medium- and long-term fertility, will decrease, but the biological properties of the system will not be affected as the pH and the saturation do not change.

Correct input-output budgets can be established only if all terms of the budget and, in particular, of the flux of weathered rock, are independently evaluated.
The process of validation consists in establishing precise input-output budgets, in measuring the desaturation of the absorbing soil complex, characterizing the stability of the organic compartment, localizing the nutrients in the mineral phases, identifying the responses to the current decomposition, and eventually modelling the fluxes according to soil characteristics.
It is thus a complicated method and it can be used only on sites where all basic data are known. Carried out on a large number of sites, it should be possible to address invariants that allow extrapolations.

Nutrient supply, a specific problem of forest stands

Forests are characterized by species that are long-living, robust (without major genetic improvement), and located on soils whose mineral reserves are limited (old soils without enrichment, soils abandoned by the food-producing agriculture).
Under these conditions a series of adaptive mechanisms have developed, leading to very interesting performances of these plants with respect to their overall capacity to use their nutrient efficiency for the production of vegetational biomass. The nutrient demand of forests for developing their annual biomass is very high, sometimes even surprisingly elevated, but a series of recycling mechanisms of the ecosystem allow optimum use of the available stock. These mechanisms represent the biological or biogeochemical cycle of the nutrient elements, presented in the diagram of Figure 1.

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[1] Capacity of stress resistance.

Figure 1 ◆ Schematic representation of the biogeochemical cycle in forests (Ranger et al., 1995).

1 • uptake by the roots
2 • temporary stockage in the tree
3 to 5 • immobilization in the tree
6 • atmospheric inputs
7 • fixation of atmospheric nitrogen
8 • canopy leaching
9 • solid restitution
10 • humus mineralization
11 • root mineralization
12 • weathering of parent rock and soil minerals
13 • drainage losses

The observation of numerous ecosystems in the framework of various programmes, in particular of the *Programme Biologique International* (PBI), enabled us to outline the main features of the biogeochemical cycle of nutrient elements:

- The needs for the biomass production of a stand are high.
- The origin of the elements is typical of perennial plants; certain elements are drawn from the soil; others come from an internal recycling process of elements from older tissues that are directed to the growing organs. For instance, N, P, or K are to a high degree recycled in that way (sometimes up to 50 % of the total need), while others, such as calcium, are practically not recycled at all.
- Elements which are taken up by the plants and restituted to the soil (between 50 and 80 %) are particularly important in the form of litter.
- Elements restituted in an essentially organic form are inaccessible pools for plants; the mineralization of the litter is therefore of major importance.
- External inputs contribute to the maintenance of soil fertiliy but are partly lost by drainage (part of the inputs not realized during the vegetation season).
- What really makes the difference for the soil is the immobilization in the woody parts, the stockage in the stable foliar biomass, and the accumulation in the litter on the forest floor.
- The definitive losses for the soil consist in the elements exported along with harvesting and in the drainage losses (in the course of the rotation period and during the phases of harvesting-regeneration).

Photo (p. 29) - Facility for studying the functioning of a forest ecosystem.
Photo: Dominique Gelhaye

The different stages in the development of a stand follow very different schemata, which is due to the fact that each and every age group has specific needs (NPK, which are elements of youth) and involves significant quantitative modifications regarding their demands.

The biological cycle has at least two functions:

- The first, which has just been descibed, leads to the best possible use of an active, but quantitatively limited pool;

- The second important function of the biological cycle is that it efficiently prevents nutrients such as calcium or magnesium from being transferred deeper into the soil. In acid soils these elements are inevitably transported out of the root profile as the competition with aluminium is unfavourable for their continued presence in the absorbing soil complex.

Deciding on the conservation or non-conservation character of forest management

The only way to derive evidence is to establish a budget of the mineral soil fertility: over one or, if possible, several rotation periods, in a suffiently large number of observation sites, and taking into account the variability of ecological situations.
The perenniality of ecosystems is based on the stability of their biogeochemical cycle of elements which, at least over the medium term, must also be apparent from well-balanced input-output budgets.

- At the soil level: It is possible to apply the same theoretical principle to cations and phosphorus of the parent rock and to nitrogen of initially atmospheric origin. One could refer to all elements, but usually only the group (compartment) of the "assimilable elements" is considered, which is decisive for the present fertility.

Based on a model describing compartment and flux (Ranger and Bonneau, 1984) the potential variation of the mineral stock (Δ S) for plants during a rotation can be formulated as follows:

Δ S = external inputs + weathering flux of mineral components - drainage - immobilization ± variation of humus stock

- At the ecosystem level:

INPUTS	=	OUTPUTS
atmospheric inputs		exports in the biomass
+		+
weathered elements		drainage losses during rotation
		+
		drainage losses during cutting

This input-output budget enables us to verify whether a long-term production can reasonably be expected. This is always easy for ecosystems where forests are monitored, but it will be important to decide if fertilization has to be applied. Factors like soil fertility and the socio-economic context will also have to be considered. Qualitative problems are much more complex. An immobilization in the system (for instance in the case of recalcitrant litter) does not show up as a deficit in the budget although it constitutes a loss for the pool of elements available for the plants. These budgets are thus often very useful, but one has to be aware of their limits. The disequilibrium of a budget may have different causes, which in any case need to be analyzed.

Though it is possible to establish budgets for particular stages in the development of the ecosystem, they are of interest mainly when they cover an entire rotation period. In this respect the longevity of forest species obviously presents a major obstacle. For lack of long-term follow-up facilities the approach most frequently applied is that of the chronosequence of stands, which, by means of extrapolation and based on several stands of different age located in conditions that are ecologically as comparable as possible, permits acquisition of data for an entire rotation within a short time.

The installation of facilities for the observation and handling of ecosystems that can be managed over the long term is a priority. The establishment of the network "RENECOFOR" operated by the (French) *Office National des Forêts* gives evidence of the interest shown in the issue and will provide references in that field.

The concept of "ecological rotation" and its consequences for sustainable management

For a given site (fixed ecology and management activities), the concept of "ecological rotation" presented by Kimmins consists in establishing a theoretical budget of nutrients in order to determine when the system returns to pre-harvest conditions. The natural budget, i.e. inputs (atmospheric deposits + soil mineral weathering) - output by drainage, is supposed to be always positive and constant while the immobilization of nutrients decreases with time. In these conditions, the point where the two curves cross corresponds to the minimum duration for complete recovery and is called "ecological rotation" length. This definition is linked to that of the renewable or non-renewable nature of resources which, strictly speaking, is not a biological, but an economic concept. If the length of the cycle of ecological renewal is not realistic economically, the resource is not renewable, while in the opposite case it is.

This paper started from an apparently different definition assuming that resources are inevitably depleted and, thus, are non-renewable. Kimmins considers only the present fertility, which, in rich soils, is within a short time restored by the decomposition of reserves. This position is certainly contestable by the ambiguities it may generate, as even for the most eutrophic forest soils it is not certain that a maximum intensification of the demand will not relatively quickly lead to problems regarding the availability of nutrient elements (for instance, in short-rotation forestry). It seems more reasonable to consider a gradient of soil richness and define the problems inherent to several large subdivisions.

Accordingly, three cases were defined:

1 - the most eutrophic soils, where sustainable management is possible;

2 - soils where sustainable management requires very specific management activities;

3 - soils for which that type of management is not realistic as they regenerate very slowly. The management could be effected only over the very long term, with periods of mining exploitation and periods of fallow. Another solution would be artificial site improvement.

It is not always evident which of the above situations applies. In fact, many plantations probably develop correctly although they curb the available capital, which means that production is sustainable, while ecosystem management is not. Many of our conifer plantations are of recent origin and only 2 to 3 generations have been harvested. In general, no data are available on the initial soil status. In addition, outside conditions may make analyses even more complicated, as is the case for the nitrogen inputs which increase production, but frequently lead to a desaturation of the soil.

The impact of silvicultural management on soil fertility

The applied silvicultural methods will influence:

- the nutrient exports caused by harvesting, which depend mainly on the respective vegetational species, cutting age, logging intensity, and production class;
- the nutrient exports due to drainage outside the rooting zone, including

  - deep drainage, which exists during the entire life of a stand and depends mainly on the latter's climate, species, silvicultural treatment, and stage of development; and

- the exceptional drainage of elements during the felling period, especially in the case of clearcuts;

- the effect of site preparation on the nutrient stock. This includes timber hauling, which may cause soil compaction; windrowing[2], which may lead to an important loss of fertility if the surface layers are removed; and the burning of logging slash.

Figure 2 provides a synthesis of the effects of moe intensive silviculture on the nitrogen demand; the run of the curve illustrates the disproportion of biomass production and nitrogen export rates.

Figure 2 ◆ Relation between intensity of forest management and annual nitrogen demand (Switzer and Nelson, 1973).

Mean annual nitrogen demand (kg/ha)

Total utilization
Partial utilization
Production (t dm/ha/year)

ExtensiveIntensive
Intensity of management

a: 40-year old natural stand
b: 20-year old natural stand
c: 10-year old natural stand
d: coppice stand (10 years) + genetic selection + working of the soil
e: d + fertilization to achieve the maximum potential of the species

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Conclusion

The soil functions relating to the mineral supply of forest ecosystems are very specific and can be summarized using the concept of the biogeochemical cycle of nutrients:

- The cycle has a strong conservation effect on the natural soil fertility because, through the restitution of organic matter, the nutrient elements drawn from the entire soil profile are essentially restituted to the soil surface, whether in the form of above-ground or below-ground litter.
- This mechanism allows high productivity although reserves are often limited.

For every type of ecosystem there is a rotation period corresponding to the ecological rotation which, in the case of very poor soils, is certainly not economically realistic. It would be useful if we were able to determine the length of this rotation period for all ecosystems, i.e. to generally apply reliable budgets.

It is necessary that managers consider soil fertility and be aware that soil is not a renewable resource, but an acquired capital which should be preserved. Although this is true also for the nutrient elements, it may be even more important for the organic matter of the soil. It represents a cation reserve, a very powerful ion exchanger which can retain the nutrients in the upper soil layer; it contributes to the good physical structure of the soil and, consequently,

[2] Collection of the wood refuse (logging slash) in lines (windrows) with the help of a specially equipped tractor.

to the aeration of the soil and its water reserves. Thus, the rules of management are those of classical agronomy.

All management decisions that lead to additional nutrient exports and reduce the stock of organic matter of the soil, or that cause physical stress must be considered in connection with soil fertility. These include: the introduction of efficient species of high biomass production; shortening of rotation periods; harvesting of the entire biomass; maintaining bare soil during cutting and regeneration periods; windrowing; and the burning of logging slash.

At present, it is possible to give orders of magnitude that permit the calculation of the exports caused by harvesting. It can be assumed that it will be possible to simulate the effects of silvicultural scenarios in some representative cases. The drainage losses that occur during rotation are more difficult to calculate, but, except for phosphorus, are frequently of the same order of magnitude as the losses due to harvesting. The budgets that have been established for several ecosystems begin to provide some indications, but the systems are too diverse for conclusions to be generalized. Modelling should be useful for this purpose.

An essential question which has not been solved thus far is: Being aware of the stresses exerted on a system, what will be the consequences for future production? Which are the indicators of the progressive destabilization of an ecosystem and which are thus the indicators of its proper functioning? How can we manage to determine objectively the "critical load tolerable by a forest ecosystem"?

Provided that they are correctly conducted, profound studies of the biomineral actions and processes of the system (dynamics of organic matter, nitrogen and cations) and long-term experiments are the only means allowing to correlate stresses and the responses of the system and to validate models of functioning. To arrive at conclusions that are more than just speculative the data of several rotation periods would be required. Long-term experiments which are from the beginning designed for that purpose are very rare.

Sustainable management must take into account the mutual relations among ecosystems. In particular, the functioning of forest ecosystems can influence the aquatic ecosystem: While acid soils can cause the acidification of brooks or lakes, the input of fertilizer, on the other hand, can lead to their eutrophication.

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For further reading:

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2 Assuring Sufficient Nutrient Supply for Trees - a Basic Condition of Sustainable Forests

Different metabolic processes determine tree growth and wood production: the sequestration of carbon by photosynthesis at the level of foliage, the integration of carbon into organic molecules, the transportation of the latter, and the multiplication and growth of cells. Apart from atmospheric carbon and the oxygen and hydrogen from water, the synthetized substances contain also mineral elements which trees can find only in the soil. By decreasing order of frequency in foliar tissues, the most important among them are nitrogen, potassium, calcium, sulphur, phosphorus, and magnesium. In addition, the enzymatic reactions that cause the synthesis of organic molecules necessitate the presence of these very elements.

Photo 1 (p. 32) - Branch sampling for foliar analysis using a gun. Photo: P. Dubois

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The frequency and availability of these elements in the soil condition the nutrient supply and growth of trees. If the mineral budget is well-balanced, trees should be able to draw from the soil and stock in their organs the amounts of nutrients required for a sufficiently elevated production (not necessarily maximum in volume in order to preserve a good technological quality of the wood). Thus we concentrated our efforts on determining the optimum mineral composition of various forest trees in order to understand in which ways trees would extract those elements from the soil and how nutrient deficiencies could be adjusted.

Foliar diagnosis

The large number of studies of the relations between stand productivity or growth of plantations and their nutrient supply as well as the large number of fertilizer trials permitted a progressive approach with respect to optimum foliar content of the main mineral elements. This descriptive approach was supported by explanatory research on the metabolic transport system, the storage and incorporation of mineral elements in the tissues of trees.
Many species and regions of France have benefited from such research works (photo 1): maritime pine (Landes de Gascogne), spruce (Haute Ardèche, limestone plateau of the North-East, Ardennes, Vosges, Massif Central), Douglas fir (Limousin), fir (Vosges and Jura), poplar (north of the Parisian Basin), Austrian pine (Pays de Loire and Mediterranean South), beech (Normandie and Basses Vosges), oak (Pays de Loire).

Table 1 provides examples of standard values elaborated in this way. Based on simple, unexpensive foliar analyses it is possible to judge the nutrient status of a stand: This is what we term "foliar diagnosis".

Nutrient uptake from the soil by trees

Like almost all plants, **forest trees draw water and mineral elements from the soil by means of fungi associated with the fine roots**. This association, which is an absolute necessity both for the tree and the fungus, is a symbiosis, which means that both partners benefit from it: the tree feeds the fungus with sucrose and the fungus explores the soil at large distances from the root (up to 50 cm), extracts water and nutrients, and transfers them to the tree. Apart from the bigger volume of soil they explore, fungi are also capable of solubilizing forms of phosphorus and nitrogen otherwise inaccessible for the roots. Their fine filaments allow them to penetrate even the narrowest pores of the soil where water persists longer during periods of drought, to which roots, however, do not have access. Finally, fungi also contribute indirectly to improving the nutrient supply of trees in that they protect their roots against diseases due to other soil fungi, the pathogens. The combined symbiotic organ of root and fungus is called mycorrhiza (photos 2 and 3).

(p. 33)
Photo 2 - Macroscopic view of a mycorrhiza: Filaments of the fungus (here in yellow) forming a coat around the root and strands exploring the soil.
Photo 3 - Cross-sectional view of a mycorrhiza under scanning electron microscope: Fungal coat (small cells) enveloping the root (big cells).
Photos: J. Garbaye

The effectiveness of this absorbing system varies according to the associated fungal species (boletus, amanita, russula, lactarius, chanterelle, etc.). For example, some of them have a particularly high phosphorus extracting capacity; others are especially efficient in absorbing water during periods of drought, in mobilizing nitrogen or protecting the roots against diseases. On a given soil, the nutrient status of the forest depends to a large extent on the available mycorrhizal fungi.
For this reason INRA has undertaken a great many efforts to improve our understanding of the functioning of the mycorrhizal symbiosis. The practical consequence of this knowledge is that there are two ways for foresters to improve the mineral supply of stands: to increase the nutrient concentration of the soil by means of fertilization, or to improve the mycorrhizal status of the trees by inoculation with selected fungal strains. Different results obtained from these two processes are presented below.

Table 1 ◆ Critical threshold value and optimum content (in parantheses) of major elements in the foliage of several forest species cultivated in France (in g of the element per kg of dry matter).

	Nitrogen	**Phosphorus**	**Potassium**	**Calcium**	**Magnesium**
Spruce	13 (16)	1.4 (1.7)	4.5 (6)	2 (3)	0.8 (1.2)
Maritime pine	8 (12)	0.9 (1.2)	4 (5)	1.7 (2.5)	-- --
Austrian pine	11 (13)	1.2 (1.5)	4 (5)	-- --	0.6 (0.7)
Fir	13 (16)	1.4 (1.8)	5 (6.5)	3 (4)	0.9 (1.5)
Douglas fir	13 (15)	1.2 (1.5)	6 (8)	2 (3)	-- --
Sessile oak	18 (23)	1.1 (1.5)	(8.5)	(9)	-- --
Poplar	-- (28)	-- (2.5)	-- --	-- --	-- --

Forest fertilization
The above-described foliar diagnosis has enabled us to identify various shortcomings regarding the mineral nutrition of our forests, deficiencies which can more or less be explained by the soil conditions. INRA has thus established a network of numerous fertilizer trials all over France. The methods of adjustment which were defined as a result of this research work could be regularly applied by forest managers. Consequently, phosphorus fertilization of maritime pine seedlings has become a general treatment in the Landes and the input of natural phosphates in spruce and Douglas fir plantations has become the general

practice in the Limousin and the Bretagne. In either case, productivity was significantly raised (photo 4).

Photo 4 - Effect of initial fertilization (phosphorus, calcium and potassium) on a plantation of 20-year old Norway spruce in Razès (near Limoges): on the right, the unfertilized part; on the left, the fertilized part.
Photo: M. Adrian

As to the applied methods, the entirety of the research activities regarding fertilization and foliar diagnosis allowed the development of a know-how which enables French researchers to belong to international expert panels and even to propose and further the acceptance of sampling procedures and standardized processes at European level.

Nevertheless many questions remain to which there is no satisfactory answer and much of the scientific knowledge about the nutrient supply of forests has so far been insufficiently used. The case of the so-called noble hardwoods (wild cherry, maple, walnut, ash) is especially worth more active research. These species differ from the above-mentioned ones in that they do not naturally form pure stands and that their roots form a mycorrhizal symbiosis of a very different type which influences their way of taking up nutrients from the soil. Repeating the fertilization of maritime pine in the course of rotation should also have a beneficial effect as the action of the first fertilization on the seedlings ceases after 25 years (Figure 1).

