Sustainable development of mountain areas depends on recycling of resources rather than their extraction and eventual discard following use, and on turning from 'end-of-pipe' thinking to forward-looking approaches to product and process design. There is a big potential for this shift in thinking to develop sustainable management practices for mountain forest ecosystems.

See also: **Harvesting**: Forest Operations in the Tropics, Reduced Impact Logging; Roading and Transport Operations. **Hydrology**: Snow and Avalanche Control; Soil Erosion Control. **Operations**: Forest Operations Management; Logistics in Forest Operations. **Site-Specific Silviculture**: Silviculture in Mountain Forests.

Further Reading

Aber J, Christensen N, Fernondez I, *et al.* (2000) *Applying Ecological Principles to Management of the U.S. National Forests*. Washington, DC: Ecological Society of America.

Heinimann HR (1999) Ground-based harvesting technologies for steep slopes. In: *International Mountain Logging and 10th Pacific Northwest Skyline Symposium,* 28 March–1 April 1999, Corvallis, pp. 1–19. Corvallis, OR: Oregon State University.

Heinimann HR (2000) Forest operations under mountainous conditions. In: Price MF and Butt N (eds) *Forests in Sustainable Mountain Development: A State of Knowledge Report for 2000*, pp. 224–230. Wallingford, UK: CAB International.

ISO (1999) *Environmental Management: Environmental Performance Evaluation – Guidelines*. Geneva, Switzerland: International Standards Organization.

Konuma J-I and Shibata J-I (1976) Cable logging systems in Japan. *Bulletin of the Government Forest Experiment Station* 283: 117–174. (in Japanese)

Price MF and Butt N (eds) (2000) *Forests in Sustainable Mountain Development: A State of Knowledge Report for 2000*. IUFRO Task Force on Forests in Sustainable Mountain Development, Wallingford, UK: CAB International.

Samset I (1985) *Winch and Cable Systems*. Dordrecht, The Netherlands: Martinus Nijhoff.

Schueler TR (2000) The importance of imperviousness. In: Schueler TR and Holland HK (eds) *The Practice of Watershed Protection*, pp. 100–111. Ellicott City, MD: Center for Watershed Protection.

UN (1992) *Managing Fragile Ecosystems: Sustainable Mountain Development*. Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3–14 June 1992. Available online at http://www.un.org/esa/sustdev/documents/agenda21/english/agenda21chapter13.htm

HEALTH AND PROTECTION

Contents

Diagnosis, Monitoring and Evaluation

M Ferretti, LINNÆA ambiente, Florence, Italy

Introduction

Over the last 30 years forest health became a popular issue together with the concern about acid rain, air pollution, and climate change. Terms like forest decline, and the German 'Waldsterben' (forest death) and 'Neuartigen Waldschäden' (new type of forest damage) became frequent in scientific literature as well as in popular media. This concern resulted in an unprecedent effort to study and monitor forest health. Since then the situation has evolved and now forest health diagnosis and monitoring is relevant to a much broader area of interest, including recent (e.g., climate fluctuation and change, biodiversity, sustainable resource management) and 'traditional' issues (e.g., pests, diseases, forest fire). Broadly, forest health diagnosis, monitoring, and evaluation aims to identify forest health problems, track forest health status through time and identify its relationship with environmental (biotic and abiotic) factors. It embraces a variety of activities and involves several topics and scientific disciplines. Forest health diagnosis, monitoring and evaluation is addressed here in terms of (1) definitions, factors affecting forest health and most known forest health declines in the world, (2) methods of diagnosis, monitoring, and evaluation, and (3) relevance and applications.

Forest Health

Importance of Definitions and Concepts

The definition of forest health is important as it provides guidance for the operational steps of the monitoring, e.g., the choice of the most suitable indicators (see below). A problem is that forest health still lacks a consensual definition. In most cases, definitions are based on the expectations of particular interest groups: a person interested in commercial timber (e.g., the owner of a pine plantation) would have a 'utilitarian' perspective (wood production), while a natural reserve manager would consider a more 'ecological' approach, taking into account, the wildlife, the preservation of species and habitat diversity, and the ecological processes. According to the approach, definitions may refer to different entities (individual trees, the stand, the forests, or the entire forest ecosystem) and consider different indicators (e.g., from injury to individual trees to the incidence and severity of pests, diseases, and mortality rates, presence and abundance of exotic species, growth rate, specific and structural diversity, fluxes of energy and chemicals from the atmosphere, and change in soil properties). This has clear operational consequences for the design of a monitoring program. Recent definitions of forest health as well as the criteria and indicators for sustainable forest management (SFM) consider key words such as 'long-term sustainability,' 'resilience,' 'maintenance' of 'ecosystems structure and functions,' 'multiple benefits and products.' Overall, this suggests that the health of individual trees is somewhat different from the health of the forest: although the detection of individual unhealthy trees is important as they may be signaling the occurrence of problems that may become serious in the future, it is important to consider that death of trees is as important as birth and growth to the vitality of forests. Thus, a healthy forest ecosystem may include unhealthy or dead trees. This means that forest health is no longer thought to be a property relevant to individual trees and stands but to forest ecosystems. In the remainder of this article the emphasis will be on forest and forest ecosystem health rather than on tree health, although reference to tree health will be made under specific chapters.

Factors affecting Forest Health

The health of forests can be subjected to many stressors (**Figure 1**) that may affect individual trees as well as the entire ecosystem.

Recognizing the stressor(s) of concern and its expected mechanism of action and pathways is important as it may help considerably the choice of the indicators to be adopted for monitoring. Natural and anthropogenic factors may act as stressors, singly and/or in combination. In addition, anthropogenic factors may substantially alter the occurrence and severity of natural ones. The role of the various stressors may change, and – according to the situation – the same factor may have a different role at a different time in the sequel of steps of a progressive or reversible decline. For example, air pollution is known to cause direct damage and even death of forest trees at very high concentrations. At low concentration, however, air pollutants may just weaken the resistance of forest trees to insect attacks; in this case a subsequent attack of an insect may cause the death of the trees that were already weakened by the exposure to pollutants. Emphasis on the interaction between different factors and on their ordering according to the peculiar site condition is also a convenient framework to identify the scenario of concern and to proceed toward a diagnosis.

Forest Declines

Instances of poor forest health have been documented worldwide. **Tables 1** and **2** report the best-known ones. Reports are almost always based on the evidence of the decline of forest trees and cover a wide array of ecological situations and forest species. Declines can occur as natural processes and as a result of anthropogenic activity.

Natural forest declines Natural forest declines (**Table 1**) include those related to the action, singly or in combination, of 'traditional' factors (e.g., pests, diseases, climate perturbations, nutrient disturbances, vegetation successional dynamics, and competition). Natural forest declines may involve individual trees of a given species at a certain site, an individual species throughout its range or within an ecosystem, and multiple species. In many cases, the cause of the decline is not obvious as there are complex interactions that need careful examination according to clear diagnostic criteria (see below).

Human-induced forest declines Different human activities may affect the health of forest ecosystems: fire and mismanagement are probably the most obvious ones. However, much work on forest decline concentrated on atmospheric pollution. Traditionally, a distinction is made between the decline of forest trees around pollution sources and those declines for which the effects of nonacute, background pollution level are advocated.