Figure 1 ◆ Response of maritime pine to phosphorus fertilization applied to the seedling in Mimizan (Landes) in 1957. Total production in cubic meters of wood per hectare.

Total production m³

● T : unfertilized control
■ P : with phosphorus fertilization (44 kg of phosphorus per hectare)

There are also situations where the nutrient content of the soil does not explain states of malnutrition. In these cases usually improper planting or insufficient physical soil properties are responsible for a poor root development, notably during the first years after planting young trees cannot properly benefit from the nutrient resources of the soil. If a tree belongs to an exotic species, malnutrition can also be due to a lack of mycorrhizal associations caused by the local absence of fungi compatible with the planted species. The last part of this chapter will show how to remedy this situation.

The correction of forest soil acidification

Many fir and spruce stands of the Vosges and the Ardennes suffer from needle loss or yellowing. Research works conducted in France at the end of the eighties showed that these symptoms were associated with calcium or magnesium deficiencies linked to soil acidification which, itself, was a result of diverse factors (silviculture badly adapted to soils already acid, unfortunate introduction of certain species, air pollution, etc.).

Experiments in several yellowing stands on acid soil showed the very beneficial effect of calcium and magnesium supplements (photos 5, 6a and 6b). After verification at an operational level this result would merit application to restore the health status of many a stand; work is in progress. The frequent correlation between the type of parent rock and the occurrence of symptoms of malnutrition together with the map of yellowing elaborated in the

Vosges enabled us to determine the primary areas of intervention where financial and technical support by the State would motivate the owners to fertilize their stands.

(p.34)
Photo 5 - Fertilizer spraying in the forest using a blowing engine. Photo: J. Garbaye
(p.35)
From left to right
Photos 6a and 6b - Yellowing spruce and spruce which turned green again due to liming. Left (6a), spruce yellowing because of magnesium and calcium deficiencies; right (6b), spruce of the normal colour after calcium and magnesium fertilization in the same trial. Photos: J. Garbaye

Controlling mycorrhization

From a network of comparative plantations in all large reafforestation areas of France INRA researchers select particularly efficient strains of mycorrhizal fungi to stimulate the growth of young trees. To do so, plants are produced in nurseries and inoculated with pure fungal cultures from the laboratory.

The approach actually presents not only an alternative to fertilization to improve the nutrient supply, but it has a certain number of specific advantages: no particular interventions in the forest (the plants leave the nursery and are delivered already equipped with the selected fungus), no energy or raw material costs, no risk of soil or water pollution, selective beneficial effect on the planted species (the competitive plants do not associate with the introduced fungus), and effects of a type not directly nutritional that reinforce the initial survival of plants (which spares replacement plantings) and the initial growth of stands.

Thus, a process using a particularly efficient strain of *Laccaria laccata* (a mycorrhizal fungus which is frequent in France) was the subject of a licence between INRA and a group of forest nurseries regarding the large-scale production of artificially mycorrhized Douglas fir plants: The fungus cultivated in the laboratory is incorporated in the soil of the nursery before the sowing of the seed (photo 7) and the obtained plants, which are massively colonized by mycorrhizae, are controlled and marketed under the label of INRA. For an additional 1,000 F per hectare only they result in the direct success of plantations which make better use of the natural soil fertility and are more resistant (photos 8a and 8b). As Douglas fir is the principal species planted in France, this environmentally friendly biological technique is certainly in demand. It is applicable on all acid soils where Douglas fir is planted on a large scale, such as, for instance, in the Limousin, the Vosges, the Ardennes, and the Bretagne.

Photo 7 - Inoculation of mycorrhizae in a forest nursery.

Photos 8a and 8b - Effect of controlled mycorrhization on the growth of a young Douglas fir plantation. Upper photo (8a): Plants inoculated with the fungus *Laccaria laccata*. Lower photo (8a): Control plants that have not been inoculated. In both cases the plate has been fixed on the post at the same height. Photos: J. Garbaye

Conclusion and perspectives

Together with the economy of water, the mineral resources of the soil that can be assimilated by trees represent the principal factor in connection with the sustainable management of our forest resources. However, as opposed to water the "soil capital" is not renewable and special efforts must be taken to maintain its natural fertility, to adjust possible deficiencies, observe its development, and select the species to be cultivated.

This is why the researchers of INRA have invested much in developing diagnostic devices (balance of elements in stands, diagnosis of the nutrient status by means of foliar analysis)

and techniques of intervention that do not endanger the big ecological equilibriums (fertilization, liming, controlled mycorrhization). This activity is now becoming more concrete as forestry professions begin to effectively use measures that contribute to the sustainable management of the forests of France.
Nevertheless, in view of the extremely complex interactions in forest ecosystems much remains to be done before we will comprehensively understand the essential mechanisms and before we will be able to say we can intervene in an optimum way. The principal fields of study that have been briefly described above must therefore continue to be the object of fundamental research and to mobilize a large number of scientific disciplines.

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Biodiversity

A worn-out term of a more or less precise meaning, biological diversity as well as its promotion and protection have become subjects of major interest for foresters. Globally, the biological diversity of forests is (even in artificially established forest ecosystems like those of the pine forests of the Landes, in south-western France) both structurally and functionally more important and more complex than the biodiversity of other continental ecosystems.
In the framework of its research activities, INRA has in several ways approached the problem of describing the structure and functioning of biodiversity:

- **Studies aiming at characterizing forest ecosystems (typologies) and their development in time;**
- **Studies of the inter- and intra-specific genetic diversity of forest species and of the spatial organisation and development of this diversity;**
- **Interactions among trees, insects and microorganisms: pests, pathogens or associated insects;**
- **The dynamism of heterogeneous stands: trees of several different species and of different ages.**

1 How to characterize the diversity of ecosystems? (M. Becker)

2 The genetic diversity of forest trees : a prerequisite of sustainable forest management (A. Kremer)

3 Trees and forests : living with insects and microorganisms
1 ◆ Insects (H. Jactel) 2 ◆ Microorganisms (J. Pinon)

4 Heterogeneous stands - an ideal objective? (A. Franc)

Photo (p. 36/37) - Indian summer in the Laurentides, Canada. Photo: © R. Rozencwajg

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1 How to Characterize the Diversity of Ecosystems?

The use of ecological methods of forest resource management has had a long tradition with French foresters. The principle, which is based on the respect for natural equilibria, consists in taking from the forest the products that are useful for society, while at the same time assuring the maintenance, and even improvement, of their long-term production capacities.

Photo (p. 38) - *Hepatica nobilis.* Photo: M. Becker

"*To imitate nature, and to assist its work, is the basic maxim of silviculture*". During this past century this fundamental rule was taught at the Forest College of Nancy, in France.

Good knowledge for good management

Efficient silviculture requires first of all a profound knowledge of the ecophysiological characteristics of the "cultivated" species, i.e. the knowledge of their responses to the basic factors of soil and climate, which the old foresters called the "temperament" of forest species. However, this knowledge and its incessant refinement would be perfectly insufficient if we were not able in the field to identify with certainty the variability of the environmental conditions, so we can select the most appropriate species to be planted or promoted and the details of the silvicultural operations to be applied on them. However, like in many other areas it was also in silviculture a long way from the development of the idea to its first implementation and to its general application. Since 1965, and especially in the 1970s, INRA first alone and later in cooperation with partners from the public and private sectors worked to elaborate, develop and test a methodical procedure to fill gaps in the knowledge of French forest ecosystems as quickly as possible. This is all the more important because due to the great climatic, geological and orographic variety[1] of our country the ecosystems of France are among the richest and most diverse of Europe.

Apart from this, forest ecosystem diversity represents an integral part of *biodiversity* in the broad sense, in which case it is not perceived at the individual species level, but at the level of biotopes, including all living beings therein. The studies described in the present article thus constitute a preferred means to comprehend the biodiversity of our forest lands.

The concept of forest sites

The general principle behind this step is to structure the existing forested surfaces or the areas susceptible to be forested into homogeneous units called "sites".
According to the definition unanimously accepted today "*a site is a piece of land of variable surface, homogeneous in its physical and biological conditions (mesoclimate, topography, soil, floristic composition, and vegetation structure). A forest site justifies that, for a given species, a specific silvicultural method may be applied, which can be expected to result in a productivity bound within known limits."*

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[1] Mountain reliefs.

Scale of work

Apart from the large climatic and geological variability of France, a variety of scientific reasons require the entire forest territory first to be geographically subdivided into units which then become the objects of a specific typology. These reasons concern essentially the "vegetation" part of the study. What is necessary is to consider the natural areas of present distribution of species (*chorology*), a kind of instantaneous cliché of species migrations at the level of geological times. Attention must also be given to the *compensations of ecological factors* (in particular, between edaphic and climatic factors), which, for instance, are responsible for pubescent oak (*Quercus pubescens* Willd.) behaving like species adapted to calcareous soils in the northern part of France, while it is indifferent to that factor in Southern France. Finally, it is also important to know that the genetic variability of certain species is such that there exist geographic races with contrasting ecophysiological characteristics (*ecotypes*).

For this reason it is recommended to work at the level of the *small natural region*, a geographic entity characterized by a certain degree of homogeneity in respect of the macroclimate (regional climate linked to the respective latitude and to the habitual movements of the large air masses). Secondly, provided that the unit so defined is sufficiently large (at least several tens of thousands of hectares), the criterion of homogeneity can be profitably applied also to the large categories of materials on which the soils formed (calcareous materials, sands and sandstone, marls and clays, ...).

The role of soil and vegetation in the elaboration of typologies

It is indispensable to establish close links between the study of soil and the study of vegetation in the course of the typology phase and to beware of any exclusion *a priori*.

Apart from the low costs of their consideration, the floristic criteria present the advantage of simultaneously offering information about both the edaphic and the climatic factors; in their assessment of mineral fertility, they often turn out to be more precise than morphological soil descriptions. However, such criteria are not the panacea of site typology: it happens that they do not very well reflect the deep water reserves to which trees have access and, in particular, their use in artificially established or degraded environments sometimes proves difficult and necessitates to previously determine the corresponding dynamic vegetation series, which is not always possible. It is for this reason that particular attention has to be given to other descriptors of the environment as well.

Methods

The present article will provide but the broad outlines of the different stages leading to the exhaustive characterization of the site types of a given area.

Photo (p. 39) - Ochre-coloured podzolic soil, characterized by its sometimes critical deficiencies of mineral elements. - Photo: INRA
Photos (p. 40) - Left: *Lonicera xylosteum*. Right: *Aquilegia vulgaris*. Photos: M. Becker

It is strongly recommended to have the actual study preceded by a "pre-study" of several months. The purpose of such a preliminary study is first and foremost to collect a maximum of bibliographic information about the area, thereby including most different fields such as climate, geology, geomorphology, pedology, plant sociology, forest history, etc. Pre-studies may result in the editing of monographs. They permit validation and precisely define the contours of the area to be studied according to, and depending on, the criteria set before, and to furnish the elements that are indispensable for the efficient preparation of the next stage, which would be the planning of the sampling prodedure.

The sampling of the phytoecological data collection points, called "surveys", represents a phase of major significance. The practice has shown that the method of transects, along which surveys are regularly distributed, is generally most efficient. By the choice of the transect pattern, which is established on a large-scale geographical map, this method is a particularly comfortable means of stratifying efforts and permits use of knowledge acquired during the pre-study in the most efficient way. Seen from a different point of view, the systematic distribution of the sampling points along the transects enables us to ensure the statistical validity of the results. The total number of surveys required varies considerably with the complexity of the studied area, but is in the order of several hundreds.

During the first phase of field work the essential phytoecological data can be collected from each survey: vegetation, soil, topographic, and geomorphological conditions. The observation areas are several ares large and their arrangement must exactly correspond to very narrow criteria of local homogeneity. Depending on the total sampling, this stage may last for one or two vegetation seasons.

The efficient interpretation of the enormus amounts of information thus collected in the field is effected through computer-assisted multivariable analyses, which, though complex, are now well developed (for instance: factorial analysis of correspondences, ascending hierarchic classification). These computer-aided systems of data preparation assist in the elaboration of a provisional general table the purpose of which is to structure on the one hand the surveys and, on the other hand, the variables collected there in site units (groups of surveys) and phytoecological characteristics associated with these units.

After that, a second, usually much shorter period of field work will have to follow, its goals being:
- to complete certain floristic surveys (as, for instance, certain species can be seen only in spring);
- but also to improve and perfect samplings which proved deficient regarding the number of surveys on certain site units; and
- finally, and in particular, to objectively select a limited number of representative surveys of each unit for a fine characterization (which is costly and therefore has to be used sparingly) of the soil, with physico-chemical laboratory analyses of samples taken in the field after the digging of soil pits.

After a last computer-assisted processing of the data, the next step will eventually be the synthesis of the results and the compilation of a catalogue of forest sites.

The catalogue of forest sites

The results of a typology study are compiled in a document commonly referred to as "catalogue of forest sites". This document is made available mainly to forest managers concerned with the area, but all persons somehow involved in forests, such as researchers, teachers, etc. can in fact find useful information in this synthesis, which presents detailed information about all identified sites: physical character, characteristic vegetation, spatial distribution, forest potential, sensitivity to various stresses...

Typology and site mapping

One should carefully distinguish between typology and site mapping. Even if the map of a site is one of the final products which foresters need to help them define the management, it involves two stages which have to be clearly distinguished in time. As only those entities can be mapped that have previously been defined, typologies must naturally precede mapping, which, however, is not the only possible way of using them. For a defined forest area, the typology of forest sites consists in the determination and characterization of all "types of sites" that may be found there.

The present situation

At the end of the 1970s, France was still behind its European neighbours with respect to the phyto-ecological characterization of its forest territory. Since that time considerable progress has been made based essentially on the above-described concepts and procedures. Thanks to the financial support granted by the Minister of Agriculture and the *Office National des Forêts* and thanks to the human and financial input of various partners from very different fields (CEMAGREF, IDF, ENGREF, ONF, INRA, University, CNRS, CRPF, IFN, etc.) it is estimated today that almost two thirds of the French forest territory are covered by a site catalogue; and work is continuing.

Site studies provide foresters with indispensable information for elaborating the space- and time-related management of the areas of their responsibility. Site information enables them to include in their considerations the concern of biodiversity in their respective territories, and to do so both at the level of the vegetative communities and the biotopes contained therein and at the species level. The site catalogue and the maps that can be established thus become both objective and constructive means for dialogue between forest managers, who are first and foremost interested in the needs of the wood sector, and naturalists, who are mainly concerned with endangered species and biotopes or, more generally, with the maintenance of the natural biodiversity of the forest territory.

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This map by Michel Becker has been reproduced from the Revue forestière française, vol. XXX, 1978 and the Annales des Sciences forestières, vol. 36, 1979.

Map established by M. Becker (Laboratory of the National Forest Research Centre - I.N.R.A.) according to surveys conducted by M. BECKER, R.-F. CLAUDE, J.-P. COURCHINOUX, and R. SCHIPFER.

FOREST OF HAYE

Site map

(Scale)

A Beech - pubescent oak site (at the top of south slopes)
B Xerocalcicole beech - oak site on south slopes
C Calcicole beech - lime site on south slope
D Beech - sessile oak site on plateau
E Neutro-calcicole beech - oak site
F Beech - pedunculate oak site in valleys
G Neutrophilic beech - oak site on plateau
H Mesoneutrophilic beech - oak site
I Mesoacidophilic beech - oak site
J Mesoacidophilic sessile oak - beech site

PRESENT DISTRIBUTION OF MAIN SPECIES

Beech
Sessile oak
Pedunculate oak
Beech and sessile oak
Beech and pedunculate oak

2 The Genetic Diversity of Forest Trees: A Prerequisite of Sustainable Forest Management

Genetic diversity has become one of the keywords of the scientists and silviculturists who are concerned about the sustainable management of forests. Behind this concern is the assumption that *high levels of* genetic diversity provide a guaranty for the perenniality of forests. Frequently taken for granted, this hypothesis is in the centre of considerations about the future development of our forests. What are the actual facts?

This question leads us to an examination of the research work that has been conducted by geneticists since their discipline has been applied to trees. It merits that a state-of-the-art be prepared, informing about the scope and distribution of diversity within forest ecosystems. That state-of-the-*art* must refer to diversity in its broadest sense, comprising all the traits hitherto studied (adaption, vigour, "anonymous" markers). The recent development of molecular tools, which allow a better understanding of both the historical and the contemporary mechanisms responsible for the maintenance and development of diversity, make it possible today that we anticipate the development of the coming years. Finally, the geneticists of INRA benefited from this diversity already long before they were in a position to understand its dynamics; and they developed breeding programmes of species used in afforestation and prepared protocols of experiments aiming at maintaining that diversity. The relation diversity = perenniality needs to be analyzed by means of this triple examination (overall condition of diversity, of its importance and distribution within ecosystems, and evolution).

INRA: Fifty years of research on the diversity of trees

What we presently know about the genetic diversity of forest trees

The most surprising and, at the same time, the most general result - in the sense that it applies to the great majority of the species studied thus far - is the *high level* of genetic diversity which forest stands feature compared to other organisms. The comparison of the levels of diversity of one species with another is usually made on the basis of common traits. For one and the same protein, for instance, one can *count* the number of genes (alleles) determining the synthesis of this protein in a population. From the bibliographic syntheses on this subject it is evident that forest trees are among the most polymorphic species of the flora and even of the fauna (except for the invertebrates). Quantitatively, this result presents itself as follows: "Two genes, controlling the synthesis of one and the same protein and randomly sampled from a forest stand have a four times higher chance of being different than if they were taken from a human population". These observations on traits that are comparable among species are confirmed by the very large amounts of data that forest tree breeders collected on traits of economic interest (growth, form, adaptation): The standard deviation of the genetic variation of these characters is often more than 10% of the mean of the considered trait.

Where does diversity reside: Between stands or among trees of one and the same stand?

There is no single answer to this question. From a systematical point of view, the results published as yet indicate two broad types of a geographical organization of diversity.

- On the one hand, there are traits which have very high variation between populations, among them, in particular, the phenological and adaptive traits. In some cases variation "patterns" were established which are common to a very large number of species. The most well-known among them follow latitudinal, altitudinal or longitudinal clines (gradients). For instance, populations originating from the most northern latitudes (or from the highest altitudes) irrespective of the studied species clearly show an earlier growth cessation than populations of more meridional latitudes (of lower altitudes). Provenance trials of populations, which consist in comparing populations of different origins in the same environment, have been carried out for most species that are of economic interest and permit to shed light on this geographic variation. While clines have been set forth for the phenological traits, the organization is often much more disordered in the case of other traits and can even for the same trait vary among species.

- On the other hand, there are traits whose diversity between trees of the same stand is clearly higher than their diversity between populations. As a rule, molecular traits (DNA markers) and biochemical traits (proteins, terpenes) belong to this group. The results from different species are to a high degree in accordance and tend to indicate a very strong homogeneity among populations irrespective of their geographic proximity. If we compare sessile oak populations from Romania to their French counterparts, for instance, the differences in allelic frequencies are often less than 10 %!

This apparent contrast gives expression to the action of different *evolutionary forces* effective on the molecular and phenotypical levels. While the phenotypical traits analyzed thus far are often a result of adaptation to the prevailing environmental conditions, the vast majority of the molecular markers remain neutral. The diversity of the first group rather *reflects* the pressures of natural selection, while that of the second reflects the history of populations (effects of migration, genetic drift). It is this dichotomy which geneticists use to distinguish between the effects history and selection have had on the present structure of genetic diversity in natural populations.

The high genetic diversity of trees: Luxury or necessity?

The state-of-the-sites *(art)* outlined above gives rise to numerous questions on the mechanisms that shaped it. At first, one is surprised by the general nature (*pattern*) of the obtained results: Actually only few species (of the temperate zone) escape the broad description of the preceding paragraphs. Only a small number of exceptions were mentioned in literature, such as *Pinus resinosa* or *Pinus torreyana*, North-American species whose particularity consists in their absolute absence (*extreme low levels*) of diversity for molecular and phenotypical traits irrespective of the considered diversity. For the majority of species having high levels of diversity, we must therefore think of systematic mechanisms that contribute to the maintenance of such levels.

The studies of the propagation (*mating*) system conducted on the forest trees of natural stands revealed a very high level of allogamy. The rates of xenogamy (*outcrossing*) generally exceed 90 %; these figures have been confirmed by controlled auto-pollination experiments (**OK**). Several species (*Fagaceae*) even evoked mechanisms of self-incompatibility. The maintenance of a high diversity due to allogamy is reinforced by the proliferant growth of the species (important fructifications cumulating over several years) which in this way inhibits losses due to the genetic drift. In fact, most of them are subject to anemophilous pollination, which permits important gene flows between neighbouring populations. All these biological particularities, which are often rather homogenous among the different species, contribute to maintaining a very high diversity. This may seem like a happy consequence of the biology of those species, but in reality controlled self-fertilization trials in trees often reveal many lethal genes witnessing a genetic "burden" (*load*) which has accumulated in the course of evolution and which is partly responsible for the high levels of diversity. Proved by a large number of studies in population genetics and quantitative genetics, and maintained in particular thanks to remarkable gene flows, the question arises whether genetic diversity is a "luxury". However, this would mean to disregard that the mechanisms that maintain diversity can themselves be subject to a genetic determinism of which we do not have any experimental proof at the moment as no relevant studies have been conducted as yet. It would also mean to conceal the selection pressures effective (*acting*),on perennial organisms (**OK**) (variability of climatic and ecological conditions). So, genetic diversity can be considered a necessity for the maintenance of species.

Photos (p.44) From left to right: Fruit and leaves of beech. (Photo: M. Pitsch)

Cone of Corean fir? (Photo: J.F.Picard)

Photos (p.45) From left to right: Fruit of maple. (Photo: M. Pitsch)

Fruit and leaves of hornbeam (Photo: INRA)

Genetic diversity: A factor of the rapid adaptation of populations

At which rate do forest trees change? This question, a hackneyed phrase among population geneticists, remains in the centre of topicality whenever climate changes are discussed. Although results are disparate and originate from population comparison tools (*provenance tests*), they correspond and we learn (*we have learned*) hat such changes can develop extremely rapid (*rapidly*). The example of the exotic species, of whose introduction to France we know, is particularly pertinent in this respect. Northern red oak (*Quercus rubra* L.) has existed on our territory for five or ten generations at the most. Comparisons of the populations introduced to France with those from the natural areas show that the first differ already remarkably from the latter. Maritime pine represents another particularly demonstrative example. Since the past century scattered populations have been planted along an axis of Bordeaux - Clermont-Ferrand beginning from the Landes. Our present evalution of the descendants (*Comparative tests*) of those populations in respect of frost resistance points (*reveal*) out a variability gradient which follows this very axis. It is certainly at least partly due to their high level of genetic diversity that forest species are able to respond very quickly to environmental stresses.

Concrete activities undertaken by INRA with a view to both the present and the future

Genetic diversity: a biological resource used in silviculture

Since the first trials of Vilmorin in the past century, which were conducted in the Arboretum des Barres and where comparisons between *Pinus sylvestris* populations were made, and especially since the 1960s, the geneticists of INRA have established devices *(experimental designs*) for provenance comparison in order to estimate the variability between populations of the same species originating from geographic regions other than (**to be deleted**) the area of distribution. These trials, which frequently lasted for several decades, enable us to identify the populations which have specific properties that can be directly used in the wood sector (*afforestation programs*). One can take into account today that experiments of that kind have been developed for all allochthonous and autochtonous species used in artificial plantations. Among the most significant results were those of the *Pinus sylvestris* populations of north-eastern France (Bitche-Haguenau) and Masuria (Poland), which were particularly interesting for their correctness (*stem straightness*); those of the Norway spruce populations of Central Europe (South of Poland, Czech and Slovak Republics Romania) because of their late flushing; and those of the silver fir populations from Southern Europe (Roumania, Bulgaria) because of their growth in height.

Finally, the genetic diversity within populations is used in the patterns of (*exploited in*) artificial selection established since 1960 for short-rotation species of predominantly economic interest (poplar, maritime pine, Douglas fir, etc.). The breeding programmes conducted by INRA tend to reconcile sustained genetic gain and high genetic diversity by focusing on the maintenance of tall trees for the populations submitted to selection. Already now improved varieties are being used in reafforestation.

Genetic diversity: A resource to be conserved

Even though the forest areas of France are continuously increasing, the presently applied silvicultural and land management practices constitute a danger for the genetic diversity of stands. On the one hand, plantations based on limited numbers of seed sources progressively substitute natural regeneration. On the other hand, the fragmentation of forests caused by diverse land management operations can lead to a reduction of the gene flows, a mechanism which is essential for the maintenance of diversity. Finally, certain species (e.g. elm) are in danger of becoming extinct. To a smaller degree, also the black poplar populations decrease as a result of plantations established on the basis of limited numbers of hybrid clones. For all these reasons conservation measures have been taken and INRA, together with other organisms (CEMAGREF), actively participates therein. INRA established comparative plantations (**OK**) (species, provenances, families, clones) for more than 60 forest tree species (i.e. 32,000 entities) which can partly function as conservation plots. In addition to this *ex situ* initiatives and to the registering, *in situ* conservation of plots is required; with a view to the maintenance of their diversity, plots must be submitted to concrete regeneration measures. These measures concern beech, black poplar, silver fir, elm, and cherry and will be extended to further species.

Research on the genetic diversity of trees: an original contribution to the sciences of evolution and the management of natural populations

Genetic diversity: A testimony of the history of populations

The genesis of populations has so far been accessible only through fossil remnants (pollen or wood) which permitted us to trace back the presence of different species in the course of the Quaternary and, in particular, to identify their refugia during the last glacial period. The maps of iso-pollen in the sediments provide also information about the recolonization rate of species. Analyses of the polymorphism of genomes transmitted exclusively by the seeds enable us today to trace back the recolonization routes followed along "lines?" (**to be deleted**) from different refuge zones. In the case of angiosperms, mitochondriae and chloroplasts are cellular organelles of maternal heredity and both contain DNA molecules. The absence of recombination in the chloroplastic (*chloroplast*) DNA therefore makes it possible to reconstruct the genealogy of different genetic variants. The geographic spread of these variants and of their near relations (**to be deleted**) reflects the migration routes followed by the trees. So (*For example*) it could be shown for oak that all stands located west of the line Perpignan-Copenhagen had come from the Iberian refuge. Also, "patches" of a diameter of about forty kilometers bear witness of "foundation" effects resulting from an erratic far (*long*) istance dispersion of seeds through a variety of agents, such as jays, waterways, anthropogenic transport, etc. This is the first experimental verification of the high speed at which Europe was recolonized by oak (more than 500 m per year). In collaboration with the palynologists, and with the support of the European Union, INRA has worked on establishing a very close-meshed (***fine scale***) geographical map of chloroplastic DNA variants and fossil pollen which is to cover all Europe. The recolonization routes derived from these maps will constitute reference elements for other organisms depending upon the ecosystem "oak forests".

Photos (p.46) From left to right: Cone of European larch (*Larix europaea* DC.). Photo: M.Pitsch.

Cone of Douglas fir. Photo: J. Goacolou.

What can silviculturists do to maintain genetic diversity?

All along the silvicultural operations the activities of foresters influence the factors of diversity development *(evolution of diversity*) by modifying population sizes in thinnings and choosing silvicultural regimes, and by modifying the gene flows as a consequence of their management decisions. In many cases the effects of silvicultural practices on the development (level and trends) of the genetic diversity are not yet clear. INRA has for several years developed devices to estimate the effect of silvicultural interventions. Natural regeneration obviously continues to be the most sensitive system; its effects are not *a priori* foreseeable and may contribute to the increase as well as to the reduction of genetic diversity. Current research activities aim at estimating the pollen flows as precisely as possible (pollen or seed migration by paternity or maternity analysis using microsatellites) in the seeding fellings and their effects on the spatial structuring of the diversity.

Conclusion

The above brief description triggers as many scientific questions as silvicultural applications. Even if the demonstration is not as evident as a mathematical theorem it shows that the high diversity assured in the present populations by important gene flows enables forest trees to respond very quickly to external demands. It also shows that, even without involving artificial selection programmes, we can within a very short time profit from that diversity by applying (valoriser?) the results of natural selection (**to be deleted**) These results should not encourage us to continue unreasonable management of genetic forest resources. They rather oblige us to intensify the conservation measures already taken. Finally, forest trees are often referred to as "carriers" in the Anglo-Saxon area (**to be deleted**), which is to underline that they house an important biological richness. The knowledge of their intra-specific diversity could thus serve as an indicator of the respective ecosystem biodiversity. In addition to the institutes traditionally involved in forest research, the results on the diversity of forest trees and the original place they take in the animated world have also encouraged new research groups. Several university teams and institutes working in the field of development have initiated research programmes on the description and evolution of tree diversity. We can therefore contribute to a collection of results which will very soon replace the present outline.

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3 Trees and Forests: Living with Insects and Microorganisms

1 ◆ Insects

Sustainable forest management pursues two important objectives. The first is the conservation of the biological diversity and the long-term preservation of geochemical balances in order to ensure the adaptability of the forest ecosystem to unforeseeable environmental changes. The second objective is to maintain the economic and social functions of forests as they safeguard employment and produce materials that are useful for society, which takes from them the resources indispensable for its upkeep. Today everybody knows that insects can cause considerable damage by affecting the survival of the trees or the production of wood. However, although we often fail to realize their importance, insects also have a dominant role in the functioning of the forest ecosystem.

Photo (p. 47) - *Graellsia isabellae* (female). Photo: A. Delplanque

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To define objective parameters of sustainable management the role of forest insects must necessarily be better taken into account.

Insects and the biological diversity of forests

With more than one million species already identified (and another 10 to 100 millions which are still to be described), insects represent more than half of the living species of the biosphere. The forest environment is no exception to this rule; it houses a very important number of insect species, each of them represented by a considerable number of individuals. For instance, more than 6,000 insect species have been inventoried in the Forest of Fontainebleau and almost 1,200 different Coleoptera have been described on the 300 ha of the Forest of Massane (France). In Europe, 60 % of the butterflies are found in forests. In terms of biomass, it is estimated that the part represented by insects in forests is more than two times higher than that of mammals and birds. As a matter of fact, not all of these insects are potential pests as, even though a quarter of the forest insect species are herbivorous, more than half of them are predators or parasitoids of insects and capable of reducing the impact of pest insects.
This huge diversity appears to be connected with the complexity of the forest environment. Composed of different, often long-living vegetational strata, forests offer a multitude of niches, shelters, microclimates, and nutrient resources throughout various seasons, which the insects use to develop. The species richness of the forest insects depends essentially on the nature, the abundance, and the old age of the tree species which structure the ecosystem. In Western Europe, for instance, it is the oaks, willows and birches which, with more than 400 species, house the largest diversity of insects, while pine and beech comprise only about one hundred species and fir less than fifty.

But the insects themselves play an important part in the development of the vegetation diversity of forests. Without insects, the pollination and thus, the reproduction, of two thirds of woody species would not be assured. In contrast, certain pests destroy more than half of the oak flowers, while others can destroy all cones of European larch. So insects influence the genetic exchange and the dissemination capacity of trees which, in turn, influence the infra-specific diversity of the plants. Pests also use trees selectively and thereby can modify the natural succession process of forest species. By destroying adult firs, for instance, the spruce budmoth creates gaps in stands and accelerates the renewal of light-demanding species. In contrast, mass attacks of larch budmoth causes high mortality in young Arolla pines (*Pinus cembra* L.) in the understorey by delaying the natural succession of pure larch stands to mixed pine and larch forests. In this way insects exert their influence also on the inter-specific diversity of forest plants.

Photos (p. 48) Left: Oak leaf roller moth (*Tortrix viridana* L.). Photo: J. Nioré
Right: Pine processionary moth (*Thaumetopoea pityocampa* Schiff.). Photo: C. Demolin

Photo (p. 49) *Graellsia isabellae* (male). Photo: A. Delplanque

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Insects and the biogeochemical functioning of forests

Insects do not only influence the structure, but also the overall functioning of forest ecosystems as their development is not without effect on the microclimates and the nutrient cycle, which, in turn, condition the growth of the plants.

The defoliation of trees by pest insects can for several months modify the microclimate of a stand by increasing wind speed and the penetration of sunlight and rainfall which are no longer intercepted by the canopy. The consequences of a vast decay can be even more serious, as was the case in Colorado, where a bark beetle outbreak provoked the death of more than 50,000 ha of conifers in a watershed area. The simultaneous reduction of interception and transpiration of water by the trees then led to increased running and infiltration, which for almost 25 years significantly increased stream flow in that region.

When the water circulation increases like that in a forest, important amounts of nutrients may be exported from the ecosystem, which affects the growth of trees. On average, however, the action of insects rather seems to be beneficial for the fertility of forest soils. Defoliators increase litter fall; the latter is then decomposed by the insects of the soil, which favours the recycling of nutrients. Further, dead insects, cast cuticles and frass constitute an important input of easily mobilizable minerals for the growth of trees. Following defoliation of oak it was found that 40 to 70 % of the nitrogen and phosphorus depositions of the soil originated directly from insects.

Damage caused by insects and maintaining economic and social forest functions

The most conspicuous impact of insects continues to be the damage they cause on trees by affecting physiological processes, growth, wood quality, or natural regeneration. Endemic pests permanently infest forest stands, thus causing limited, but continuous production losses. For example, the annual rate of defoliation attributed to insects varies between 5 and 15 %. However, the worst damage results from mass attacks, whether they are cyclic or episodic. The Canadians determined that, since the beginning of the century, *Choristoneura fumiferana* Cl. had infested more than 250 million hectares. The Scandinavians during a period of 10 years attributed the loss of 7 million m^3 of spruce wood to bark beetles. In France, practically all maritime pine forests of the Maures and of Estérel (120.000 ha) disappeared due to a mass infection by *Matsucoccus feytandi* Duc. Pine processionary moths cause cyclic and regular damage to the Southern European pine forests. Some insects can also be detrimental to the health of the forest users. For instance, the hairs of the caterpillars of processionary moths frequently provoke severe urticarial rashes or even real allergic reactions. The maintenance of the economic and social forest functions is therefore necessarily connected with pest control.

However, to respond to the objectives of sustainable management, we are to develop methods which respect the environment and which, consequently, question neither the biological diversity nor the functional equilibrium of the ecosystem.

Methods of insect control

In this context, the application of insecticides in the forest is not recommended. These products, which are often not highly selective, can pollute soil and water, affect natural enemies and, over time, may lead to insect resistance. Although the use of more selective products might reduce these risks, the forest market is too limited to make their development worthwhile. The use of insecticides in forests therefore remains reserved for specific insects, such as certain defoliators. Continued effort is needed to improve the formulations and adjust the dates of treatment so that the applied doses can be reduced.

One of the priority objectives of forest entomology at INRA therefore remains the development of preventive methods based on the use or reinforcement of the natural resistance potential of forest trees and stands.

◆ The first approach is the **selection of trees that are resistant** to pest insects. It is based on the large intra-specific variability of forest species which leads to the co-existence of trees of different sensitivity in forests. Research work carried out at INRA showed that the infestation levels by green oak leaf roller in oak depend in particular on their date of flushing, while poplars suffer more or less serious defoliation by poplar leaf beetles depending on the pilosity of their foliar surface. Similarly, the attractiveness of conifers for xylophagous insects was found to depend on the terpene composition of their resins and their defence potential on their capability to synthesize certain polyphenols. If these traits are submitted to sufficient genetic control and remain compatible with the objectives of wood production, they can be used to improve the individual resistance of trees. However, the principles of sustainable management impose that the resistances obtained by selection or transgenesis are no longer only to be used, but should themselves really be managed by integrating three considerations: the preservation of the chances to find the sources of resistance that are useful for the future, which involves the maintenance of the biological diversity of the forest species and, thus, a policy of conservation of the genetic resource; the use of the existing resistances in limited areas to prevent pest insects from circumventing these defences before the end of the forest cycle; and, finally, the control of the innocuity of the resistances for non-target insects so as not to disturb the equilibrium of the ecosystem.

◆ The research of preventive methods of insect control involves also the **management of forest stands**. In fact, numerous examples illustrate the connection between silvicultural practices and the risks of insect outbreaks. If a species is poorly adapted to a site, this can cause serious health problems, as has been proved by the high infestation by green spruce aphid on Sitka spruce trees planted on humid soils. Equally, young pine stands are more frequently infested by the caterpillars of the processionary moth when they are planted at low density and fertilization increases their sensitivity to the pine shoot moth. The thinning of pine stands reduces the risk of bark beetle attacks, while their pruning increases the rate of attacks by stem borers (*Pyralidae)*. To adjust the silvicultural techniques and the management decisions to the health constraints is a particularly promising way because of its simplicity and its relevancy to the principles of sustainable forest management.