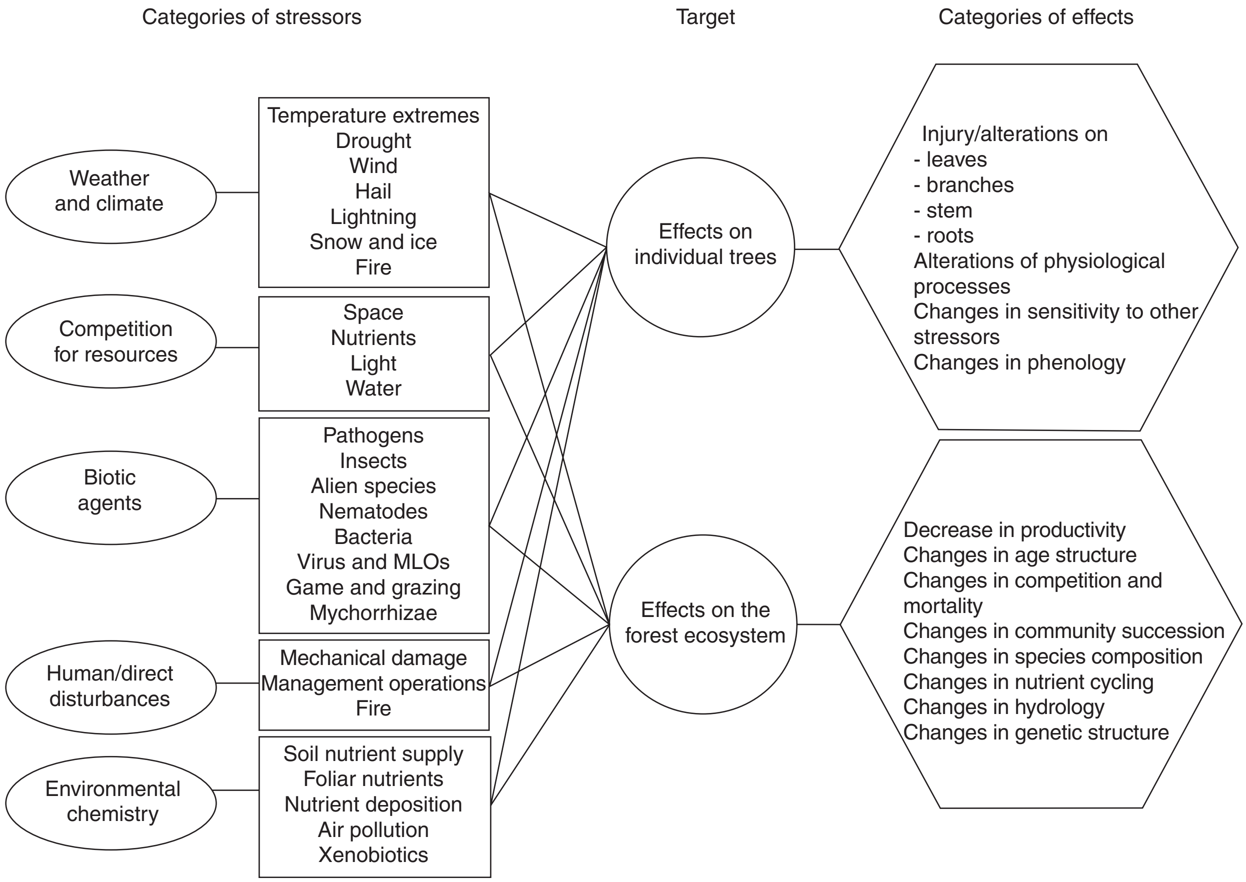

Figure 1 Stressors that may affect forest trees and ecosystems causing various effects. MLOs, mycoplasma-like organisms. Compiled on the basis of Committee on Biological Markers of Air Pollution Damage in Trees (1989) *Biological Markers of Air Pollution Stress and Damage in Forests*. Washington, DC: National Academy Press.

Declines around pollution sources Declines around pollution sources usually involve a distinct spatial pattern, with the most damaged areas being located close to the pollution source. Here, acute foliar injuries are almost always present; they are caused by concentration of pollutants that are directly toxic to plants. As the distance from the source increases, chronic injury and/or indirect effects may occur. The best-known cases of declines around pollution sources for which conclusive studies have been reported are shown in **Table 2**. Tree mortality and/or damage have also been reported around sources of pollution in Europe (Arc Valley, Maurienne, France; Øvre Årdal, Norway; Leanachan Forest, Fort William, Scotland, UK) and evidence for other cases in the Kola Peninsula of China, Korea, and the former USSR is emerging.

Forest declines and regional air pollution Well-documented cases of regional forest decline that can be attributable to air pollution are limited (**Table 2**). This reflects the inherent complexity of research into cause and effect; with few exceptions, at the regional scale the concentration and deposition of air pollutants is usually not enough to cause direct injury to the trees; rather, secondary effects (e.g., soil mediated) can occur, but they usually are less obvious and involve a suite of other factors. Examples of regional effects of air pollutants include the effects of ozone (O_3) on the decline of *Abies religiosa* (Desierto de Los Leones, Mexico) and on the pines (mostly *Pinus jeffreyi* and *P. ponderosa*) in the western USA. In Europe, the damage to Norway spruce (*Picea abies*) in the area between the northern Czech Republic, south Poland, and southeast Germany due to sulfur dioxide (SO_2) is the most widely known example. In several other cases, air pollution was suspected to be involved but evidences were not conclusive.

Methods in Forest Health Diagnosis, Monitoring, and Evaluation

Diagnosis

Identifying whether the forest of concern is healthy or not and, if unhealthy, what could be the cause of

Table 1 Cases of tree and forest declines

Geographic area	*Region/country*	*Species/forest*	*Early record*
Africa	Benin	*Casuarina equisetifolia*	—
	Botswana, Zambia, Zimbabwe	*Pterocarpus angolensis*	1950s
	Gambia River	Assorted species in mangrove forests	—
	Côte d'Ivoire	*Terminalia ivorensis*	1970
	Sahel	*Azadiracta indica*	1990
	South Africa	*Ocotea bullata*	—
	South Africa	*Pinus radiata*	—
	Sudan	*Acacia nilotica*	1930
	Uganda	Assorted species	1984
	Tanzania	*Pinus patula*	—
Asia	Bangladesh	*Heritiera fomes*	1915
	Bhutan	*Abies densa*	1980
	China	*Pinus massoniana*	—
	China	*Pinus armandi*	—
	India	*Shorea robusta*	1907
	Japan	*Cryptomeria japonica*	1970
	Japan	*Abies veitchii, A. mariesii*	—
	Sri Lanka	*Calophyllum* sp., *Syzigium* sp.	1978
	Sri Lanka	Assorted species in montane rainforest	1978
Europe	All regions	*Quercus* spp.	1739
	All regions	Various species	1980s
	Central and Southern Europe	*Abies alba*	1810
	South and Central Sweden	*Pinus sylvestris*	1980s
	South and Central Sweden, Central Europe	Norway spruce	1889
	Spain, France, Germany, Switzerland, Italy	*Fagus sylvatica*	—
Latin America and the Caribbean	Argentina	*Austrocedrus chilensis*	1948
	Argentina	*Nothofagus* (forests)	—
	Brazil: Minas Gerais, Rio Doce valley	*Eucalyptus* spp.	1974
	Chile	*Pinus radiata*	—
	Chile	*Nothofagus dombeyi*	—
	Chile	*Nothofagus* spp.	—
	Colombia	*Quercus humboldtii*	—
	Colombia	*Eucalyptus globulus*	—
	Galápagos Islands, Ecuador	*Scalesia pedunculata*	1930s
	Mexico	*Abies religiosa*	1981
	Mexico	*Pinus hartwegii*	1981
	Peru	*Eucalyptus globulus*	1983
	Uruguay	*Celtis spinosa*, *Eucalyptus* spp., *Quercus* spp., *Satia buxifolia*, *Schinus* spp.	1990
North America	'Inland empire'	*Pinus monticola*	1927
	Alaska	*Chamaecyparis nootkatensis*	1880
	Eastern Canada and northeast USA	*Betula* spp.	1930
	Eastern Canada and northeast USA	*Acer saccharum*	1970s
	East USA	*Quercus* spp.	1900
	East USA	*Fagus grandifolia*	—
	East USA	*Picea rubens*	1970s
	East USA	*Abies balsamea*	—
	Northeast USA and Canada	*Fraxinus pennsylvanica*	1930s
	South California	*Pinus ponderosa*	1950s
	South California	*Pinus jeffreyii*	1950s
	Southern USA	*Pinus echinata*	1930
Pacific region	Australia	*Eucalyptus marginata*	1920
	Australia	*Eucalyptus* spp.	—
	Australia, New Zealand	*Pinus radiata*	1966
	Hawaii	*Metrosideros polymorpha*	1970s
	Hawaii	*Acacia koa*	1970s
	New Zealand	*Nothofagus* spp.	1950
	New Zealand	*Metrosideros* spp., *Weinmannia racemosa*	1920
	New Zealand	*Cordyline australis*	1980
	Norfolk Islands	*Araucaria heterophylla*	1970
	Papua New Guinea	*Nothofagus* spp.	—

Table 1 Continued

Geographic area	*Region/country*	*Species/forest*	*Early record*
	Queensland	*Avicennia marina*	—
	Tasmania	*Eucalyptus delegatensis*	1960s
	Tasmania	*Eucalyptus obliqua*	1960s
	Tasmania	*Eucalyptus regnans*	1960s
	Tasmania	*Eucalyptus nitida*	1960s

Source: Data from Ciesla WM and Donabauer E (1994) *Decline and Dieback of Trees and Forests: A Global Overview*. Rome: Food and Agriculture Organization; Innes JL (1993) *Forest Health: Its Assessment and Status*. Wallingford, UK: CAB International.

Table 2 Cases of tree and forest declines related to air pollution

Type	*Geographical area*	*Site/region/country*	*Species or forest type involved*
Decline and dieback around pollution sources	Europe	The Rhone valley, Switzerland	*Pinus sylvestris*, *Abies alba*
		San Rossore, Pisa, Italy	*Pinus pinea*
	North America	Copper Basin, Tennessee, USA	*Mixed hardwood forest*
		Redford, Virginia, USA	*Pine forest*
		Spokane-Mead, Washington, USA	*Pinus ponderosa*
		Sudbury, Ontario, Canada	Various vegetation types
Declines related to regional air pollution	Europe	East Germany – North Czech Republic – South Poland	*Norway spruce*
	Latin America	Desierto de Los Leones, Mexico	*Abies religiosa*
	North America	Western USA	*Pinus jeffreyi*
			Pinus ponderosa
			Various other species
Declines with unclear relation to air pollution	Europe	Central and South Europe	*Abies alba*
		Greece	*Abies cepha lonica*
		Southwest Sardinia, Italy	*Pinus pinea*
		North and central Europe	*Picea abies*
		North and central Europe	*Pinus sylvestris*
		The Netherlands	*Pinus sylvestris*, *Pseudostuga menziesii*
	North America	Eastern USA and Canada	*Pinus strobus*
			Fraxinus nigra
			Fraxinus americana
			Betula papyrifera
			Acer saccharum
			various hardwoods
			Pinus sp.
			Abies balsamea
			Picea rubens
			Abies fraseri
		Southeastern USA	*Pinus taeda*
			Pinus echinata
			Pinus elliottii

Source: Data from Innes JL (1993) *Forest Health*: *Its Assessment and Status*. Wallingford, UK: CAB International.

the observed unhealthy condition can be a difficult task. Acute injury on trees is easy to diagnose; on the other hand, nonacute, subtle effects on trees and/or ecosystems can be difficult either to identify in the field or to ascribe to a particular cause. In many cases, different factors may interact (see **Figure 1**); depending on the case, an accurate diagnosis needs careful examination of the various potential causal agents and the use of diagnostic criteria and tests.

Diagnostic criteria Several criteria have been developed that can provide a convenient framework for cause-and-effect research and for diagnostic purposes (**Table 3**). These criteria are based upon traditional human and plant pathology and have been developed further to take into account the complexity of certain situations. For example, the criterion of strong correlation implies that both cause and effects can be identified and measured and this is not always

Table 3 Diagnostic criteria for forest health diagnosis

Koch (1876)	*Committee on Biological Markers of Air Pollution Damage in Trees (1989)*	*Schlaepfer (1992)*
The infecting agent must be present in all patients showing symptoms of disease	Strong correlation	Detection and definition of the problem
The infecting agent must be isolated from the patient	Plausibility of mechanism	Description of magnitude, dynamics, and variability of the phenomenon
The infecting agent must produce the disease under controlled laboratory condition	Responsiveness or experimental replication	Detection of associations in space and time between the symptoms and the hypothetical causes
	Temporality	Experimental reproduction of the observed symptoms
	Weight of evidence	Explanation of mechanism
		Validation of the models

Source: Data from Koch R (1876) Untersuchung über Bacterien, V. Die Aetiologie der Milzbrand-Krankheit, begründet auf die Entwicklungsgeschichte des Bacillus anthractis. *Beitrage zur Biologie Pflanzen* 2: 277–310; Committee on Biological Markers of Air Pollution Damage in Trees (1989) *Biological Markers of Air Pollution Stress and Damage in Forests*. Washington, DC: National Academy Press; Schlaepfer R (1992) *Forest Vegetation and Acidification*: *A Critical Review*. In: Schneider T (ed.) *Acidification Research*: *Evaluation and Policy Applications*, pp. 27–44. Amsterdam, The Netherlands: Elsevier.

possible: the physiologically active dose of an air pollutant (the fraction of the pollutant present in the atmosphere that enters the plant through the stomata) cannot be measured as a routine procedure e.g., during large-scale monitoring. In addition, one must consider that correlation does not necessarily mean causation, and this is the reason for which the other criteria in **Table 3** need to be considered.

Diagnostic procedure for individual trees While a forest is more than the sum of the trees present, the diagnosis at individual tree level remains important for different situations, including commercial plantations and recreational forests. Individual tree diagnosis is supported by a number of textbooks that provide useful identification keys, practical examples, pictorial atlases as well as the approach for a sound diagnostic procedure. Tree-related diagnosis is also related to pathology and entomology (*see* **Entomology**: Bark Beetles; Foliage Feeders in Temperate and Boreal Forests; Sapsuckers. **Pathology**: Diseases affecting Exotic Plantation Species; Diseases of Forest Trees). A suitable diagnostic procedure involves the collection of preliminary information (species identification, site condition, recent tree history) and close examination of the case in hand. A careful examination of the aerial parts of the trees is essential to identify and describe the symptoms and injuries together with the location in relation to existing knowledge about the species being considered. If the case in hand matches the known description, confirmatory evidence is sought and – if found – the diagnosis is achieved, its reliability being dependent on the weight of evidence. If the case in hand does not match existing knowledge, or if no confirmatory evidence is found, additional investigations have to be considered which may involve destructive sampling. In some cases the problem may remain unexplained either because the damage is too old or the evidence is insufficient for a diagnosis.