◆ A third way of averting insect mass attacks consists in **reinforcing or re-establishing the mechanisms of trophic regulation** that exist in forests. In fact, many species consume or parasitize pests, but in the case of introduced forest species it may happen that certain pests are imported without their natural enemies and thus cause epidemics, as was the case, for instance, for the cedar aphid *Cedrobium laportei* R. in France. The acclimatation of parasites collected in the area of origin of the plant can therefore lead to a re-establishment of the trophic balance, as indicated by the reduced levels of infestation by cedar aphid after introduction of one of its hymenopterous parasites (*Panesia cedrobii*) from Morocco. In other respects it is feared that monospecific forests are particularly exposed to entomological risks. Phytophagous insects are in fact favoured in these ecosystems offering abundant and accessible nutrient resources, but also subject to minor control by few and little varied natural enemies. In Aquitaine, INRA has conducted an original experiment to analyze these processes by integrating plots of broad-leaved trees within the ecosystem of maritime pine. The objective is twofold: to fragment the habitat of the insect pests in order to complicate the localization of host trees and to provide new ecological niches for parasites and predators so as to assure their development and numbers to efficiently control the pest populations.

Photo (p. 50) - *Graellsia isabellae*: Caterpillar in its last stage on *Pinus sylvestris*. Photo: A. Delplanque

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Conclusion

A large number of insect species are indispensable for the well-being of the forest, while others threaten its profitability. However, the preservation of the first and the control of the latter are not incompatible: They must both proceed from the same functional analysis of the ecosystem so that they are not ignored when forest management plans are being developed.

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3 Trees and Forests: Living with Insects and Microorganisms

2 ◆ Microorganisms

It is estimated that, in France, 2,500 ha of forest must be restored every year as a consequence of phytosanitary accidents and that every year 150,000 ha suffer growth losses attributed to pests and parasites without the longevity of these stands being questioned. If exotic parasites such as Dutch elm disease or chestnut bark disease are imported, the consequences can be much more serious.
Trees are in permanent contact with microorganisms, which have very different functions. Some of them are beneficial, such as mycorrhizal fungi or antagonists of the pathogenic soil flora, nitrogen-fixing bacteria or microorganisms assisting mycorrhization. Others eliminate the vegetational remnants and recycle their elements. Finally, some are tree parasites. Among the latter the most threatening are the fungi and some bacteria and viruses.

Photo (p. 51) - Cluster of *Collybia fusipes* at the base of a dying oak. Photo: B. Marçais

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The development of populations of parasites depends almost always on the climate. However, the most far-reaching damage results in most cases from a triggering factor: a climatic accident (frequently a drought) which makes trees vulnerable to opportunistic parasites or a human error, such as the introduction of a new parasite, the selection of a poorly adapted species, the reduction of the genetic diversity, or a silvicultural process too favourable for parasites.
The contribution of forest pathological research to sustainable forest management is twofold: economic and ecological. In the first case the purpose is to prevent the health of trees from being impaired, to reduce losses and mortality in order to obtain wood of sufficient quality and quantity. This objective has also a qualitative dimension: to minimize the frequency of stem imperfections (deformations, canker, decay) even though they do not endanger the respective stand or the individuals that compose it. The second objective aims at maintaining the diversity of stands and the diversity within each and every species. The disappearing of sensitive trees may seem to represent a favourable development, but it can be accompanied by the loss of other, useful or favourable, traits; and it can even threaten the survival of a species if only a small proportion of its individuals is resistant.
Forest pathology has its place at the interface of two diversities: that of stands and species and that of the parasites. These diversities can be analyzed at two levels: inter- and intra-specifically.

Inter-specific variability

Forest species

Forest trees of the same genus can live together in the same region (even in the same plot) or be ecologically separate. Species of the same genus show differences in their behaviour regarding diseases. Studies conducted by the INRA teams of Angers, Orléans and Nancy showed, for instance, that among European and American poplars one can find species that are highly resistant to diseases (rust diseases caused by *Melampsora*, canker caused by *Xanthomonas populi*). Sometimes the optimum response of a species to a parasite results first in that species being able to resist another calamity. A multidisciplinary research project conducted in Nancy and Clermont-Ferrand disclosed that after the drought of 1976 less significant infection of the roots of sessile oak (compared to pedunculate oak) by root-rot agents resulted from the better adaptation of that species to the lower groundwater level (deeper rooting).

The presence of trees of different genera in a forest stand usually contributes to better forest health. In fact, it happens very rarely that one parasite is polyphagous. In mixed stands, the inoculum a parasite emits from aerial organs will partly be lost as it is deposited also on non-host trees which it cannot infect. Certain vascular parasites (Dutch elm disease) or root- and butt-rot agents (*Heterobasidium annosum* in spruce) propagate as they are favoured by root grafts between adjacent trees. Such grafts can connect only trees of the same genus and occur more frequently when they also belong to the same species. This favourable contribution of diversity does not apply where parasites require two hosts in the course of their development, which, however, applies only to rusts. *Melampsora pinitorqua*, for instance, a pine needle rust, must alternate between aspen and pine. In any case, studies conducted at Bordeaux show that a strong synchronism between the respective parasite and the stage of receptivity of the pine is needed before risk is established.

Parasites

The diversity of species able to infect the same host exists also for parasites. Three scenarios are possible: In the first one, there is competition between the parasites, without such competition representing any evident advantage for the tree. On poplar leaves, for instance, the contamination by *Marssonina brunnea* in spring will reduce the foliage available for later infection by rusts. In other cases the presence of several parasites will provoke a detrimental chain of events: foliar parasites can impair the health of a tree, which consequently becomes vulnerable to bark and/or root parasites. In the third case the diversity of the microflora is of advantage to the tree through the competition between pathogenic and non-pathogenic agents. It was demonstrated that soils rich in certain non-pathogenic *Fusarium* species limit the damping off caused by pathogenic species of *Fusarium*. The colonization of conifer stumps by *Phlebiopsis gigantea* (a non-pathogenic wood-rotting fungus) makes the stumps unavailable for *Heterobasidium annosum*. In the case of poplar tree rust, the intervention of a hyperparasite (*Eudarluca salicis*) was observed several times, but its controlling effect on the parasite population is not significant.

Photo (p.52) - Section of a spruce trunk infested by *Heterobasidium annosum*. Photo: C. Delatour

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To sum up, one can say that stands composed of different species seem to be more advantageous as, other than monospecific stands, they act as a brake on the dissemination of parasites. Closing the balance, the species diversity of parasites means a zero balance or a net loss for the tree. This balance will be positive only in the case of interaction with microorganisms which, though harmless for trees, are in competition with the parasites.

Photo (p. 53) Variability of the pathogenicity of *Melampsora larici-populina* (agent of poplar leaf rust) and of poplar resistance. Photo: J. Pinon

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Intraspecific variability

Forest trees

The intra-specific diversity of forest trees is well known, in particular for those species that are the objects of improvement efforts regarding their resistance to diseases. At INRA, this approach is presently applied to several species, in particular to poplar and larch. With respect to the hosts, differences in their susceptibility to parasites show themselves at various infra-specific levels: sub-species or race; provenance; family; and individual. These differences express themselves very clearly in the face of foliar, cortical and vascular parasites. The collaboration between breeders and pathologists from Orléans and Nancy enabled us to develop reliable tests to detect these resistances. Because of the development of laboratory tests and the access to molecular or biochemical markers these resistances can be detected at an increasingly early stage. The genetic determinism of these resistances is progressively elucidated and it becomes possible to access genes involved in resistance. We know today that poplars use two strategies to be resistant: either a complete resistance, which seems to be governed by a very small number of strong genes, or a partial resistance based on genes that are superior in number, but whose effects are less powerful. The first ones could be involved in a strategy of precocious recognition of the aggressor, which would then immediately be destroyed. The second ones would not oppose the invasion of the host tissues, but would delay the progression of the fungus and reduce its sporulation capacity. This distinction between mechanisms is not neutral in terms of the durability of the resistance. It must be confronted with the infra-specific diversity of the parasites (physiological races). Also, the two strategies do not systematically exclude each other.

Parasites

◆ **The variability of the pathogenicity**. The intra-specific diversity of parasites is being better and better established. It is characterized by the particularity of parasites being able to distinguish host entities of generally indistinct morphology. It was found in the research works conducted in Clermont-Ferrand that the honey fungus includes several rather distinct species of which, in Europe, only two are clearly pathogenic: *Armillaria ostoye* in conifers and *A. mellea* in broad-leaved species. Within a parasitic species, the special form (in fungi) or the pathovar (in the case of bacteria) infect only certain genera or certain species of the host. The physiological race infects specifically the one or the other clone of the host. For about fifteen years numerous physiological races have been examined in Nancy in *Melampsora larici-populina* and *M. allii-populina*, which cause poplar leaf rust. Certain races can break the complete resistance of a poplar clone, while others will be able to render ineffective that of another clone which does not bring into play the same resistance genes. This means that a host may seem completely resistant, but can nevertheless become highly vulnerable as soon as the race capable of attacking it develops. The confrontation of the tree's resistance genes with the genes determining the pathogenicity of the parasite (virulence) is in this case effected at a very small scale which evokes a gene-by-gene system. This type of interaction is presently only known in poplars with at least one parent (*Populus deltoides*) of North-American origin, i.e. at least one parent which did not develop with the European parasites. As opposed to this, only quantitative interactions, which are often subtle, have thus far been detected between the indigenous host (*P. nigra*) and the races of the parasite. If populations of races develop, the resistance of those *P. nigra* is, though partial, clearly more durable than that of the hybrids including *P. deltoides*.

◆ **Dissemination**. The second level of diversity studied in parasites is that of individuals. Access to individuals is essential to learn about the modes of dissemination of certain parasites. In basidiomycetes, the groups of somatic compatibility can be identified by *in vitro* comparison of two isolates of the parasite. Although certainly not all individuals can be separated in that way, this method offers a first approach to the infra-specific variability. Recently, the studies of molecular biology (in particular the polymorphism of the ribosomal DNA) permitted important advances. In Nancy, the two above-mentioned methods were combined and it was then possible to establish that the contamination of oak roots by *Collybia fusipes* was frequently unique to one single individual of aerial dissemination. In Lyon, the most recent methods of molecular biology permitted to individually identify the strains of *Xanthomonas populi* (agent of bacterial canker in poplar) and to establish the poor dissemination potential of that agent.

Conclusion

For environmental just as much as for economic reasons, suppressive control methods (fungicides) are not envisaged in forests, except for nurseries or treatments at certain points to avoid catastrophes. Whatever the degree of artificialization of a forest stand; to assure the adequacy of tree species and forest site remains a rule of prime importance. It permits to reduce the effects of weak parasites[1] against which there is no other way of fighting.

In recent years INRA has made remarkable progress in the field of the diversity of species and their parasites and the rise of molecular biology is accelerating this process. This knowledge enables us to improve our understanding of the fundamentals of host resistance and pathogenic potential. It leads to multiple progress in breeding and in the choice of genotypes whose resistance will be more durable (resistances which can hardly be broken), and whose management can presently take into account the diversity of the parasite and its populations. Knowledge about the diversity of parasites enables us also to understand their dissemination and, therefore, to determine rules for the management of infested stands. Finally, the advanced risk assessment in highly artificilized stands (poplar forests) is becoming reality.

A less well-mastered field has been the establishment of complex stands *de novo*. The contribution of pathology consists in knowing the dissemination modes of the parasites and their potential hosts, thus allowing the definition of the stand structure most unfavourable for the major parasites. However, an equilibrium needs to be achieved between such a structure and the phenomena of competition between trees which might result therefrom.

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4 Heterogeneous Stands - an Ideal Objective?

Heterogeneous forests are often highly present in human imagination, as is evident, for instance, from the success of Bambi. The interest which the public, and man in general, show for the maintenance of heterogeneous forest stands is thus of great importance and is sometimes vigorously expressed.
This highly emotional link also corresponds to the vague feeling that heterogeneity seems to be the rule in nature. Is there also a rational basis of this interest?

Photo (p. 55) - Xerophytic vegetation, granite hillocks. In the background, the primary tropical forest seen from the Inselberg of the Nouragues - French Guiana. Photo: T. Boujard, F. Meunier, M. Pascal

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Role and importance of the heterogeneous forests

In temperate as well as in tropical forests the majority of the regular forests (one species, one age, simple structure with closed canopy) are the outcome of silviculture, while forests essentially unmodified by man often show a high diversity both in respect of species and age. On the other hand, European beech forests on the Atlantic, for instance, are natural formations rarely accompanied by other species. The association between "simplicity" on the one hand and an "artificial character" on the other, between "heterogeneity" and a "natural character", is therefore not so evident.
Diversity is frequently associated with tropical forests. Even though it is true that the latter are sometimes growing luxuriantly, temperate forests are not always monotonous. The forests of the Appalachian Mountains, in Eastern North America, those of the Pacific coast mountain ranges of North America, China and Japan and, even more, the forests of the southern hemisphere in Chile and New Zealand are, in the field of diversity, absolutely a match for most of the tropical forests. As a consequence of the geological and climatic history, it happened by chance that the flora of temperate Europe was greatly impoverished during the last ice ages, while the Mediterranean forest, though very close by, is naturally very heterogeneous.
The question of maintaining this heterogeneity, which is synonymous with richness, is the crucial point of the idea of sustainable development.
"Sustainable development" is a rather new concept which prolongs and extends the older term of "sustained yield" on which it is based. Sustained yield means to harvest the timber of a forest without endangering the future of the forest capital; so it is implicit that the maintenance of the wood potential would guarantee the maintenance of the biological potential. Sustainable development includes "sustained yield", but extends the concept by the explicit effort to maintain the biological potential while at the same time integrating the economic, ecological, and social functions of the forest.
It turns out that in temperate forests, and especially in the temperate forests of Europe, the species which form the basis of the heterogeneity of stands, in particular the noble hardwoods, are at the same time those whose wood presents the most highly valued qualities among the wood-based consumer goods: the mechanical qualities of ash, the aesthetic qualities of cherry wood, the musical qualities of maple undulated wood. The first skis, for instance, were all made of ash. So these species are at the same time of high ecological and economic value.

This means that, through the necessary integration of economic, social, and ecological qualities, heterogeneous forests are at the centre of problems connected with sustainable forest management.

Photo (p. 56) Camp des Nouragues (ECOTROP-CNRS). Suspension bridge providing access to the canopy - French Guiana. Photo: T. Boujard, F. Meunier, M. Pascal

Diversity and stability

In the context of ecosystems, sustainability is very frequently associated with diversity and complexity, which may be based on the simple, and possibly simplistic, conception that it is useful not to put all one's eggs in one basket.

However, the reality is far from being that simple. Theoretical models of the seventies show that instability can be linked to complexity. Let us take the example of a terrestrial or lacustrine animal ecosystem where species are usually classified into different categories, such as herbivores and carnivores, or predators and preys. Not all relationships among species are strong and intensive. On the contrary, many works of animal ecology focus on the trophic links, which, like the road map of a country, indicate the principal interactions between animal species. Some of those relations are of prime importance, while others are secondary. So it can be shown that the reason for the instability and thus, the poor sustainability of ecosystems is frequently that they are very sensitive to exterior disturbances when all their relations are equally important. A major part of the stability of ecosystems seems to be due to a hierarchic ranking of the interactions between individuals and species, between primary and secondary relationships, or even completely missing relationship. This surprising relation between stability and complexity is one of the major tracks scientists have picked up in ecology, a discipline in which heterogeneous forests have to play an important part.

It should also be noted that, in heterogeneous temperate forests, maximum diversity is often achieved during a transient post-pioneer stage, based on oak, maple, ash, and cherry, for example, and that, in the course of evolution, this diversity has been frequently impoverished in favour of more stable formations, such as beech stands. However, though relationships between diversity and stability are complex, our understanding of them is continuously improving.

Improvement and regeneration

In the silviculture of regular forests, we usually distinguish between a stage of regeneration and a stage of improvement. These two stages are clearly separate in time and succeed each other in the rhythm of rotations. The forest area is divided, almost squared, in management units where the respective regeneration or improvement operations are planned.

The structure of heterogeneous forests is more complex. Regeneration tasks can be effected in close proximity to stands of different maturity. Where all operations are individualized, it is no longer possible to distinguish clearly between a stand's different stages of life. These forests must be managed by combining (1) improvement, the care of mature trees; and (2) regeneration, which involves operations for the benefit of young trees. To master this mixture of two phases of a very different biological logic in one single management unit will be an important mission of the coming years.

Modelling

Modelling is one method of improving our knowledge of the dynamics of forest stands, whether they are regular or heterogeneous. The modelling of heterogeneous stands is obviously more complicated than that of well-established, regular stands. Modelling started several decades ago, especially in North America and in Scandinavia. The principal developments, which led to the interest in heterogeneous forests, is the necessity to take into account the tree level and the stand level.

Photo (p. 57) - View from the look-out of La Verdière. Photo: © C. Nouals - CEMAGREF

Indeed, when a structure is homogeneous, there is by definition a confusion between local and global scales. For instance, this is true for simple systems in physics, such as crystals or low-speed laminar flows, like in a canal. The observed structures are thus frequently invariant to changes in scale and one model may, except for a scaling factor, describe both the global and the local structures in the vicinity of a particular point. The same applies to regular forests. Using the same equations, a growth model permits simultaneous simulation of the development of a stand and the average tree. Apart from some fluctuations, all trees can be considered as average trees of the stand. The number of variables required for the knowledge of a stand is low and the models are simple.

Things are completely different in the case of heterogeneous stands, where it is necessary to distinguish at least between "tree" and "stand" levels. For instance, the term "species" has a meaning at the tree level, and sometimes at the level of a group of trees, but not at the level of a whole stand if the latter is mixed. This is why modellers have refined their tools and developed models at these two levels. In their effort they follow the procedure of the physicists who also distinguish several levels or scales when they elaborate models of heterogeneous structures, such as alloys or turbulent flows. A promising way towards progress is certainly within reach if the emerging rapprochement between the biological (knowledge of the forest) and the physical (modelling of heterogeneous environments) disciplines can bear fruit. Although great hopes are placed in this direction, it is probably too early to evaluate whether the complexity of heterogeneous forests can end up on a reasonable level compatible with the levels of simulation which can be mastered.