Diagnostic tests Besides the above criteria and procedure, careful diagnosis may involve the use of diagnostic tests. Biochemical, physiological, and morphological tests are available (see the section on 'Indicators'). With few exceptions, diagnostic tools involve complex sampling procedures and laboratory analysis and can be expensive. This may limit their applicability at the large scale.

Monitoring

Definition Monitoring is a general term to identify a type of study that can be applied to several environmental resources. Monitoring can be defined as 'the systematic observations of parameters related to a specific problem, designed to provide information on the characteristics of the problem and their changes with time.' Emphasis should be placed on the connection between the monitoring and the management of the resource being considered, e.g., the monitoring is carried out to track the progress toward a management objective. The management action can be understood at local level (e.g., thinnings) or at the large scale (e.g., political negotiations to decrease pollutant deposition). Note that the emphasis on management objectives forces the monitoring designer (1) to obtain an unambiguous definition of forest health from stakeholders and (2) to establish clear conceptual and/or mechanistic models to link forest health as defined and the expected management action. These are important as effective monitoring can only be based on explicit assessment and measurement endpoints.

Two important characteristics of monitoring are its time dimension and its nature of routine, systematic and organized activity. This implies monitoring should be based on a careful design, which has to cover a series of issues (**Table 4**).

Monitoring approaches Monitoring can be carried out to obtain information about the status and trend in the spatial and temporal development of forest health over a defined spatial and temporal domain, and for cause-and-effect investigations. Forest health monitoring can be of value also in the framework of before-and-after studies but in this case it needs to be placed in the context of an experimental design.

Status and trend (extensive studies) In general, the assessment and monitoring for status and trend of forest health is carried out on regional populations of forests, with regions being small (e.g., local, subnational scale) or large (e.g., national, international scale). At the stand level, assessment of status and trend can be necessary for economically important forests and it was carried out for example in commercial pine plantations in the southeastern USA, and *Acer saccharum* forests (syrup production) in southeast Canada and the northeastern USA. In such cases, careful diagnostic approaches and specific indicators are essential. At the large scale, status and trend investigations usually concentrate on a few, easy to measure, low-cost, and sometime simplistic indicators that are measured at many sites by trained observers. However, as many observers are needed for this type of survey, their skill in forest pathology and entomology may be not always high, and – together with the indicators used and the limited time available for site visits – this can have consequences for the quality of the results. In many cases, a careful diagnosis cannot be carried out, and causes of poor forest health may remain unexplained unless the observed phenomenon is very obvious. This clearly indicates that – in most cases – large-scale monitoring programs have a role as detection monitoring, to identify problems to be investigated in more detail at a later stage. In this respect, integration between a survey approach (e.g., terrestrial and aerial surveys) and extensive and intensive studies can provide a number of benefits for detecting, diagnosing, and monitoring health problems. Status and trend surveys must allow inferences on a statistical basis. False-positive (Type I) and false-negative (Type II) errors as well as sufficient precision of the estimates of population parameters must be considered, and a statistically based sampling design is essential to ensure the success of status and trend monitoring.

Cause-and-effect (intensive studies) Cause-and-effect investigations aim to establish a relationship between stressors(s) and response(s). In the field stressors are difficult to isolate from other factors that need to be accounted for. For this reason, cause-and-effect investigations require data about a number of variables, usually referred to as stressor (independent variables, or predictors, in a statistical model), response (dependent variables), and intermediate (covariates) variables. Cause-and-effect investigations can be very expensive and usually are carried out on a limited number of selected sites. In general, sites for intensive studies are selected purposively, according to the hypothesis being tested and/or the scenario of concern (e.g., plots along gradients of pollution, age, or succession). Under some circumstances, plots can be installed as case studies: this can occur to study the effects of extreme/catastrophic events that may offer the chance for studies otherwise impossible. Although sites for cause-and-effect studies are selected on a preferential basis (thus prohibiting statistical inference), observations and measurements within sites should always be based on a sampling design.

Indicators of forest health An indicator is a characteristic that can be measured or assessed to estimate status and trends of the target environmental resource. A number of indicators can be used in forest health monitoring and the choice of the most suited ones depends on the problem being examined, the available resources, the available expertise, and the

Table 4 Design issues for a forest health monitoring program

Design issue	*Areas of concern*
Definition of the scientific problem	Users' needs and clear questions for the designers
Sampling design	Formal definition of nature, iteration, selection, and number of (sub)samples; inferences
Quality assurance	Standard methods with known performances; data reproducibility and consistency
Field and laboratory work (when needed)	Safe procedures and logistics
Data management/analysis/reporting	Proper data management, accessibility, data analysis and reporting

ecological, spatial, and temporal coverage of the investigation. Indicators can be considered according to their nature (e.g., stress, response), ecosystem compartment (e.g., atmosphere, vegetation, soil), platform used (terrestrial, aerial, satellite), and method of detection (from visual assessment in the field to biochemical analysis in the laboratory). An overview of indicators most frequently adopted in forest health monitoring programs is given in **Table 5**. It is notable that **Table 5** does not cover the zoological component of the ecosystem which is important but which is very seldomly covered in forest health monitoring. This reflects both the 'old,' tree-oriented, concept of forest health and the difference between the spatial scales used in typical forest studies (mostly based on a plot size of less than 1 ha) and those needed for e.g., bird investigations (typically more than 30 ha). Recent emphasis on

Table 5 Most common indicator categories and measurement methods

Area	*Compartment*	*Indicator category*	*Type of measurement*
Atmosphere	Air	Meteorological parameters	Instruments in the field
		Concentration of chemicals	Instruments in the field
	Wet deposition	Quantity	Instruments in the field
		Concentration of chemicals	Instruments in the field and laboratory
	Dry deposition	Quantity	Instruments in the field and laboratory
		Concentration of chemicals	Instruments in the field and laboratory
Vegetation	Trees	Species	Direct observation
		Abundance	Direct observation, inventory, remote sensing
		Diameter at breast height	Direct measurement
		Height	Direct measurement
		Tree rings	Measurement in laboratory
		Crown condition	Direct observation, remote sensing
		Chemical indicators	Instruments in laboratory
		Biochemical indicators	Instruments in laboratory
		Physiological indicators	Instruments in the field and laboratory
		Physical indicators	Instruments in the field and laboratory
		Stem condition	Direct observation
		Root condition	Instruments in the field and laboratory
		Litter fall, quantity and chemistry	Instruments in the field and laboratory
	Herbs, shrubs	Species	Direct observation
		Abundance	Direct observation
		Chemical indicators	Instruments in laboratory
		Biochemical indicators	Instruments in laboratory
	Ferns, lichens, mosses	Species	Direct observation
		Abundance	Direct observation
		Chemical indicators	Instruments in laboratory
	Fungi	Species	Direct observation
		Abundance	Direct observation
		Chemical indicators	Instruments in laboratory
Soil	Solid phase	Physical properties	Instruments in the field and laboratory
		Chemical indicators	Instruments in the field and laboratory
		Biological activity	Instruments in the field and laboratory
	Soil water	Physical properties	Instruments in the field and laboratory
		Chemical indicators	Instruments in the field and laboratory
		Biological activity	Instruments in the field and laboratory
Water	Groundwater	Chemical indicators	Instruments in the field and laboratory
	Runoff water	Chemical indicators	Instruments in the field and laboratory
	Lakes	Chemical indicators	Instruments in the field and laboratory
		Biological indicators	Instruments in the field and laboratory
	Streams	Chemical indicators	Instruments in the field and laboratory
		Biological indicators	Instruments in the field and laboratory
		Biological activity	Instruments in the field and laboratory

Source: Data from Innes JL (1993) *Forest Health*: *Its Assessment and Status*. Wallingford, UK: CAB International; Bundesforschungsanstalt für Forst – und Holzwirtshaft (ed.) (1998) *Manual on Methods and Criteria for Harmonized Sampling*, *Assessment*, *Monitoring and Analysis of the Effects of Air Pollution on Forests*. Hamburg, Germany: BFH; D'Eon SP, Magasi LP, Lachance D, and DesRoches P (1994) *Canada's National Forest Health Monitoring Plot Network*: *Manual on Plot Establishment and Monitoring*. Petawawa, Canada: Canadian Forest Services; Olson RK, Binkley D, and Böhm M (eds) (1992) *The Response of Western Forests to Air Pollution*. Ecological Studies no. 97. Berlin: Springer-Verlag; Tallent-Halsell NG (1994) *Forest Health Monitoring 1994*: *Field Methods Guide*. EPA/620/R-94/027. Washington, DC: US Environmental Protection Agency.

forest ecosystem health and the role of biodiversity to promote sustainable forest management has led to a reconsideration of this approach, and now soil biota, rodents, birds, butterflies, and small and large mammals are increasingly considered.

Terrestrial investigations

1. Visual indicators of tree condition consider the appearance of plant organs, in general foliage, reproductive structures, branches (often as a single unit, the crown), and stem. The roots are usually difficult to examine as routine indicators, but are of interest in in-depth cause-and-effect research. The examination of the various organs usually considers the frequency and intensity of symptoms as well as their cause, when possible. In the case of reproductive structures, the timing and abundance of flowering and fruiting are important. **Table 6** reports a list of indicators used in forest health surveys in Europe and North America. Since visual indicators are based on visual estimates they are prone to observer bias, and this needs to be taken into account with adequate Quality Assurance programs (see below).
2. Quantitative measurements of leaf/needle biomass and needle retention can include systematic collection of litter by litter traps, direct measurement of leaf area index (LAI), the identification of needle traces from branches and stems, and the analysis of digital images of crown condition. All these methods are useful as they provide objective data respectively on primary productivity, past needle retention, and crown condition. However,

Table 6 Indicators of tree condition considered in forest health monitoring programs in North America and Europe

Canada ARNEWS	*US FHM*	*Europe: UN/ECE ICP Forests*	
		Level I	*Level II*
Abiotic foliage symptoms – level	Catastrophic mortality	Crown defoliation	Crown defoliation
Abiotic foliage symptoms – type	Crown density	Crown discoloration	Crown defoliation type
Bare top height	Crown diameter	Damage category	Crown discoloration – age foliage affected
Crown closure	Crown dieback		Crown discoloration – color
Crown condition	Damage category (type)		Crown discoloration – location
Current foliage missing	Damage location		Crown discoloration – nature
Diameter at breast height	Damage severity		Crown discoloration – type
Dominance	Damage/cause of death		Crown morphology
Foliage damage – disease	Diameter at breast height		Crown shading
Foliage damage – insects	Foliage transparency		Damage to leaves/needles – extent
Height to top of live crown	Height		Damage to leaves/needles – type
Height to base of live crown	Live crown ratio		Damage to the branches – location
Needle retention	Social class		Damage to the branches – type
Seed	Tree age		Damage to the stem – location
Stem form	Tree age at diameter at breast height		Damage to the stem – type
Storm damage			Deformation of foliage – extent
Total height	Tree history		Deformation of foliage – type
Woody tissue damage – disease			Diameter at breast height
Woody tissue damage – insects			Dieback/shoot death – extent
Wood tissue damage – other			Dieback/shoot death – type
			Epiphytes
			Flowering
			Foliage size
			Foliage transparency
			Fruiting
			Height
			Removals and mortality
			Social class

ARNEWS, Acid Rain National Early Warning System; FHM, Forest Health Monitoring.
Source: Data from Innes JL (1993) *Forest Health: Its Assessment and Status*. Wallingford, UK: CAB International; Bundesforschungsanstalt für Forst – und Holzwirtshaft (ed.) (1998) *Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests*. Hamburg, Germany: BFH; D'Eon SP, Magasi LP, Lachance D, and DesRoches P (1994) *Canada's National Forest Health Monitoring Plot Network: Manual on Plot Establishment and Monitoring*. Petawawa, Canada: Canadian Forest Services; Olson RK, Binkley D, and Böhm M (eds) (1992) *The Response of Western Forests to Air Pollution*. Ecological Studies no. 97. Berlin: Springer-Verlag; Tallent-Halsell NG (1994) *Forest Health Monitoring 1994: Field Methods Guide*. EPA/620/R-94/027. Washington, DC: US Environmental Protection Agency.

their application is usually limited at intensively monitored sites because of technical and operational difficulties and costs.

3. A number of nonvisual indicators are available to assess tree health (**Table 7**). Most of them require time and appropriate equipment and can hardly be incorporated in large-scale surveys. Rather, many of them are attractive for intensive studies and cause-and-effect research.
4. Indicators for ecosystem-level health assessment. Ecosystem-level health assessment goes beyond the health of individual components: individual trees may die from insect attack but the ecosystem can still be healthy. The reverse is also true: for example, nitrogen deposition may substantially affect the nutrient balance of the system. This may affect species composition and diversity, population and community dynamics, herbivores' behavior, soil biota, soil water, and runoff quality without necessarily killing trees. In general terms, health assessment at the ecosystem level needs to consider resilience, vigor, and organization of the ecosystem as well as the presence of stressors that may exceed the tolerance limit of the system (see below). Resilience, vigor, and organization can be interpreted in operational terms as diversity, integrity of the physical, biotic, and trophic networks, productivity, equilibrium between demand and supply of essential resources, resistance to catastrophic change, and ability to recover. Also, the occurrence of endangered species has to be considered. To measure these characteristics, a number of proxies have been adopted, most of them being already listed in **Table 5**. Indicators such as birds and various other groups of taxa (e.g., rodents, small and large mammals) would be a useful complement. References and methods for ecosystem-level studies and monitoring are available, covering carbon and energy dynamics (above-and belowground primary production estimation from global to local levels), nutrient and water dynamics, and manipulative experiments.

Remote sensing Remote sensing is mostly based on analysis of imagery that can be collected from aircraft or from satellites; it includes aerial photographs, airborne or spaceborne multispectral scanner recordings, and radar recordings. Applications can be relevant at a variety of spatial scales, from local ($>1:25\,000$) to global ($<1:2\,50\,000$). It is important to acknowledge that different scales require different platforms and sensors: for example, satellites NOAA-AVHHR are the most used at the global scale, while sensors like the Landsat Thematic Mapper (TM), SPOT HRV/Xs, and IRS-1C/LISS are used at the regional scale. However, technical progress is rapid in this respect.