Most of the models accepted by the scientific community are founded either on an empirical basis, by fitting lines to data sets issued from measurements on permanent or semi-permanent plots, or on a more functional basis, with the focus on the understanding and modelling of the physiological processes that form the basis of the growth metabolism, such as photosynthesis, water consumption, nitrogen and nutrient cycles, etc. All these models are now well established; they have proved successful for regular stands and have been relentlessly widened to heterogeneous stands since seminal works on gap models in the 1970s in North Eastern United States. To what extent they can answer relevant biological questions on long term sustainability of heterogeneous stands is a matter of conjecture, and it can be hoped they will further expand in this direction.

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Dynamics of Forests and Stands

Forest ecosystems are dynamic systems whose evolution is conditioned by natural and anthropogenic factors both of which can be either direct (silviculture) or indirect (CO_2, nitrogen depositions, ...). It is of prime importance to apprehend this stand dynamics. We have decided to illustrate these aspects with two examples.
The first of them concerns research on modelling and simulation of stand growth in response to applied silviculture (i.e. stand management).
The second focuses on one of the most significant results of forestry research, namely on the considerable increase in the productivity of northern hemisphere forest ecosystems. This phenomenon has consequences for forest management itself, and for the sustainability of forest ecosystems.

Spacing experiment of Vancouver fir (*Abies grandis*) plantations planted in spring 1958.
Photo (p. 58/59): © O. Sébart

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1 Management of forest stands (J.F. Dhôte)

2 The productivity of European forests is increasing :
a fact of considerable consequence (M. Becker)

1 Management of Forest Stands

Maintaining the ecological integrity of forests is fundamental in the European forest tradition; thus managers invest much time and energy to successfully regenerate their stands. Depending on the assigned objectives different methods are applied. The most important cultural operation is thinning. Silviculture is an activity of low intensity, in particular as it requires only small amounts of chemical input. Nevertheless the forested landscapes we have in mind are highly artificial. This apparent paradox is first and foremost due to the very long-term dynamics of forests. Because of this characteristic time aspect it is important for foresters to predict the evolution of stands, especially by methods simulating the birth, growth and death of trees. The mortality process can either be natural or occur accidentally, as a consequence of diseases, tornadoes, windbreakage, or simply as a result of the competition among trees for light or soil resources in the very hierarchic society represented by the forest.

Photo (p. 60): M. Pitsch

Silviculture: How to regenerate and shape forests

By "silviculture" we understand all general decisions and specific practices adopted and carried out by a forester in order to manage a forest stand. The general choices concern the strategy which is adopted for the regeneration of the site and include two major options:

◆ **The regular high-forest** consists in regenerating the site rapidly and in its entirety; the best known example is the plantation after the clearcutting of a mature stand (Figure 1.a). To this category belong also stands generated from seedlings obtained by natural regeneration (Figure 1.b); in that case the pre-existent adult stand is not clearcut, but a series of smaller cuttings permit the setting up of seedlings and their optimal development until the young generation sufficiently covers the ground. Regular high forests obtained by this method are never absolutely pure (other species are associated with main species in a proportion of 10 to 40 %) and the age difference among trees can reach up to 30 years.

Figure 1.a ◆ Regular spruce high forest from plantation.
Figure 1.b ◆ Regular beech high forest with 10% of sessile oak.
Figure 1.c ◆ Coppice with reserves of sessile oak and coppice of hornbeam cut every 25 years.
Reserve stratum
50-year old reserve
100-year old reserve
150-year old reserve
25-year old coppice
Figure 1.d ◆ Selection high forest based on fir, spruce, and beech.
fir
spruce
beech
m: mature trees
p: "poles" (intermediates)

s: seedlings

◆ **The irregular high-forest** combines several different methods which have in common trees of every age and usually of several different species permanently coexisting in the stand; in this case regeneration is natural (by seedlings), continuous in the course of time, and irregular on the surface of the site. An example of this system which is very common in France is the coppice-with-standards, also called coppice with reserves (Figure 1.c), which comprises two superimposed storeys of vegetation: The "reserves" are big trees that are more than 10 m high and aged between 30 and 200 years; they are cut when they reach maturity and replaced by young trees already established. Under the reserves there is usually an understorey consisting of a coppice stand of chestnut, hornbeam, oak, lime, etc., depending on the region and the richness of the soil; this coppice stand is completely cut every 12 to 30 years and regenerated by means of sprouts on the stump (vegetative reproduction). Other examples are the selection forests, or forests (Figure 1.d) which do not include coppice stands, but an uninterrupted series of trees of all sizes, from young seedlings to mature trees.

Maintaining the ecological integrity of forests is of fundamental importance in the European forest tradition; thus forest managers invest much time and energy to successfully regenerate their stands. The choice of the silvicultural method depends on the objectives assigned to the forest (timber production, game development, protection of the soil, landscape, access to the public, genetic conservation) and the specific constraints which weigh on the owner (the surface of his forest, his financial means, and his knowledge about forests).

Various cultural practices

Once the forester has chosen a method of regeneration, he will carry out various cultural practices to shape the stand.

The cutting

The most important of these operations is shelterwood cutting: In the case of a regular beech (*Fagus silvatica*) stand cultivated to produce high-quality wood (sawing, peeling, slicing) this means that a young beech generation consisting of 100,000 to 500,000 seedlings per hectare at the beginning has to be brought up to a final number of about 100 high-diameter (50 cm and more) old trees per hectare. This is obtained by a series of 10 to 15 thinnings aimed at progressively remodelling the stand. Beautiful trees are selected and then the density is gradually reduced by exploiting the most dangerous competitors of these trees; sick trees are eliminated; trees of the understorey which protect the stems of big trees against bark scorch or sucker branches are conserved. Thinning therefore consists in controlling the vertical structure of the stand (distribution of trees in the different strata), the species composition, and the competition among trees.

Artificial pruning

Other practices can be adopted especially at the time of regeneration and during the earliest stages of development. Artificial pruning consists in cutting and removing dead or living branches and possible reiterations or forks from trees. This costly operation is practiced when the general shape of trees is bad, and is reserved for the most promising trees in terms of survival, vigour, quality, etc.

Competition with the herbaceous plants

In very open stands regeneration may be slowed down or compromised by the exuberant development of the herbaceous layer. When the problem becomes critical, selective herbicides are sometimes applied in order to accelerate the growth of dicotyledons (blackberry, bushes, small woody plants, ...) which, in the competition for water with the seedlings of the desired species, have a less negative effect than the graminaceae. It should be added that such herbicide applications are only to accelerate the flora substitution which would have occurred anyway, though more slowly; that they are to a high degree regulated in forests (nature of products, dosages, spreading dates, and methods of preparation are defined); and that in any case only one or two treatments are practiced in the course of a long period of 80 to 200 years (the rotation period of the stand). INRA and CEMAGREF contribute very much to the scientific knowledge about interactions between herbaceous and woody plants and to the technical and legal training of foresters on that issue of herbicides.

Silviculture and forest landscapes

Finally, it should be underlined that silviculture aims first and foremost at maintaining forests and thus gives high importance to the regeneration of stands. Another objective of silviculture is to shape these stands by thinning. This method requires that stands are frequently visited and therefore provides a good knowledge of the state of each and every forest stand (inventories; control of the regeneration; control of the windfall, i.e. trees uprooted or topped by the wind). Moreover, the method of thinning is mainly based on stand analysis (diagnosis of the quality and vigour of trees) and on a permanent control of competition. Thus silviculture needs very little chemical input, and most of the mineral elements necessary for growth are recycled. Compared to agriculture, silviculture can thus be called a low-intensity activity.

Artificial landscapes shaped in the course of centuries

Nevertheless the forest landscapes which we consider are to a high degree artificial. For instance, in the deciduous forests of northern France, which some people might consider very "natural", a trained eye will easily recognize traces of silviculture practiced since the Middle Ages! So the coppice stands with standards are the heritage of a frantic forest exploitation for the production of firewood, charcoal (industrial usages) and acorns (feed for livestock) from the Old Regime to the end of the past century. For the same reason oak (*Quercus petraea* and *Q. robur*) occupies today a very large area of that zone although beech is ecologically more efficient there.

This apparent paradox (low-intensity forest management, but artificial forests) is first and foremost due to the very long-term dynamics of forests. Oaks live for more than 300 years; the National Forests based on oak and treated as regular high-forest stands are exploited in a final cutting when the trees are between 180 and 250 years old. In addition, even in the case of low-intensity forest management the association of (main and subordinate) species is controlled. To use the example of oak and beech again: the higher market value of oak wood made foresters prefer oak to beech although the more rapid development of the latter would assure it a more important place. This shows that it is possible to reconcile a production goal with the maintenance of a certain genetic diversity.

How to predict the evolution of stands: Modelling of stand dynamics

Because of the characteristic longevity of forests a forester should know the main dynamics of stands; he must know how dynamics are influenced by his silvicultural choices; and he should be able to anticipate the evolution of stands with a view to current decisions. Today these problems are solved by means of simulations based on growth models.

Our knowledge about the dynamics of forest stands refers mainly to pure stands in regular high-forest systems, for which the first permanent observation plots were established between 1880 and 1930. They provide a series of detailed data which cover an observation period of 60 to 110 years. Statistically designed plots have been installed since 1950 to compare various methods of thinning on more reliable scientific bases.

Demographic aspects: The birth and death of trees

- **Mortality of trees**

It is about the mortality of trees that the most valid quantitative data are available. It is part of the spontaneous evolution of forests. So the renewal of natural forests (e.g. tropical rain forests) is based on the disappearance of overaged trees (diseases, windfall) and their replacement by a succession of species adapted to the microclimate of the gap thus created. These situations are simulated by the family of "gap models" (Shugart, 1984).

Photo (p. 63): G. Cattiau

Also in the regular high forests of the temperate zone, the so-called "natural" mortality takes impressive dimensions. For instance, the density of a beech stand of the Forêt de Haye in the French Département Meurthe-et-Moselle (Lorraine) which had never been subjected to any thinnings, and which has been observed since 1883, was reduced from 15,000 to 250 trees per ha between the age of 28 and 135 years, without foresters or wars having anything to do with that reduction! Today this mortality is well described by the "self-thinning" rule, which relates the number of surviving trees to their mean dimension. It is observed in extremely dense closed-canopy stands and concerns mostly slender trees which cannot keep up with their more vigorous neigbours (see also the considerations of social status below).

Apart from excessive competition, the second source of mortality is due to "windfall and windthrow" (trees uprooted or broken by violent winds). For most species, but particularly for conifers, this represents a major risk; that is evident from the considerable damage caused by the storms of November 1982 and January-February 1990 and by the tornadoes of July 1984. The stability of spruce stands has been studied in great detail and it is now possible to quantify which types of stands are most sensitive. In very dense stands (plantations which are never thinned) the trees are thin, badly rooted, and thus to a high degree endangered (by the wind); too heavy thinnings in very high stands are also at risk. Conifer cultures therefore orient themselves to the formation of vigorous, well-rooted trees by means of low plantation densities and early thinnings. In regions with strong dominant wind (such as Scotland) the entire silviculture is constrained by the risk of windbreakage (harvesting sometimes at a height of 20 m).

- **Germination of trees**

The germination of trees and the difficulties of regeneration have been studied in several cases, with the focus on fructification, damage by animals or diseases, setting of seeds, effects of ecological conditions (Oswald et coll., 1981). Although these results are of value to silviculturists it must be recognized that the germination rates of trees are more difficult to anticipate and quantify than their mortality rates.

Production of biomass

- **Height and biomass production, a close relation**

Forest cover produces assimilates which are redistributed in the different organs (leaves, roots, trunk and branches) or recycled in the ecosystem. The growth models describe the part of the fixed biomass which is most easily measured and most important from the production point of view, namely the volume increment of the entire stand. The volume increment depends first on the fertility of the site. The richer it is, the more important the height increment and the production of the aerial part will be. The close relation between height increment and volume production has been proved very early. It is called the "law of Eichhorn" (1904) and represents a basic assumption of forestry.

- **Density of vegetation cover, trees, and stands**

The second determining factor of volume production is the degree of canopy closure. When the cover is very sparse as a result of heavy thinning, the total increment decreases. However, if the thinnings remain moderate, the decrease will be small, if not imperceptible, depending on the species. For the forester this means that after a thinning he can expect the same total production with fewer trees, i.e. better individual growth. Seen from another point of view this means that the practice of thinning does not compromise the productive capacity of the stand. In general, growth models estimate the growth as a function of the density of the stand.

The forest stand: a very hierarchic society in competion for light

Without any anthropomorphism, foresters have for a long time stated that trees arrange themselves spontaneously according to a very strict social hierarchy. These positions were codified by the terms "dominant, co-dominant, dominated, suppressed", plus the "emergents", particularly in natural aequatorial forests.

If the forester does not intervene at all, the hierarchy of the trees by classes of size (height, diameter) is set up very early, as soon as the canopy closes, and remains relatively stable. The trees which are initially among the tallest of a certain area are such either as a result of their greater vigour of genetic origin, of accidental factors or maybe of heterogeneities of the soil. Later, changes of social rank are in most cases regressions: a tree surrounded by more vigorous neighbours will firstly get tired in the race for height necessary to have continued access to the light. It will eventually miss the bus and find itself relegated to the understorey. Such trees find themselves in the shadow with a heavily reduced foliage and thus have limited photosynthetic capacity, but should maintain a high trunk length. This physiological disequilibrium frequently ends up in death, while trees of lower height can survive in the diffuse light of the understorey. So one can see that the understanding of the social hierarchies is mainly based on the phenomenon of competition for light.

Different forest species vary in sensitivity to this competition. In this context, foresters speak of intolerant species, which are sensitive to shadow, such as pedunculate oak (*Quercus robur*), and tolerant species, which are less sensitive (beech, fir) in that respect.

Growth models to simulate the evolution of trees and stands

All the results presented above are today combined in the form of simulators, interactive softwares permitting experienced foresters to test different silvicultural treatments and to analyze their effects on the state of the respective stand. Some of the applications of these simulators refer to the long term, which means the entire period of rotation (80 to 250 years, depending on the species).

At present, such models exist in France for pure and regular stands of maritime pine, spruce, Douglas fir, black pine, beech, and oak (Barthélémy et al. 1995).

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2 The Productivity of European Forests is Increasing: A Fact of Considerable Consequence

In recent years global changes have become a subject of increasing preoccupation both in Europe and North America. Although serious divergences continue to divide the community of climatologists, the vast majority of them predict that a noticeable warming of the terrestrial atmosphere will occur in a relatively short time. According to current models it will be a global warming of between 1.5 and 4°C on average from now to 2050, with strong regional variations. The phenomenon is attributed to the considerably increasing atmospheric "greenhouse gas" concentration. Among these gases, carbon dioxide (CO_2) is most important and it is carbon dioxide which, through accelerated combustion of fossil energies (coal, petrol, natural gas), has since the dawning of the industrial age been most exhausted into the atmosphere. In view of this quasi irreversible dynamism, one of the upcoming questions is how the increasing atmospheric CO_2 content will influence the functioning of ecosystems, in particular that of forest ecosystems.

Photo (p. 65): P. Dubois

Cf. also the article about "Forests faced with increasing atmospheric carbon dioxide", on page 13 ff.

Will the influence of elevated atmospheric CO_2 be mainly *direct*, in the form of improved photosynthesis - we know that CO_2 is a growth-limiting factor for most plants -, or *indirect*, through concomitant change of climate conditions (primarily temperature and precipitation).

Forests and global change

There are many ways of approaching this difficult problem. One of them is to start from the fact that such questions on the potential consequences of global change are actually not completely new. We know that the atmospheric CO_2 concentration increased from approximately 280 ppm in 1850 to 370 ppm in 1996 and that the increase has accelerated during the past four decades. Further, a positive long-term trend in the development of the mean temperatures of our planet has already been proved: approximately +0.7°C since 1880. So it might be postulated that these changes have already provoked some sensitive responses by forest ecosystems. If so, it is important to retrospectively analyze and quantify them.

An analytical device: Dendrochronology

Dendrochronology is based on the reconstruction of earlier tree growth and seems to be a method particularly appropriate for this approach; it already proved very efficient in the analyses of normal and disturbed forest ecosystem functioning. For example, in the framework of the French programme DEFORPA it identified various factors responsible for the new-type forest damage observed in mountain forests of north-eastern France (Vosges, Jura) several years ago. One of these factors was climate, in particular successive years characterized by severe droughts.

Dendrochronology was also used to investigate potential long-term changes, at the century time scale, regarding the radial growth of trees of temperate European forests. In the following, the most significant results of those investigations will be summarized.

Methods and investigated forests

Several different broad-leaved and conifer tree species and various forest areas, located in mountainous and hilly areas, were the objects of dendrochronological studies. Common to all these studies was the very intensive sampling of trees from many different stands which were selected such that the ecological variability of the investigated regions (altitude, exposure, topography, soil, vegetation) was represented in the best possible way. Further, to be able to efficiently distinguish radial growth from the effects of natural tree senescence and year-related effects, stands of most different ages (between 20 and 200+ years) were selected.

On each and every site only dominant or co-dominant trees, i.e. trees subject to little competition by their neighbours, were subjected to an "increment boring" using a tool with a kind of hollow bit called "Pressler's borer". With the aid of such a borer small wood samples ("increment cores"), 4 or 5 mm in diameter, were taken from stems. The cores reach from the bark to the "centre" (pith) of trees and are usually taken at 1.30 m from the ground. Maximum precautions are taken to avoid unnecessary damage of the investigated trees. One or two increment cores were taken from every tree.

The most important studies completed so far refer to natural production forests, i.e. forests where species are spontaneous and where forest management successfully reconciles the two goals of wood production and ecosystem conservation. For statistical reasons the number of observed sites and trees is very high; for example, for fir in the Vosges, 277 sites and 1,662 increment cores; or for beech, 158 sites and 948 increment cores.
The following species were investigated:

- fir in the mountains of the Vosges and the Jura;
- spruce in the Vosges;
- beech in the Vosges, on limestone plateaux and alluvial terraces of Lorraine, in eastern France;
- oak on the clay soils of the Plateau Lorrain (sessile oak and pedunculate oak).

In addition, two situations completely different from the above ones were studied:

- Corsican black pine in the Pays de la Loire, in western France, where that species is now frequently used in reafforestation; the goal of silviculture there is primarily wood production.

Fragment of an increment core from pedunculate oak. The lines of small perforations in black show the large vessels which trees form every year at the beginning of the vegetation season (early wood). They permit exact dating of every individual ring.
Photo (p. 66/67): M. Becker

- *Pinus uncinata* in the High Pyrenees (in the south of France) at the upper timber line; in this case there is no "forest" in the traditional sense of the word, but a very open vegetational formation not subject to any silviculture. Trees there are dispersed; their growth is therefore not compromised by the competition of their neighbours.