Remote sensing by aerial photographs can provide valuable information concerning yellowing, crown density, and mortality. In this respect, color-infrared (CIR) imagery is believed to provide more useful information than black-and-white imagery, although

Table 7 Possible nonvisual indicators of tree condition

Morphology and histology	*Biochemistry*	*Physiology*
Cellular structure	Biochemical substances	Photosynthesis
Foliage surface properties	Myo-inositol	Respiration
Tree rings	Detoxification systems	Transport and allocation of photosynthate
	Peroxidase activity	Assimilate level
	Superoxide dismutase	Assimilate transport
	α-Tocopherol	Transpiration
	Ascorbic acid	
	Glutathione	
	Enzyme and amino acids	
	Arginine, hystadine, tryptophan, and putrescine	
	Glutamic acid, aspartic acid, glutamine, and asparagine	
	Adenine nucleotides and pyridine nucleotides	
	pH of foliar substances	
	Fatty acid composition	
	Protoplast composition	
	Electrical conductance	
	Foliar pigment concentration	
	Mineral nutrition	
	Tree ring chemistry	
	Needle wax chemistry	

Source: Data from Innes JL (1993) *Forest Health*: *Its Assessment and Status*. Wallingford, UK: CAB International.

it seems less valuable when damage differentiation is not clear. A more sophisticated and expensive technique is based on multispectral imagery; it is based on the spectral characteristics of the green vegetation (pigment absorption in 0.4–0.7 μm range) whose changes can be related to changes in chlorophyll-*b* content. In the past, the resolution of satellite imagery was insufficient to detect the condition of individual trees, and applications were mostly useful to provide information about insect and fungal problems over large forest areas. However, recent technical progress and the use in combination of geographic information systems (GIS) and Landsat TM data make it possible to identify site susceptibility to insect attacks as well as to detect attacks on individual trees. An example is the identification of mountain pine beetle (*Dendroctonus ponderosae*) attacks on lodgepole pine (*Pinus contorta* var. *murrayana*) in various districts of British Columbia, Canada. These data are used to inform forest management and this is a valuable advance. Remote sensing and its application to forest monitoring are undergoing rapid evolution. Applications are now available in many fields related to forest health, including forest biodiversity, structural parameters, productivity, and carbon and chemical content of the foliage. For example, studies of ecosystem gross and net primary production (GPP and NPP, respectively) at the global scale received great benefits from recently improved remote sensing from the Earth Observing System. Implications for estimates of forest growth, seasonal dynamics of CO_2 balance for global carbon cycles studies and thus for important political and economic questions are obvious. From the monitoring point of view, advantages of using imagery include the opportunity to keep a permanent record of the forest under investigation and the possibility of adapting the sampling design and the sample size for imagery-based studies according to the investigation being undertaken. Disadvantages include the impossibility of making a careful diagnosis, and the difficulty of recognizing detailed symptoms and obvious damaging agents; in addition, assessment is made using a coarser method. Subjectivity is not completely solved, although it does not seem to be a major problem since images taken at different years can be rescored by the same interpreter.

Quality assurance An important part of any monitoring programme is quality assurance (QA). QA is a key issue for investigations aiming to generate representative results at the large scale (national, international) and in the long term, as it aims to improve the consistency, reliability, and cost-effectiveness of the program through time. QA is a systematic, formally organized series of activities that defines the way in which tasks are to be performed to ensure an expressed level of quality. The QA program ensures (1) proper design of the monitoring and its documentation, (2) the preparation, use, and documentation of standard operating procedures (SOPs), (3) the training of field crews, ring tests between laboratories, calibration and control phases, and (4) the formal, statistical evaluation of data quality.

Data management Data management (i.e., storage, evaluation, accessibility) is an increasingly important issue and can even determine the success or the failure of the monitoring program; it should be carefully planned at the early stage of the monitoring design. A data management plan should be prepared with details about (1) needs and goals, (2) available computer resources (hardware, software, protection, maintenance), (3) data resources (nonspatial data and GIS resources, data load, data standards, database design and file formats, metadata), (4) human resources, (5) data management strategies (data acquisition, QA/quality control data maintenance, legacy data, data security, data archives and storage, data applications, data dissemination), and (6) implementation.

Evaluation

Evaluation approaches and limitations Evaluation of data generated by forest health monitoring is usually driven by the monitoring approach adopted, the technique used, and the indicator adopted. Usually, data are evaluated in order to identify spatial and/or temporal trends and/or to identify cause-and-effect relationships. Data analysis is subjected to the nature and properties of the data (determined by the sampling design adopted, the metric of the indicator used, and by the frequency distribution of the observations), the comparability of the data (both in space and time) and by the reference adopted, i.e., the definition of what is to be considered 'healthy' or 'normal.' While the data issues can be managed from a technical point of view, the question about 'health' thresholds is controversial. For example, the classification adopted by the UN/ECE program in Europe identifies 25% crown defoliation as a threshold for damage. The 25% threshold was set to indicate a sort of 'no – return' limit, i.e., a tree whose defoliation exceeded that limit would have no chance to recover. This is now demonstrated to be untrue and cases of rapid recovery have been reported.

Uncertainty in health thresholds occurs because stressors may affect forests with different intensity and frequency. For example, herbivores are usually present on the foliage of trees. Yet their action affects the health of the trees only when they exceed some tolerance limit. Therefore, a first information need is to know this limit. In addition, tolerance limits may be exceeded cyclically and this can be seen as an integral part of the ecosystem dynamics. Thus, a second information need is to know the historical frequency of the insect infestation. It implies that an indicator of forest health has a range of natural and historical variation: if such a range is known, then it would be possible to establish thresholds that can be used as diagnostic tools. Recognizing the inherent variation of the potential stressor has a clear importance for evaluating the health of a given forest.

Evaluation methods Evaluation methods include various statistical and geostatistical approaches and are subjected to the same data limitations reported for the evaluation approach. Several references exist that may help in making decisions about most appropriate statistical analysis. When status and trend monitoring is concerned, data processing should provide summaries of descriptive statistics (e.g., totals, descriptors of central tendency, descriptors of frequency distribution), estimates of population parameters (e.g., estimates of population means, totals, and proportions), comparison between two subsequent sampling occasions (with statistical tests), and comparison between sites/group of sites (with statistical tests). It is important to remember that both parametric and nonparametric statistics need sampling to be based on random elements. Similarly, decisions about the most suitable statistical test should be based on the metric of the indicator used and the frequency distribution of the observations. Association and relationship between indicators can be explored by means of various univariate and multivariate statistical analyses. In the case of large-scale, long-term monitoring the use of models to incorporate the effects of covariates (e.g., the age of the trees or the effect of difference in methods) and for mapping purposes is essential.

In the case of cause-and-effect monitoring, relationships between indicators of for example, tree condition and indicator of stress (e.g., drought indices, pollutant deposition) are usually investigated by means of various multivariate techniques (e.g., discriminant analysis, ordination techniques, factor analysis, multiple regression). Recent work has focused on multiple regression techniques that may allow the quantification of the proportion of the variance of a response (dependent) variable (e.g., tree crown defoliation) explained by various predictors (independent variables).