The chronological series of the widths and surfaces of the annual rings that correspond to each increment core are then cross-dated with great precision, an operation which consists in minutely checking the exact dating of each and every annual ring[1].

Results

A strongly increasing potential of radial growth in the course of the past century
The development of average increment indices in the course of time is possible for each forest species and each region: since 1850 or so in the majority of the studies, since 1930 for the black pine plantations of the Pays de la Loire (there are very few older plantations), and since 1750 for the *Pinus uncinata* stands of the High Pyrenees (where several hundred year old trees could be found).

All curves obtained show great interannual variations and marked periods of depression of growth at the decade level which are to a very high degree due to concomitant climate fluctuations. However, all curves indicate also marked long-term increases of radial growth:

- fir in the Vosges (north-eastern France): + 160% since 1850; a plateau was observed between 1930 and 1982, followed by a considerable rise since 1983;
- fir in the Jura (north-eastern France): comparable increase; + 130% since 1865, with the same plateau from 1930 onward;
- spruce in the Vosges: continued rise of + 130% since 1865;
- beech in the Vosges: + 90% since 1850, with a clear acceleration of the phenomenon since 1950;
- beech on limestone plateaux of Lorraine (north-eastern France): between + 60% and + 120% since 1880, depending on the type of silviculture applied to stands;
- beech in alluvial terraces of Lorraine: + 125% since 1860;
- sessile oak on argillaceous soils of the Plateau Lorrain: + 90% from 1850 to 1987, with a continuous acceleration of the phenomenon since 1850;
- pedunculate oak in the same context: + 55% "only" from 1850 to 1987;
- Corsican black pine in the Pays de la Loire (western France): + 50% since 1930;
- *Pinus uncinata* in the High Pyrenees (southern France): stability between 1750 and 1850; + 100% since then.

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[1] There are certain incidents, first and foremost of climatic origin, which can lead to "false rings" or, in contrast, "missing rings". Interpolation is based on the use of characteristic years which are progressively shown, years in the course of which the growth of most trees was considerably weaker or greater than in the preceding year. After that, the surface of every ring is calculated from its width and its distance from the core. The ring surface presents the advantage of being more directly in proportion with the volume increment than width. Finally, to make up for the part of the data variation which is a result of normal biological senescence of trees, each and every annual surface is "standardized", i.e. converted to an independent age index of the corresponding ring (also referred to as "cambial age"). This standardization is effected in two successive stages.
◆ First, the average of all ring surfaces of the entire sample are calculated for every cambial age, from 1 to 200 years and more. The curve thus obtained will at the beginning be "smooth". Considering the great differences in the current age of the sampled trees, every cambial age will correspond to annual rings elaborated at most different times and, therefore, under most different ecological, silvicultural, and meteorological conditions the growth-inhibiting effects of which compensate one another. In fact, the curve illustrates the biological law of the relationship between radial growth and the senescence of trees of the respective area.
◆ After mathematical adjustment of the described curve the indices of radial growth are calculated. Each of those indices corresponds to the proportion (expressed in %) of the ring surface which was measured to the surface estimated from the curve adjusted to the same cambial age. All these indices can then be validly compared leaving out of account the age of the corresponding rings, which is fundamental for the desired purpose.

A mathematical model using meteorological data from a site at Strasbourg (monthly precipitation and monthly mean temperatures, available since 1881) was established for fir in the Vosges. This model "explains" 79% of the observed variation and in a very satisfying way reconstructs both long-term trend and most frequent growth fluctuations. Considering only this first example one might have been tempted to conclude that the influence of increasing atmospheric CO_2 on tree growth is more indirect (via the climate) than direct (stimulation of photosynthesis). But applying the same method to fir in the Jura led to a somewhat different conclusion. In this case modelling the observed long-term trend only with the help of climatological data (those of Besançon, Neuchâtel and Geneva) did not prove very satisfactory, but complementary introduction of known data of atmospheric CO_2 into the model raised the rate of explanation to 89%. A comparable result was also obtained for pedunculate and sessile oak of the Plateau Lorrain (78 and 73%, respectively).

How are the results to be interpreted?

Outside France very recent dendrochronological studies suggest that the productivity of various forest ecosystems has significantly increased in the course of the past century. This increase has been observed in boreal forests of Europe and North America and in mountain forests of the temperate zone. Moreover, German scientists who applied different methods obtained a similar result in the Black Forest by directly comparing the total wood production of two successive generations of spruce on the same experimental designs.

Nevertheless some uncertainty remains in respect of the interpretation of the results. For example, it is absolutely legitimate to wonder about the dimensions of the observed increases. Two different questions may be subjects of discussion when investigating a potential bias. Both refer to the relevance of the investigated tree samples in respect of the pursued goal.

- The first question is about the spatial structure of the sample and the ecological diversity of the corresponding stations. There is well-founded suspicion that very old trees are preferably found on unfavourable sites: The less this is compensated for by weaker competition, the slower the radial growth, and the later the exploitable age. In the Jura, for instance, preliminary data indicated that the increase in growth rate was not realistic (+ 400%) because the oldest trees available in the overall sample were most frequently located at high altitudes and in difficult sites, and were subject to a particular silvicultural system ("single selective cutting"). This is why the above result actually refers to a sub-sample of trees selected according to rigid criteria: a typical uniform high-forest; age less than 150 years; altitude between 900 and 1100 m. For the other examples, the different forms of stratification effected to detect potential bias did not indicate considerable changes in the average curves.

- The second question concerns the internal structure of the sampled stands and the representative character of the selected trees. One might in fact wonder whether the old trees available and selected today would have been selected with the same probability if the study had been conducted 40 or 80 years earlier. It is difficult to affirm that categorically. We do know that, unless there are major local perturbations (phytosanitary problems, storms, etc.) or deliberate interventions by foresters, the social hierarchy of trees usually does not change in the course of their lives, at least not in more or less even-aged stands. High-altitude *Pinus uncinata* stands without competition or silvicultural management avoid these constraints and also in their case considerably increasing growth has been observed.

Recently a new important argument has come to support the thesis of **general increase in forest ecosystem productivity**. In cooperation with scientists from Québec a series of stem analyses were conducted in order to reconstruct the dynamic growth in height of black spruce in the boreal forest of North Québec, in stands where human intervention was absent and where the level of air pollution (except for CO_2) is extremely low. It appears that growth in height, which is known to be a much more certain criterion of productivity than diameter growth, is really much more rapid today than it was a hundred years ago.

For some time studies about potential changes in forest productivity have been conducted also by other European countries; the vast majority of preliminary results indicate marked increases, too.

Even though the existence of the phenomenon seems to be well established, the underlying physiological mechanisms are not evident. Experimental studies that have been conducted so far to prove the effect of atmospheres enriched with CO_2 have delivered different, sometimes contradictory results. However, most of them reveal more or less positive effects. One should keep in mind also that the importance attached to atmospheric CO_2 in the above-described models is at the moment purely statistical. Other factors, some of them correlated to CO_2, might also have played a certain role, for instance other greenhouse gases and/or atmospheric nitrogen depositions linked to agriculture and automobile traffic. So it is probably necessary to duplicate studies with a view to quantifying the impact of environmental changes on tree physiology, not only at the stage of seedlings and young plants, but also in mature trees and at the level of the stands they constitute. In view of the expected global changes such research activities will be of major importance.

Photo (p. 69): G. Paillard

Despite the uncertainties that remain with respect to exact causes of the phenomenon it appears certain that forest ecosystems, at least those of the temperate zone, have already now heavily responded to the man-made changes in environmental conditions that have occurred since the middle of the 19th century. This new finding, which only a few years ago was completely unknown, will have to be seriously considered in forest management, as some of the latter's rules have so far been based on the temporal constance of the growth potential. Rhythm and intensity of periodical stand "thinnings" will have to be managed. Wood yields can, and must, increase and all industries of the wood sector will both positively and negatively be influenced by that fact. The different aspects of that influence should be predicted as accurately as possible.

Finally, the question of the stability or longevity of certain ecosystems, in particular forest ecosystems, probably merits more careful study, especially if the effect of climate changes (temperature, precipitation) compounds that of elevated atmospheric CO_2. Certain tree species are in danger of being intolerant of these new conditions. Moreover, given the length of the generations of those species, their capacity for natural migration towards situations more appropriate to their ecology will probably be insufficient. To appreciate this aspect and to anticipate these species shifts artificially, and early enough, will be a great responsibility for foresters. They realize that in cases of failure they will be confronted with increasingly numerous, grave, and frequent forest diebacks.

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Man and His Forests

The United Nations Conference on Environment and Development (Rio Summit 1992) emphasized the important part man plays in management. For this publication, we decided to present the relationships between man and his forests by focusing on four topics:

- ◆ Considering the longevity of trees, good forest managers must set themselves long-term goals. Planning the complex activities, interventions, and operations which are necessary to realize these goals is the object of **forest planning**; its concepts, methods, and the questions it poses to science are outlined in the following. Being a paragon of synthesis, successful forest planning is one of the pillars of sustainability.
- ◆ It is particularly justified to wonder about the wide range of **job opportunities** offered by forests and forest industries (notably in rural zones), an aspect which carries weight in the economy of France.
- ◆ However, people benefit also from **non-market forest goods and services**, which are of a highly diverse nature and include aesthetic and ecological (soil and water conservation; carbon sink capacity) values as well as protection of species and genetic diversity (biodiversity) and many others. Serious efforts are necessary to better qualify and quantify them, so that they can be considered in a more appropriate manner.
- ◆ Finally, special mention is to be made of **agroforestry** and its different scenarios combining forest and agricultural activities. Well-considered agroforestry systems could open up new ways towards a more diversified agriculture.

Book of hours "Très riches heures du Duc de Berry". November: Acorn harvesting. Miniature by Pol of Limbourg and Jean Colombe, France, 15th century. Musée de Condé, Chantilly.

Photo: © Giraudon (p. 70/71)

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1 A tool of sustainability : forest planning (J.L. Peyron)
2 Forests and forest industries, sources of employment (D. Normandin and J.L. Peyron)
3 Forests as producers of non-market goods and services (D. Normandin)
4 Agroforestry : a new or revised scenario (D. Auclair)

1 A Tool of Sustainability : Forest Planning

Forests constitute slowly renewable natural resources. Their ecological complexity, slow growth, and biological character imply a sophisticated, thoroughly planned management embodied simultaneously in space and time. Forest management necessitates planning. It rests on very long-term considerations, frequently in the order of one or two centuries, which lead to more precise, concrete, and formal prescriptions applying to periods of 10 to 30 years.

Photo: © O. Sébart (p. 72)

An old, but up-to-date procedure

To manage a forest means to ethymologically adapt it to its owner's or, by extension, society's needs. However, this is one of the most simple meanings of the term "management". Forest management planning or, more simply, forest planning, is a particularly old discipline. Its spirit can be traced back to the decree signed in Brunoy on 29 May 1346 by Philippe VI of Valois, King of France: *"The Masters of Forests [...] shall survey and visit all forests and all woods which they include, and they shall effect the sales as needed, with a view to continuously maintaining the said forests and woods in good condition."*
Step by step a real "forest culture" has developed around this concept which, though not in words, at least in facts goes beyond owner categories and has greatly influenced also other fields.

The old age of the concept of forest planning does not mean it is not open to new ideas. That society's demands change in the course of time and new ways of approaching them emerge naturally makes us analyze how the second might better meet the first. This characterizes somehow the finality of research activities applied to forest planning; it necessitates particularly so-called quantitative methods, as they are based on a mathematical formulation and on mathematical tools.

Enhancing the innocuity and efficiency of human interventions in forests

Forest management consists in effecting cuttings and other interventions in the different stands of a forest according to a set rhythm and order. These interventions meet multiple criteria.

Ecological criteria undeniably rank first among them. The adaptation of species to their natural environment, the "site", is particularly important because it forms the basis of all forest functions, whether they refer to protection, production or public access. Ecological criteria involve also the conservation of soils, animals and plants, included in the meaning of the term "biodiversity"; tree health in view of attacks by pollutants, pathogenic fungi or insects; and stand resistance to major aggressions such as wind, snow, fires, or large herbivores. Finally, one can put forward the budget of certain chemical elements: the beneficial sequestration of carbon in wood; mineral elements whose exportation from forests may lead to impoverishment of the milieu; the water with its multiple links to vegetation, ...

Also the search for a global biological equilibrium at forest level is a criterion frequently applied, although managers do not necessarily give priority to this goal.

Reference is also made to **economic criteria**. They concern particularly the growth and productivity of stands, i.e. their profitability, and thus involve the costs of management and interventions, the price of timber and other forest products such as foodstuffs, medical products, hunting returns, décor elements, resins, cork, fragrant oils, etc. Also the number of employments necessary for direct or indirect forest activities represents an economic criterion. Regularity of income and expenditure through forests is a frequent goal; it is to the economic criteria what the global biological equilibrium is to the category of ecological criteria.

Finally, there are **criteria of strongly cultural and social character**. The scenery of the landscape in forests favours the practice of many recreational activities in forests; its external beauty contributes greatly to the development of tourism in the respective region. The protection against noise or optical nuisances plays an important part. People's awareness of forests being among the last refuges of nature is a strong sentiment which explains much of the relationships between man and forest. Like ecological or economic considerations, social concerns make long-term global stability of forests in many cases a desirable goal.

The importance of the above-mentioned criteria depends on the relevant situation. For example, some of them clearly involve public rather than private policies: clean air, job creation, quality of external landscape. Every owner will apply the criteria in a different way to define his/her strategy. Contrary to some contentions, forest planning is essentially a procedure which must take into account the individual case and, therefore, could not be normative.

On the basis of these criteria, an owner will first narrow his strategy within constraints that delimit the framework of possible or acceptable interventions. Within these limits, he can then consider enhancing a management goal of his choice.

Sometimes these constraints are essentially of ecological or social nature. For example, one might prefer a local species which is integrated in the landscape and brings a large number of plants and animals in its train to a more productive species which is introduced and presents risks; in other cases it may be decisive to achieve a global forest equilibrium in the course of time, assessed on the basis of age or diameter class distribution. Constraints thus set the limits within which forest managers then try to pursue given economic objectives, such as forest revenues. In the case of minor constraints management will be mainly economically determined; severe constraints, on the other hand, may make the economic objective appear ridiculously small with ecological or social aspects being decisive. There are also economic constraints, such as earning sufficient returns to fund an ecological or social objective with the latter being enhanced in proportion to revenues. However, a management strategy which focuses too much on productivity risks affecting fragile ecological equilibria or fails to take into account social needs.

It is evident that forest management necessitates above all that multiple management criteria of ecological, economic, and social character are reconciled.

Finally, research activities in the field of forest management aim at elaborating methods to approach such problems as implementing management goals in accordance with a well-determined, objective criterion and perfectly identified constraints.

A management reasoned out in space and time

For a given tree crop, forest management involves two temporal stages:

◆ The long term exceeds the period at the end of which a tree crop can be completely regenerated; within this period all realistic modifications can be envisaged; the owner defines the target condition, which is not constrained by the current stand condition.

◆ The short term comprises a period shorter than the regeneration period of the tree crop; the owner has to attend to existing trees constraining the implemention of certain modifications and tries to assure the best possible transition towards the long-term target condition.

Forest management involves also a pronounced spatial aspect which, in the concept of structure, is tied to temporal factors. At the level of small crops in the order of several ares to several hectares, i.e. at stand level, distinction is made between two types of structures:

◆ Even-aged (or regular) structure means that all trees of a stand have the same or approximately the same age; consequently, trees of all ages can be found only at the level of several stands, i.e. at forest level. This structure is usually represented in histograms of areas by age classes like the ones on the left side of Figure 1.

◆ Uneven-aged structure describes a stand with trees of different ages and usually also different species. Such a structure cannot be graphically represented using areas by age classes because that would necessitate that the age of each individual tree is determined, which is not realistic given the present state of the art; instead, frequency curves of diameters like the ones on the right side of Figure 1 are applied.

This distinction with respect to structure induces very different management methods.

Even-aged or regular structure:
Histogram of areas
by age classes

Uneven-aged structure:
Frequency curve of tree diameters
for one or several stands

Area
Age classes

Number or frequency
Diameter

Area
Age classes

Number or frequency
Diameter

Figure 1 ◆ Representation of current (above) and balanced (below) structures for "even-aged" (left) and "uneven-aged" (right) stands; the histogram above on the left refers to a forest with stands of different ages, while the histogram below on the left characterizes a forest of regular age classes; similarly, the frequency curve of tree diameters above on the right is that of a forest with surplus merchantable timber, while equilibrium is described by the curve below on the right, achieved in the course of time by increment felling.

Management planning of even-aged stands

Management planning of forests necessitates advance analyses of natural stand environments, of their present and past quantitative and qualitative features, and, finally, of the socio-economic and cultural context.

The analysis of natural environments permits definition of zones homogeneous with respect to the natural environment and, thus, with respect to possible target species, their growth conditions, and their impact on the above-described ecological, economic, and socio-cultural criteria. For each of these homogeneous zones, and as a function of the strategy that has been elaborated, the owner or manager will determine the best possible forest management for the long term, i.e. the stands that will succeed to the existing stands. This includes in particular the choice of preferred species, their desired density after several years (density of plantation in the case of reafforestation; density after selection of plus trees and/or elimination of minus trees in the case of natural regeneration) as well as the timetable, weight and type of thinnings required to progressively reduce the number of trees until the final crop is ready for harvesting.

The above-described homogeneous zones consist of various stands of different species, ages, etc. Each of them could be the object of optimum management until its harvest; thereafter, the long-term target stand would be established and then managed. However, such management frequently proves incompatible with the owner's global objectives. Such global objectives are no longer applied at the stand level, but at the forest level; they include maintaining a global biological equilibrium, searching for a certain regularity of expenses and income, taking into account the interaction of operations planned in neigbouring stands, and the like. Even though forest management can today be effected on a much larger scale, global long-term objectives obviously frequently consist in leading forests towards balanced age-classes as represented by Figure 1 below on the left. Such long-term objectives necessitate that the management of some of the stands deviates for a short time from the management that would be optimal for them and accepts the corresponding cost; although the latter remains usually small it can be interesting to determine it.

Photo: M. Adrian (p. 75)
Study on the growth of coppice stands in the French region Centre. Observation and measurement after the end of the vegetation period in the experimental coppice stands of INRA Orléans.