Relevance and Applications of Forest Health Monitoring

Relevance

Forest health monitoring programs have potential in many respects. While they were started in relation to air pollution and within that framework as a contribution to international conventions and legal mandates, now the area for application is much broader. A first advance was to place more emphasis on traditional damaging agents. More recently, forest health monitoring has been included in program related to issues such as biodiversity, carbon sequestration, long-term ecological research, and international processes dealing with SFM and long-term resource management. For the above reasons, forest health diagnosis, monitoring, and evaluation is an area of concern for politicians, decision-makers, resource managers, and scientists as well as for the public. In this perspective, progress towards integration between monitoring networks with different topics (e.g., freshwater and forests) and scale of interests (local, regional, global) can provide a considerable added value.

Forest Health Monitoring Programs

Forest health monitoring is carried out at a variety of geographical scales, from local to international. Initial development occurred in Europe and North America, where comprehensive monitoring programs were developed (**Table 8**).

Monitoring Results: Examples

The data collected by monitoring programs provided insight into different topics. Examples may include the documentation of (1) changes in tree condition, (2) the incidence of pests on forest health, and (3) the role of various natural and anthropogenic factors that may affect forest health.

Changes in tree condition The collection of data about tree condition in Europe revealed that complex patterns could occur both in space and time. The development of the condition of trees varies with the species and the region being considered. **Figure 2** shows an example related to Scots pine (*Pinus sylvestris*) in Europe. As with many environmental variables, the frequency of trees with more than 25% defoliation changes through time; it fluctuates in the Mediterranean region (rapid increase and decrease), while the trend is different for the North Atlantic

Table 8 Forest monitoring programs in Europe and North America

Program feature	*Europe EC and UN/ECE ICP Forests*	*North America*	
		Canada ARNEWS	*USA FHM*
Aims	To monitor the effects of anthropogenic factors (in particular air pollution) and natural stress factors on the condition and development of forest ecosystems in Europe and to contribute to a better understanding of cause-effect relationships in forest ecosystem functioning in various parts of Europe	Early recognition of air pollution damage to Canada's forests and to monitor changes in forest vegetation and soils caused by pollutants	Determine the status, changes, and trends in indicators of forest condition on annual basis
Structure	Different monitoring intensity levels: Level I (less intensive) Level II (more intensive)	Connected with other terrestrial survey	Different monitoring intensity levels (Detection Monitoring – DM: less intensive; Intensive Site Ecosystem Monitoring – ISEM: more intensive). Connected with aerial and other terrestrial survey.
Plot selection	Systematic grid (Level I); purposive (Level II)	Purposive	Systematic grid (DM); Purposive (ISEM)
No. of plots	C. 5900 Level I; C. 850 Level II	150	C. 4000 (DM); 21 (ISEM)
Coverage	30 countries	National	National (C. 34 conterminous USA plus Alaska)
Started in	1986 (Level I); 1995 (Level II)	1984	1990 (DM)

Source: Data from Bundesforschungsanstalt für Forst- und Holzwirtshaft (ed.) (1998) *Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests*. Hamburg, Germany: BFH; McLaughlin S and Percy K (1999) Forest health in North America: some perspectives on actual and potential roles of climate and air pollution. In: Sheppard LJ and Cape JN (eds) (1999) *Forest Growth Responses to the Pollution Climate of the 21st Century*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

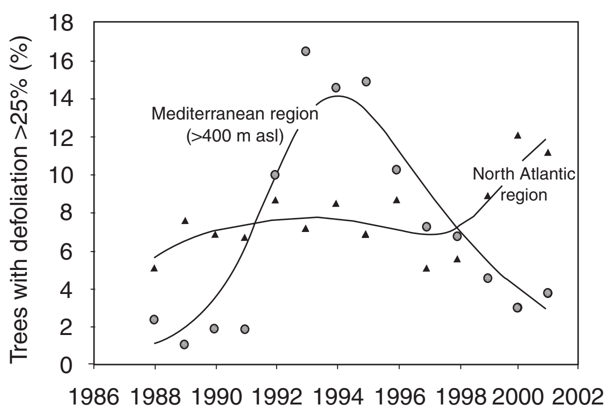

Figure 2 Frequency of Scots pine (*Pinus sylvestris*) trees considered damaged (defoliation over 25%) over the period 1988–2001. Based on data by EC and UN/ECE (2002) *Forest Condition in Europe. Results of the 2002 Large-scale Survey*. Geneva and Brussels: UNECE and EC.

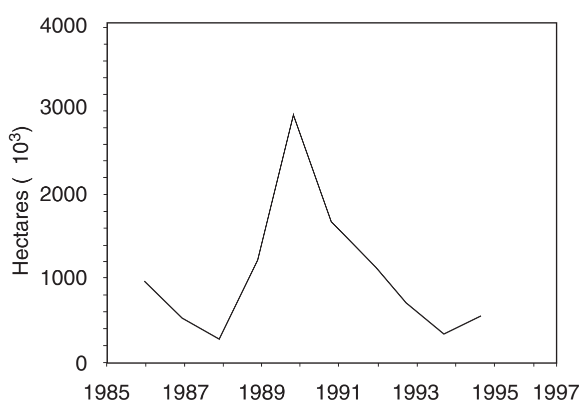

Figure 3 Area with aerially detected defoliation by gypsy moth (*Lymantria dispar*) in the USA over the period 1986–1995. Based on data by Forest Insect and Disease Condition in the US Report 1986–1995.

region, where an increase of defoliated trees was obvious only in the years 2000–2001. The interpretation of this as a directional trend needs caution, as the previous example clearly shows that it may be reversed in a few years.

Assuming that data are comparable through time and space, the data in **Figure 2** confirmed that no general decline in the health of forest was occurring: rather, the dynamics seem to be specific for individual species at certain sites or group of sites.

Incidence of pests The changes in the severity of an insect's action is exemplified by the aerial survey in the USA (**Figure 3**) which shows remarkable

Table 9 Significant predictors of defoliation and foliar concentration of nitrogen (N) and sulfur (S) in *Picea abies* and *Fagus sylvatica* in Europe

Predictor	*Response*					
	Defoliation		*Foliar N concentration*		*Foliar S concentration*	
	Picea abies	Fagus sylvatica	Picea abies	Fagus sylvatica	Picea abies	Fagus sylvatica
Soil type	–					
Stand age	+	+	–		–	
Altitude			+		+	
Precipitation	–			+		+
Air temperature		–				
Deposition of nitrogen	–		+		n.e.	n.e.
Deposition of sulfur	+		n.e.	n.e.	+	+

+, Positve correlation; –, negative correlation. n.e., not examined.
Source: Data from EC-UN/ECE (2000) *Intensive Monitoring of Forest Ecosystems in Europe*. Brussels: UN/ECE.

variation in gypsy moth (*Lymantria dispar*) defoliation over the period 1986–1995.

Role of various natural and anthropogenic factors
Data collected at the intensive monitoring sites in Europe indicate that, at many plots, the present deposition of acidifying compounds may exceed the critical load for the impact on soil; excess occurs at 45%, 65%, and 80% of sites for pine (mostly Scots pine, $n = 57$), spruce (mostly *Picea abies*, $n = 96$), and beech (mostly *Fagus sylvatica*, $n = 42$). However, the statistical studies carried out so far have confirmed that natural factors have the major role in determining forest condition at the sites concerned. Statistically significant effects of nitrogen and sulfur deposition were also detected although their role is less clear in size and direction (**Table 9**).