Management planning of uneven-aged stands

Many of the principles developed above for even-aged stands are valid also for uneven-aged stands; however, it is evident that modes of application vary largely with the new conditions. The analysis of natural environments, stands, cultural and socio-economic context obviously remains a necessity, while searching for a balanced structure is more than in the case of even-aged stands linked to the concept of forest planning. The equilibrium is defined at the level of every homogeneous zone, but in view of the intimate and omnipresent mixture of species and tree sizes it is to be applied to each individual stand. In the case of uneven-aged stands the main global objectives the owner wishes to pursue are thus assigned at stand level and no longer at forest level.

Consequently, the long-term equilibrium is for each and every stand defined through a particular structure which is sometimes outlined by means of a general typology, sometimes described more precisely by a frequency curve of diameters similar to that of Figure 1, below at the right. In either of the two hypotheses the structure is obviously chosen such that it corresponds in the best possible way to the owner's management criteria.

If a stand is in accordance with the selected objective, it is sufficient to determine the periodicity of fellings (the cutting cycle); the number of trees to be harvested in every diameter class in order to restore the status which immediately followed the preceding felling is automatically inferred from the rotation. The removed volume is therefore equivalent to the increment of trees during the set period, less any mortality (net increment). After each cutting standing volume and number of stems of each diameter class will be the same as before.

If a stand does not correspond to the selected objective, cuttings should be effected in such a way that it progressively gets closer to this objective. This means, in particular, to harvest more or less than the net increment, depending on whether the target volume is lower or higher than the present volume, preferably by reducing the over-represented diameter classes.

Conclusion

Research in the field of forest planning concerns in particular elaboration of quantitative methods which, as the term implies, are to measure the effects of a specific management system as compared to those of another one. Knowledge of an economic optimum is thus not only useful for managers whose objective is high profitability; it enables others who wish to give priority to a different criterion to estimate the costs involved, which is very useful at a time when pressure is undeniably exerted in favour of a more collective forest management not accounting for ownership considerations. An objective and balanced discussion among foresters and pressure groups necessitates doubtlessly the availability of comprehensive and precise information; quantitative methods are a means of acquiring them.

Forest planning constitutes a framework for the day-to-day work in forestry. Its indications are valuable, but must not entirely limit the manager's scope of manoeuvre. Even limited to its strategic role, it remains an original and indispensable tool of forest cultures. But forest planning must also adjust to new conditions; it must approach and solve more, and more delicate problems; and to be able to do all that it must progress continuously. Quantitative methods offer rich opportunities for this development.

Such an approach opens up many new possibilities for other scientific activities, particularly for those concerned with the elaboration of growth models. It represents therefore a very promising field of forest research.

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2 Forests and Forest Industries, Sources of Employment

The French forest and wood sector includes complex activities: forest and forest harvesting as well as all branches of the wood-working and wood-processing industries. Wood-based products offer a wide range of uses: buildings, furniture, packaging material, stationery, domestic and hygienic uses, etc. In France, the sector faces major deficiencies.

Photo: © Giraudon - French Ministry of Defence, Historical service of the land forces (p. 77)
Manual of fortifications, timber sawers. Drawing by Claude Masse (1652-1737), France. Historical service of the land forces, Vincennes, France.

The forest and wood sector in France
The forest and wood sector includes all branches of the production, logging, transformation, and marketing of wood (Figure 1) which, along a series of technological operations, permit management of forest resources, provision of raw material, and treatment of the latter such that the supply of households is guaranteed. In France, not counting fuelwood, these activities presently provide approximately 61 million m^3 equivalent of roundwood (m^3 erw = estimated volume of raw timber required for the production of a wood-derived product) annually, i.e. about 1 m^3 per year per inhabitant. Recycling, notably of waste paper, provides for a quarter of these needs (16 million m^3 erw); three quarters (45 million m^3 erw) are provided by transformation of raw wood. One half of the latter corresponds to structural timber (sawn timber, veneering wood, and peelers), another half to pulpwood (wood board and paper pulp industries). The average national harvest of raw industrial wood usually amounts to approximately 32 million m^3 (mean 1988-1993; 70 % of the raw timber demand); 22 million m^3 of which is structural timber (more or less the entire need, although not well distributed among hardwoods and softwoods) and 10 million m^3 of which is pulpwood (half the demand). As a result of the strong competition which big producer countries (notably North America and Scandinavia) exert on the open world market, the French forest and wood sector altogether presents a structural deficit of about 13 million m^3 erw in volume. The main deficiencies are, in decreasing order of value, pulps and paper-boards, furniture, and coniferous sawn wood. In 1994 the foreign trade deficit of the French forest and wood sector amounted to 12 billion francs (= 2.2 billion $).

Figure 1 ◆ The forest and wood sector

			Wood-working industries	**Wood-processing industries**	**Utilization**
Forest management	**Forest harvesting**		Sawn wood Veneer wood	Buildings	Construction
		Timber			
Owners	Skilled forest workers			Furniture industry	Furniture products
			Boards		
Managers	Loggers				
		Pulpwood		Packaging material	Wrappings
Silvicultural operations	Transport workers				Stationery
	Forwarders		Pulps	Paper Cardboard	Hygienic and domestic uses

(p. 78)

Estimated jobs in the forest and wood sector (in thousands of full-time jobs) in 1991

Fields of activity	**Employed**	**Self-employed**	**Total number of jobs**
- silviculture and forest services	16.1	50.0 (1)	66.1
- forest harvesting	7.0	21.0 (2)	28.0
total primary sector	**23.1**	**71.0**	**94.1**
- mechanical wood working	92.0	6.5	98.5
sawn wood	23.5	3.0	26.5
panels, veneers, impregnation	12.5		12.5
- furniture industry	**89.8**	**20.0**	**109.8**
- paper and cardboard industry	**105.8**	**0.8**	**106.6**
paper pulp	2.0		2.0
total secondary sector	**287.6**	**27.3**	**314.9**
wood-working industries	38.0	3.0	41.0
wood-processing industries	249.6	24.3	273.9
total first and secondary sectors	**310.7**	**98.3**	**409.0**
- wood building industry	108.1	23.8	131.9
- trade in wood-based products	82.5		82.5
total primary, second., tertiary sectors	**501.3**	**122.1**	**623.4**

Sources: Enquête statistique sur les structures économiques de la sylviculture, Office National des Forêts, Mutualité Sociale Agricole, Enquête de branche exploitation forestière et scierie, UNEDIC, enquête artisanat.
(1) Work of private forest owners equivalent to full-time jobs.
(2) Skilled forest workers and independent subcontractors (loggers, transport workers).

The wood production and transformation branches create an estimated added value of 80 billion francs p.a. if only production, harvesting, wood-working and wood-processing are considered, and 125 billion francs (i.e. 1.7 % of the gross national product) if construction (use of wood products in building) and timber trade are included. For the sectors of silviculture and forest harvesting this added value is estimated at 8.5 billion francs, i.e. an average of 610 francs per hectare of forested area (about 14 million ha) or 260 francs per m³ of industrial timber harvested. The marketing of the above sorts of wood (products), plus (to a considerably lower degree) hunting, represents the principal source of income of forest managers. It provides the revenues necessary for the maintenance and renewal of forested areas. More generally speaking, the financial resources earned by the domestic uses of wood-derived products fund necessary production factors and notably labour during the entire transformation process.

Jobs in the French forest and wood sector

Determination of the number of jobs provided by the forest and wood sector is compromised by the essentially patrimonial nature of the management of a large portion of forest resources (private forests represent three quarters of the total forested area), by the fact that crafts play a major role in many branches, and by the strong business fluctuations in the consumption of products derived from wood. The results presented in the table were selected arbitrarily from different sources and must thus be considered orders of magnitude. Taking into account these characteristic features, it is among other things important to distinguish between employees and self-employed persons (forest owners, self-employed craftsmen and entrepreneurs, heads of enterprises), which makes estimations even more complicated.

Excluding the work of forest owners, which is very roughly estimated and usually does not correspond to a professional activity, the total number of jobs in the forest sector would be 570,000, of which 90 % are wage- or salary-earning employments. More than a third (38 %) of this total are service jobs in the construction, wholesale and retail businesses. Their linkage to the wood-working and wood-processing industries is rather weak in view of the statistical nomenclature and the diversity of materials used by enterprises of these sectors. Considering only employments in the fields of production, harvesting, wood-working and wood-processing the number of jobs would be in the order of 360,000 full-time jobs, of which 310,000 are wage- or salary-earning employments. These jobs of the primary and secondary sectors are distributed as follows: 44,000 jobs for silviculture (16,000) and forest harvesting (28,000); 41,000 jobs for the wood-working industries; and 274,000 jobs for the wood-processing industries.

Employment in forests (silviculture, logging) thus represents only 12 % of the total number of employments offered by the primary and secondary sectors of the forestry and lumber business. This distribution differs markedly from that observed in the agricultural sector, where agriculture occupies 1.2 million people, while agro-food industries furnish only half of this figure. It is estimated that 1,000 ha of forested area provide 1 job in silviculture and 2 jobs in forest harvesting, while 1,000 ha of agriculturally used area procure work equivalent to 40 full-time jobs. However, in France and all over Europe agricultural employment is strongly supported by the public, which is much less the case in forestry. At the level of downstream industries agricultural and forest/wood sectors, however, have the same relative importance: about 20 jobs per 1,000 ha (of agriculturally used or forested area). It can also be estimated that logging 1 million cubic meters of raw timber requires about 850 jobs in forest harvesting and nearly 10,000 jobs in industrial branches. Improving the French forest and wood sector thus involves a double advantage for society (reduction of foreign trade deficit, job creation).

Parquet grinders. Gustave Caillebotte (1848-1894). Musée d'Orsay, Paris.
Photo: © Hervé Lewandowski - RMN (p. 79)

The role and development of the forest and wood sector in view of the overall employment situation

The 310,000 wage- or salary-earning employees of the primary and secondary sectors of the forest and wood industries represent 1.5 % of the total wage- or salary-earning employments. A vast majority (68 %) of this total refers to activities of the tertiary sector, i.e. services and trade. In proportion to the agricultural and industrial sectors, the forest and wood sector represents approximately 5 % of the wage- or salary-earning employments. With all due modesty, this portion is indisputably significant - more so in terms of total employment where the sector of wood production, logging, wood-working, and wood-processing is approximately of the same importance as sectors like the automobile industry or the textile industry, and by far exceeds the plastics, glass, basic chemical, and iron and steel industries.

Despite very strong international competition the French forest and wood sector has suffered only limited staff losses in the course of the past two decades (Figure 2); these losses are in the same order of magnitude as those observed for industry as a whole. Only the agro-food and plastics industries experienced rising staff numbers during this same period. In all other cases (agriculture, goods of first transformation, producer and consumer goods) job losses were frequently much higher than in the forest and wood sector. This indicates that the sector is rather crisis-proof, which to some degree is due to the quality of French forest resources and their management. The present mission of science is to promote and develop the technological and economic means to strengthen this sector. It is important for the landscape management of certain rural zones, where job creation is rare, that the competitive position of the sector be reinforced and at the same time ecological and social constraints be respected and accounted for in forest management.

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(p.79)

Figure 2 ◆ Development of the employment situation in the forest and wood sector and in other primary or secondary sectors between 1975 and 1990.

Indices (100 in 1995)

Agro-food industries
Plastics industry

Wood sector
Metal working industries
Industry globally
Glass industry
Automobile industry

Chemical industry

Agriculture

Leather industry
Textile industry

Iron and steel industry

75. 76. ... years

Sources: INSEE, general population census.

3 Forests as Producers of Non-Market Goods and Services

Forests provide society with a wide variety of goods and services. First, they constitute the reserve of a renewable resource, wood, which man has for a long time used to satisfy his needs for housing, transportation, tools, writing material, and energy. Secondly, forests furnish diverse plant and animal products (resin, cork, branches and foliage, mushrooms, game, ...), and, finally, they make an important contribution to the maintenance of ecological equilibria and to landscape management and offer places for relaxation and recreation which are gaining appreciation as people feel increasingly confined by growing urbanization and industrialization.

Photo (p. 80): Displaying blackcock. Photo: J.C. Malausa

Protection and management of timber resources

As a consequence of progressive population growth and the concomitant needs of society many regions on earth have been confronted sooner or later, depending on the significance of their forest resources, with the necessity to protect and manage their forests. In France, measures to avoid clearing of forests have been taken for a long time (since 1860). In addition, methods of forest resource management have been implemented to enhance the renewal of these resources and to ensure wood supply over the long term. Initially, efforts were made to control cuttings and make them compatible with natural vegetation dynamics. Later, growing demands with respect to quantity and quality required application of techniques that increased natural growth and directed management to those forest products that corresponded best with the demands of the wood-working and wood-processing industries and, thus, satisfied consumer needs. This is the subject-matter of silviculture, which proposes higher and very long-term investments by public and private agents charged with silvicultural management.

Although protection of forested areas is far from being assured everywhere (notably not in the tropics), French forests are presently not in danger of being reduced. Particularly since the middle of the century recession in agriculture has rather led to considerable extension of forests. Forested areas have increased from 11 million ha in 1945 to more than 14 million ha in 1990. This remarkable, though not evenly distributed increase was supported by the initiative of the *Fonds Forestier National*, which helped to afforest, or reafforest, over 2 million ha since 1946. As a consequence of agricultural overproduction forests presently extend at a rate of approximately 20,000 ha annually. It it true that during the same period demands for agricultural productivity have caused a significant reduction of hedges or lines of trees. However, people's desire to promote a more eco-friendly form of agriculture and their awareness of the ecological significance of the described tree formations presently encourages their improved protection and even reestablishment. Forests and woods in the strict sense have, in some cases for a very long time, mainly been managed by government authorities, which has ensured their perenniality. According to results of the French National Forest Inventory the standing volume of French forests is currently growing at a rate of about

20 million m³ per year. French forests are thus not overcut, neither as a result of domestic uses (fuelwood) nor through industrial exploitation.

An attempt at conciliation between timber production and non-market services

Today the main problem in France is to determine which forest resource management methods are suited to provide society over the long term with the goods and services it expects from forests. On the one hand, French forests, which occupy a quarter of the national territory, supply a wood sector which, though deficient in value, offers more than 300,000 employments (not counting trade and building industry), many of them in rural zones. At a time when agriculture is losing almost 50,000 jobs per year, the activities of wood production, logging and transformation play an important role in the management of rural areas. In addition, they represent presently the principal source of income for forest managers, thus permitting investments necessary for the maintenance and renewal of forest resources. However, these activities are subject to heavy international competition by countries with more abundant resources which, in addition, are frequently managed in a less sustainable manner than in France. The constraints of a competitive supply of wood-working and wood-processing industries thus plead for intensification and rationalization of wood production. On the other hand, concerns about the conservation and improvement of our environment are strongly supported. In forestry these concerns become evident in a desire for close-to-nature forest resource management and they fit in an international context (Conferences of Rio, Helsinki) where commercial strategies of large timber-producing countries are represented as well. Although concerns are legitimate and show themselves mainly in terms of biodiversity maintenance and landscape preservation, they often lead to increasing constraints with respect to the timber supply of industries.

For this reason society must make a compromise on the economically competitive production of an indispensable raw material the use of which is in many cases more eco-friendly than that of rival products (plastics, metals, ...), and a less profit-minded forest management system. However, conditions of such compromises are delicate and sometimes subject to vigorous debates. On the one hand, scientific data on functions of the complex forest ecosystem are still incomplete, which makes it difficult to objectively assess global consequences of different forest management systems. On the other hand, discussions are so complicated because the ecological and social services provided by forests do not fit into the framework of market economy; they constitute "externalities" (spillover effects on the market). Public and private forest managers are encouraged to produce services for which they are not paid, and without a tangible value indicator (price) it is difficult to assess the characteristics and the exact level of social need, to evaluate benefits, and to compare them to the direct or indirect costs (limitation of marketable uses) entailed by the management of non-market services. It turns out to be extremely complicated to reconcile these two aspects of forest management.

Economic analysis and management of non-market forest services

Economic analyses traditionally investigate financial relations among individuals. The growing concern about the protection of our environment, which is becoming a scarce resource, has lead to development of economic analytical methods adapted to non-market services. They are essentially based on assessing the benefits of the conservation of natural assets, i.e. the value assigned to them by society. For this purpose it is necessary to define the concerned goods and to characterize the nature of the services they procure. The development of their value and the applied methods of assessment depend primarily on the functions of such goods and services. Usually a distinction is made between goods which are meant for (direct or indirect) usage and goods which are not subject to concrete or immediate utilization (non-usage). In the latter case, motives for the preservation of the environment originate from the desire to conserve this resource for oneself (value of option) or for future generations (value of legacy). It is obviously difficult to determine the financial value of such objectives, as they frequently include a strong ethic dimension. Furthermore, determination of society's "willingness to pay" necessitates identification of the concerned individuals. Environmental goods generally belong to the economic category of collective goods and thus can be "consumed" simultaneously by several individuals. This entails particular difficulties with respect to finding interested agents, evaluating their preferences, determining their solvency and the methods of financing to be envisaged.

The table provides a schematic representation of **important economic characteristics of non-market services** procured by forest resources. A distinction is made between two categories, depending on their effect on ecological equilibria or people's conditions of life. The first group includes effects of forests on soil conservation, quality and regime of water, and carbon sequestration, and the role forests play as reserves of numerous animal and plant species. Some of these effects have been utilized for a long time. This applies mainly to soil-fixing effects in areas subject to erosion or leaching (soil rehabilitation in mountain areas and protection of coastal dunes in France since the middle of the 19th century). The second category concerns effects of forested areas on landscapes or as places of recreation (walking, collecting forest fruits, ...).

TYPES OF GOODS	NATURE OF SERVICES	EXTENT OF EFFECTS	POPULATION CONCERNED
◆ **Ecological**			
Physico-chemical (soils, water, air)	indirect use (effects on other environmental goods)	local (soils, water) not local (air)	residents* entire society
Biological (biodiversity)	deferred uses (for oneself or for future generations)	not local	entire society
◆ **Amenities**			
(recreation, landscape)	direct use	local	residents*

* *In this context the term "residents" includes all individuals who regularly (inhabitants) or occasionally (tourists, passers-by) benefit from the environmental services of a forest.*

Photo (p. 82, top): Pascale Inzérillo
Photo (p. 82, below): Fawn. Photo: L. Barbier

Photo (p. 83): Hubert Robert (1733-1808). View of the gardens of Versailles on the Green Carpet. Detail left lower corner, group of loggers at rest with travelling merchants. Photo: © G. Blot - RMN

It is evident that many of the non-market forest services are not immediately consumed and are *a priori* of benefit to a large portion of the population which is, however, difficult to define. It is not surprising that only for few elements it is possible to assess the value society

assigns to them. The intensive, frequently emotional treatment of some particular issues in the mass media (notably discussions about a few animal species) and the existing information deficit add to these difficulties of assessment. Moreover, to most people forests are still "natural" areas and collective goods that cause a strong feeling of symbolic ownership although they represent cultivated and exclusive areas even when they belong to public-law owners (State, territorial authorities). Forests seem to **manifest man's "longing for nature",** a result of our extremely artificial ways of life. Finally, the vast majority of French forests are multifunctional areas simultaneously providing marketable goods and several non-market services, which may prove to be antagonistic (for instance, tourism and protection of fauna and flora). In most cases forests constitute **multiple-use territories**, which makes the choice of management practices an even more sensitive issue.
However, it should be pointed out that the forest management practices that are usually applied interfere less with the environment than is sometimes maintained. For example, more than two thirds of the French national forests have been registered as natural landscapes of particular ecological value for animals or plants (ZNIEFF). Even in cases of relatively intensive silviculture, forest management has proved to affect the environment much less than most other activities of production or consumption. In any case forest management never causes severe stresses, but, on the contrary, procures certain services.

Management of non-market forest services is today mostly effected in accordance with specific regulations, or it is taken over by the State. In 1994 public authorities assigned 780 million francs to activities carried out by the Office National des Forêts in connection with soil conservation (mountains, dunes), biotope conservation (biological reserves), and public access. If the management of non-market forest services proceeds in accordance with regulations, this entails expenses for society, either in terms of direct effects or through reduced production for the market. These expenses result from a compromise between different recipients which does not necessarily correspond to the optimal equilibrium desired by society. It will be one of the important missions of research to progressively furnish biological elements and economic objectives that allow optimum support in decision-making processes of that field.

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4 Agroforestry: a New or Revised Scenario

Agroforestry can be defined as a complex land-use system which combines trees or other woody perennials and crop or animal production on the same unit of land. Many traditional agroforestry systems are being used all over the world, including fodder-trees or multi-purpose trees, live hedges, intercropped fruit trees, improved fallows with shifting cultivation, home gardens, windbreaks, forest grazing, etc.

Mediterranean silvopastoral systems. Sheep farmers in the Buëch (Southern French Alps) use the thinned stands of pubescent oak (*Quercus pubescens* Willd.) for a late spring grazing.
Photo (p. 84): M. Etienne

In "developed" countries, advances in agriculture and agronomic sciences have led to intensive monocultures and to a clear separation of different productions. To allow a better control of natural regeneration, silvicultural management suppressed grazing in forests and oriented itself to dense high-forests to produce commercial timber. Consequently, traditional systems, which were considered low in productivity, became uncommon.

However, unreasonable development of intensive monocultures sometimes led to degradations of the environment. In several cases land consolidation in the bocage landscape of Bretagne aggravated the damage caused by water and wind erosion; excessive prohibition of grazing in the Mediterranean forests in connection with important rural decline favoured the development of a highly combustible shrub vegetation; intensified agriculture provoked in many places problems of water pollution by excessive nitrate concentrations,...

On the other hand, modern agricultural systems often require large amounts of input (fertilizers, pesticides, herbicides), which increases the production costs and causes environmental risks.

Various traditional and modernized forms of agroforestry and the novel practices which are being developed might offer solutions for the multiple demands society has today both with respect to agricultural and environmental policy.

Although advances in basic and applied research favoured the development of disciplines that permitted a deeper knowledge of either of the two, the sciences of synthesis, which progressed less rapidly, are at present increasingly concerned with enhancing complex systems like agroforestry. Agroforestry research has been conducted for about twenty years, mainly in tropical regions. Initially, it concentrated on the characterization of traditional agroforestry systems.

At present, research is directed towards the understanding of the functioning of agroforestry systems and their economic and ecological impacts as well as towards the development of systems adapted to the current socio-economic constraints.

In Europe, and particularly in France, agroforestry systems in the broad sense comprise four types:

- rangeland or forest grazing;
- trees on agricultural plots, either on grazed pasture or with crops;
- hedges;
- "farm" forestry[1].

Research results

Agroforestry systems

Thanks to their diversity and adaptation ability agroforestry systems can be the driving forces of sustainable development; but this requires joint management of all their elements.

There are certain poorly managed agroforestry systems which can cause environmental damage, e.g. problems of erosion caused by overgrazing in forested ranges, which, in arid zones or in the Mediterranean region, are even today very difficult to manage. An analysis of the failures shows that, in most of the cases, such failures were due to the omission of one or several elements.

Overgrazing in some silvopastoral systems of the southern Mediterranean is essentially due to the impossibility of controlling the herds and the forest at the same time. The large number of persons involved in such systems, coming from different backgrounds and usually having contradictory objectives (mostly breeders and forest managers), makes global management extremely difficult and each participant acts according to his own interests. While breeders try to find the best food resources for their herds, foresters seek the optimum protection of forests. However, an important part of the resource is located in the forest; if there is no relevant agreement, many breeders can put large herds out to graze under the trees, which will cause damage by browsing, de-barking, trampling, eventually leading to erosion problems. On the other hand, prolonged closure of forests against grazing favours the development of underbrush; the latter will rapidly become highly combustible and, due to the lack of resources, will lead to social conflicts with breeders.

Research conducted in realistic size in large forest areas of the French Mediterranean region showed that, with a good forest management which takes into account all partners, it is possible to obtain sustainable silvopastoral systems that are satisfactory for the forest and land managers, for the farmers, and for the many other users of the forest: hunters, walkers, bee-keepers, neighbouring owners, and the groups in charge of fire prevention. In such systems the biological and technical aspects are important, but the social, or even the psychological aspects are decisive. A silvopastoral system cannot be sustained if it represents a simple juxtaposition of the interests of breeders and foresters; it requires that all participants are ready to consider the whole and to take into account all partners in their initiatives. As a result, several types of silvopastoral systems have been implemented, associating various partners: livestock farmers established in public forests managed by the French Office National des Forêts (ONF); groups of farmers having their herds graze on networks of forested firebreaks managed by intercommunal syndicates; joint management of the natural ecosystems in regional wildlife parks by the ONF, the representatives of the municipalities,

[1] Forest stand which is part of a farm.

farmers, etc. The establishment of all these systems necessitated important initiatives among which research played a crucial role.

Relations between trees, herbs and animals

A silvopastoral system has three major biological components: trees, herbs, and animals. All these components are in positive or negative interaction. The manager's task is to favour the first and to reduce the effect of the second.

During the first stages of their development, trees are very sensitive with respect to competition from herbaceous plants and potential animal damage. The means of reducing competition, or the sensitivity towards competition, have been investigated:

- various mechanical or chemical techniques of grass control or techniques of mulching to eliminate herb competition;
- various types of protection against animals, e.g. individual tree-shelters.

Dry cattle resting on a firebreak in the mountain range of the Maures (Provence).
Photo (p. 86): M. Etienne

When trees have passed that developmental stage, the duration of which is species- and site-related, they can themselves influence the growth of the herbs. As long as trees are sufficiently spaced to permit the penetration of light (closure of the canopy <70%), the most important action of trees on herbs is a phenological shift which can be particularly beneficial for the nutrition of herds:

- In early spring the growth of grass can be retarded, but at a time when the fodder supply is usually sufficient outside forests.
- At the end of spring, when herbs and grass begin to be sparse and to dry up in the pastures, the presence of trees offers a shelter which allows the maintenance of a herbaceous layer for several weeks.
- At the beginning of winter the shelter of the trees still allows some growth of herbs at a time when in the open land temperatures can become negative.

In contrast, dense forest stands eliminate any fodder resource; they can only serve as shelters for the animals when climate conditions are unfavourable. Through the reduction of heat losses, the shelter effect of trees on animals can considerably improve the meat yield.

When the natural vegetation of forests is not sufficiently enticing or nourishing, it may be necessary to improve the pastures. This can be effected through oversowing fodder species adapted to the environmental conditions, in particular to the shade of the trees, fertilizing, and maybe manual or mechanical removal of brushwood. Some fodder species, such as subterraneum clover (*Trifolium subterraneum)*, have proved well adapted. Others, like "Maku" lotus, which is commonly used in New Zealand, are still being studied under the conditions prevailing in France.

It must be noted that every technical intervention can have a short-term beneficial effect, but that this effect will fade very quickly unless it is followed up over the long term. An experiment conducted for a period of ten years in a natural forest showed that it is only after the first five years that the effect of the improvements, the costs of which decrease regularly as a result of the preceding activities, becomes really sustainable. The maintenance cost of a well managed silvopastoral plot will become lower than the cost of the classical mechanical or manual brushwood removal which is otherwise required for fire prevention.

The control of vegetation is indispensable for the nutrition of the herd. Similarly, the behaviour of the latter must be adapted to the presence of trees. To avoid damage, training of the herd can be very useful. Animals that are used to the situation will cause less damage than young stock newly placed in a tree environment. On the other hand, if fodder resources are insufficient, the trees themselves can become a source of nutrition, which is why it is in any case important to adopt a global management of the system.

The trees
Advances in silviculture and forest genetics favoured the plantation of species of high production capacity, in particular for high-quality timber. With a farmer in the vicinity, agroforestry or farm forestry permits relatively intensive forest management, which approaches "tree cultivation". The continued care of individual trees is, among other things, promoted by formative pruning, which is necessary to obtain high-quality timber, or by phytosanitary control. So the combination of efficient genetic material and the presence of a manager who has an interest in the trees and in their culture can ensure the longevity of the system.

Biogeochemical cycles
Intensification of agriculture has in some cases caused pollution of groundwater as a result of elevated concentrations of mineral elements, such as nitrogen, or phytosanitary products. In order to remedy this situation trees or forests are often called upon as "antipollutants". Studies of the mineral elements of the soil, plants, and the atmosphere indicate that the amounts mobilized by trees are usually very small compared to the quantities involved in the entire ecosystem. Through the diversification of activities on agricultural land and the reduction of very intensive agricultural practices, agroforestry itself has a positive overall effect. Nevertheless, an agroforestry system can only to a very small degree contribute to the purification of elements from intensive cultivation in the vicinity.

The same is true for the sequestration of carbon. With respect to atmospheric carbon dioxide concentrations biomasses in agroforestry play a positive, though a negligeable role in reducing the greenhouse effect caused by industrial activities. By reducing the intensification, good agroforestry practices can reduce the input of fertilizers, pesticides, etc., and can thereby partially contribute to a reduction of the pollutant emissions.

Erosion
In view of the catastrophes which occurred as a consequence of massive land-use zoning in certain regions the effects of hedges on the environment have been comprehensively studied. The effects on the circulation of water and particles on the surface and in the soil have therefore been well quantified. In addition, the microclimate in the regions of the "bocage" landscape type or around windbreak networks has been well quantified. Results indicated among other things that the optimum structure of a windbreak should be slightly porous so as to reduce turbulence. Moreover, these results also provided a means to determine with great accuracy the area protected by a hedge according to the latter's height and structure.

The future
Thus far, research has enabled us to characterize and to basically understand the functioning of traditional agroforestry systems, and to improve them. Now, research is developing in three complementary directions:

- improvement of our basic knowledge about the competition between elements of the system;
- synthesis of the knowledge that has been acquired in these particularly complex systems, especially by the development of models;
- development of new agroforestry practices adjusted to the demands and constraints of present society.

Competition phenomena

As mentioned above, research has started studying the biological interactions between herbs, trees, and animals. However, even if knowledge of these phenomena is improving, their quantification is still lacking accuracy. This is why scientists continue to study the distribution of light on agroforestry plots, both quantitatively and qualitatively, and the effect of light on temperature which, in turn, influences respiration, transpiration, and phenology. The competition for water and mineral elements takes place mostly in the soil and research on the functioning of root systems is developing.

Trial to introduce fodder plants within a thinned spruce stand in Auvergne, France.
Photo (p. 88): M. Etienne

System analysis

Because of the complexity of agroforestry systems, the interactions between elements can have retroactive effects which are difficult to grasp in a study of the respective individual components. Better understanding can be achieved with the help of models which incorporate all phenomena. Such models, which are based on biological functioning, are currently being developed.

In agroforestry systems, socio-economic aspects have for a long time been decisive, but research is now oriented to the coupling of biophysical and economic models. The integration of agroforestry plots in areas that are used for crop or livestock farming will modify the practices applied by farmers and may necessitate structural changes. Such changes will have global effects, i.e. not only on the respective farm, but on the landscape. These phenomena, which are becoming increasingly significant today, are under investigation.

New forms of agroforestry

The progress made in gaining knowledge on traditional systems enables us not only to improve these old systems and to orient them towards the objectives of managers or communities, but also to propose new systems that are better adjusted to present-day objectives.

The experiment in the Mediterranean silvopastoral systems directed to fire prevention permitted the testing of systems adapted to modern forestry of more temperate areas. Advances in genetics allow forest stands to be much less densely stocked than in the past, causing the development of ground vegetation; the latter can be managed together with animal husbandry, which makes it possible to practice wood and animal production at the same time under optimum conditions.

In a context of rural decline an approach which is currently being tested consists of planting trees for high-quality timber on agricultural plots together with crops or pasture. Thus, agricultural management becomes more diverse and the plot has a longer-term economic objective.

If they are optimally managed, agroforestry systems can respond to a series of different, sometimes contradictory demands of contemporary society. Knowledge has enabled us to modernize traditional practices which, although formerly considered antiquated, have proved well adapted to the demands of sustainability, and to develop even better adapted practices on the basis of those traditional systems.

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Conclusion

At the moment of closing this publication the reader will certainly have perceived the complexity of the notion of "sustainable forest management" and the diversity of scientific fields that support this concept and that are covered by INRA research teams and by its partners. The very first lines of this publication pointed out that the necessity to reduce its volume forced us to do without some important topics that also have a share in sustainable management. Moreover, some subjects will have been presented rather from the cognitive point of view of research than from the point of valorization.

However, if we make a quick summary of the research work which INRA has conducted during the past 25 years, alone or with others, notably of those research activities that really meant a breakthrough for innovations in sustainable forest management, progress has been made especially in the following fields:

- characterization of environments and of their capacities, and knowledge of the ecological needs of species;
- knowledge on genetic diversity of forest trees and on the conditions of utilizing or conserving such diversity, and production of improved varieties including a better **adaptation** to environmental conditions;
- means to facilitate decisions in silviculture and forest planning: growth models;
- wood quality control by silviculture (beech); prediction of the technological value of local or regional resources;
- elucidation of the main (edaphic, climatic, atmospheric) causes of forest decline;
- biological (directed mycorrhization) and physico-chemical (melioration and fertilization) methods to control the nutrition of trees;
- environmentally acceptable methods to control insect pests or pathogenic micro-organism populations;
- knowledge about the risks of fire and methods of fire control (prescribed burning).

Also the large dimension of the field to be covered and the limited public research means available to INRA and other institutes explain why major topics have been treated only briefly or insufficiently. Basics, which could support **expertise**, have thus not been included.

In the context of **biodiversity** and forest management, for instance, the "naturalistic" approach has obviously prevailed so far, resulting in a limited involvement of INRA research teams. Now, a particular effort is required with respect to the **functional** aspects of biodiversity, an approach which will be indispensable if forest managers need to have access to relevant criteria for their "planning".

Quality and quantity of **water resources** depend largely on forest covers, but this relationship is not yet well known. More generally speaking, interrelations of forest ecosystems with neighbouring ecosystems (landscape ecology) are among the topics that have not yet been comprehensively treated.

Serious trend studies show that **plantation forestry** will be an important issue in the future. Its ecological and economic viability encourages further research efforts. Among the aspects that have been discussed only marginally in the articles of this publication, mention should be made of the following:

◆ selection for **adaptive traits**: water use efficiency, drought resistance; marker-assisted selection opens new opportunities;
◆ improvement of **wood quality** by genetic and silvicultural means with a view to providing a **competitive** resource for industry.

Promoting wood and its competitiveness compared to other materials includes proving its "environmental superiority". Comparative **life cycle analyses** taking into account the energy cost and all environmental factors: emission of fossile carbon, carbon sequestration, water and nitrogen cycles, utilization of input,... from the elaboration of the material (which, for wood, is in the forest) until its recycling will thus become a topic of high priority.

Finally, the humanities and social sciences, notably those among them that have to do with forest economy and forest policy, or with forests in landscape management, have experienced little development in France; they would clearly merit a more holistic effort.

Finally, how can I not point out that all these issues and their large dimensions necessitate a continued effort of cooperation. Several cooperation structures exist: GIP ECOFOR (Public Interest Groupings on Forest Ecosystems), diverse Scientific Interest Groupings (GIS). Their action needs sustained support.

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Yves BIROT

Sustainable Forest Management : Contribution of Research

Contents

- Facts and figures on the French forest

Preface

- Sustainable forest management :
a strong demand by society to the scientific community *(Y. Birot)*

Forests and Climates

- Interactions between climates and forests at the local, regional, and global levels *(G. Aussenac)*
- Forests faced with increasing atmospheric carbon dioxide *(J.M. Guehl)*
- Forests and water : relations between forest ecosystems and water resources *(G. Aussenac)*

Forests and Their Soils

- How sustainable is soil fertility? *(J. Ranger)*
- Assuring sufficient nutrient supply for trees - a basic condition of sustainable forests *(J. Garbaye, M. Bonneau)*

Biodiversity

- How to characterize the diversity of ecosystems? *(M. Becker)*
- The genetic diversity of forest trees : a prerequisite of sustainable forest management *(A. Kremer)*
- Trees and forests : living with insects and microorganisms
  1 ◆ Insects *(H. Jactel)* 2 ◆ Microorganisms *(J. Pinon)*
- Heterogeneous stands - an ideal objective? *(A. Franc)*

Dynamics of Forests and Stands

- Management of forest stands *(J.F. Dhôte)*
- The productivity of European forests is increasing:
a fact of considerable consequence *(M. Becker)*

Man and His Forests

- A tool of sustainability : forest planning *(J.L. Peyron)*
- Forests and forest industries, sources of employment *(D. Normandin and J.L. Peyron)*
- Forests as producers of non-market goods and services *(D. Normandin)*
- Agroforestry : a new or revised scenario *(D. Auclair)*

Conclusion *(Y. Birot)*