See also: **Biodiversity**: Biodiversity in Forests; Endangered Species of Trees. **Environment**: Impacts of Air Pollution on Forest Ecosystems; Impacts of Elevated CO_2 and Climate Change. **Experimental Methods and Analysis**: Design, Performance and Evaluation of Experiments; Statistical Methods (Mathematics and Computers). **Genetics and Genetic Resources**: Genetic Aspects of Air Pollution and Climate Change. **Hydrology**: Impacts of Forest Management on Water Quality. **Inventory**: Forest Inventory and Monitoring; Large-scale Forest Inventory and Scenario Modeling. **Resource Assessment**: GIS and Remote Sensing; **Sustainable Forest Management**: Overview; **Tree Physiology**: Mycorrhizae; Nutritional Physiology of Trees; Stress.

Further Reading

Ciesla WM and Donabauer E (1994) *Decline and Dieback of Trees and Forests: A Global Overview*. Rome: Food and Agriculture Organization.

Edmonds RL, Agee JK, and Gara RI (2000) *Forest Health and Protection*. Boston, MA: McGraw-Hill.

Elzinga CL, Salzer DW, Willoughby JW, and Gibbs JP (2001) *Monitoring Plant and Animal Populations*. Oxford, UK: Blackwell Science.

Huettl R F, and Mueller-Dombois D (eds) (1993). *Forest Decline in the Atlantic and Pacific Regions*. Berlin: Springer-Verlag.

Innes JL (1993) *Forest Health: Its Assessment and Status*. Wallingford, UK: CAB International.

Innes JL and Haron AH (eds) (2000) *Air Pollution and the Forests of Developing and Rapidly Industrializing Countries*. IUFRO Research Series no. 4. Wallingford, UK: CAB International.

Innes JL and Oleksyn J (eds) (2000) *Forest Dynamics in Heavily Polluted Regions*. IUFRO Research Series no. 1. Wallingford, UK: CAB International.

Manion PD and Lachance D (eds) (1992) *Forest Decline Concepts*. St Paul, MN: American Phytopathological Society.

Olson RK, Binkley D, and Böhm M (eds) (1992) *The Response of Western Forests to Air Pollution*. Ecological Studies no. 97. Berlin: Springer-Verlag.

Pankhurst CE, Doube BM, and Gupta VVSR (1997) *Biological Indicators of Soil Health*. Wallingford, UK: CAB International.

Sala OE, Jackson RB, Mooney HA, and Howarth RW (eds) (2000) *Methods in Ecosystem Science*. New York: Springer-Verlag.

Schlaepfer R (ed) (1993) *Long Term Implications of Climate Change and Air Pollution on Forest Ecosystems*. Progress report of the IUFRO Task Force 'Forest, Climate Change and Air Pollution.' Vienna: IUFRO.

Sheppard LJ and Cape JN (eds) (1999) *Forest Growth Responses to the Pollution Climate of the 21st Century*. Water, Air, and Soil Pollution no. 116. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Spellerberg IF (1994) *Monitoring Ecological Change*. Cambridge, UK: Cambridge University Press.

Spiecker H, Mielikäinen K, Köhl M, and Skovsgaard JP (eds) (1996) *Growth Trends in European Forests*. European Forest Institute Research Report no. 5. Berlin: Springer-Verlag.

Strouts RG and Winter TG (1994) *Diagnosis of Ill-Health in Trees*. London: HMSO.
Wulder MA, and Franklin SE (eds) (2003) *Remote Sensing of Forest Environments: Concepts and Case Studies*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Biochemical and Physiological Aspects

R Ceulemans, University of Antwerp, Wilrijk, Belgium

Introduction

Forest ecosystems fulfill various functions with economic, social, and ecological significance. They also form habitat for various species of plants and animals. However, forest ecosystems are exposed to serious threats from attacks by parasites and diseases, from air pollution, fires, and climatic changes. As forests are sensitive ecosystems, they are susceptible to these disturbances, whether caused by biotic or abiotic influences. These biotic and abiotic influences could be of natural origin (such as fires, insect or pathogen attacks, and species invasion) or anthropogenically caused (such as air and soil pollution, global climatic changes, and fragmentation). In this article some physiological and biochemical aspects of tree responses and forest health will be reviewed. The contribution is focused on air pollution (in particular ozone) and climate change (in particular elevated atmospheric CO_2 concentrations) and how these relate to forest health. These two issues provide a good basis for understanding the links between biochemistry and physiology and forest health. So, the contribution is restricted to these two stress factors as they are used as examples of how trees respond to external stresses.

With regard to air pollution, various atmospheric pollutants might affect tree growth and forest health such as nitrogen dioxide (NO_2), nitrogen oxides (NO_x), ozone (O_3), sulfur dioxide (SO_2), hydrofluoride (HF_6), and hydrocarbons (such as CH_4). Air pollution can change the physical and chemical environment of forest trees. Pollutant stresses, as well as competitional, climatic and biological stresses, have important implications for forest growth and ecosystem succession because they provide forces that favor some genotypes, affect others adversely, and eliminate sensitive species that lack genetic diversity. Pollutant stresses in a forest ecosystem are superimposed upon and interact with the naturally occurring stresses that trees are already experiencing. These additional stresses can accelerate the processes of change already underway within ecosystems.

Forests and the human uses of forests and forest products have an impact on greenhouse gas concentrations in the atmosphere. There is a feedback from the climate system where forests are affected by the changes in climate, and the chemical composition of the atmosphere. Forest ecosystems and wood-based products also have the ability to sequester atmospheric CO_2 and thus offer an opportunity to mitigate climate change. However, this balance must be correctly understood, quantified, and modeled if we wish to assess the potential of forests to regulate sudden climatic changes, to improve the reliability predictions, and to reduce the uncertainty of the consequences of climatic change on forest health and forest ecosystems. As photosynthesis is the key process that all autotrophic organisms (trees, green plants, and algae) use to exchange mass and energy with the environment, this process will first be briefly reviewed.

Photosynthesis and the Importance of Nitrogen

Photosynthesis is the principal process to perform two essential transformation processes – on the one hand the conversion of high-quantity solar energy into high-quality chemically fixed energy, and on the other hand the conversion of simple inorganic molecules (CO_2, H_2O) into more complex organic molecules (sugars and carbohydrates). The harvestable product of a tree, generally the stem, depends not only on photosynthetic carbon uptake by the foliage, but also on respiration of the various organs and carbon investments into renewable organs (leaves, fine roots) and generally nonharvested organs (branches and large roots). Consequently, there is no obvious relationship between photosynthesis and wood production. A fast-growing tree generally needs high photosynthesis, but the reverse is not necessarily true. When growth is related to total net photosynthesis integrated over the entire growing season and the total light intercepting leaf area, positive relations are generally obtained. However, photosynthesis remains the principal physiological process that also closely reflects the response of a tree to abiotic or biotic disturbances.

Abiotic factors such as light, temperature, CO_2 concentration, vapor pressure deficit, and nutrient status, but also air pollution, climatic changes, and drought, have a major effect on net photosynthesis, and thus on tree growth and productivity. All