Methods to estimate forest health

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A range of different indices are available for assessing the health of trees in forests. An even larger range can be used for the assessment of the health of forest ecosystems. Most studies made in connection with "forest decline" and the impact of air pollution and other environmental stresses on forests have concentrated on the assessment of crown transparency and crown discoloration in individual trees. These are non-specific indicators which are now known to be sometimes of relatively little value when determining the health of a forest ecosystem. Numerous problems exist with both, and the standardisation of assessments between and even within countries has not been achieved. Consequently, studies claiming to compare "defoliation" between different countries cannot be substantiated. The emphasis on crown transparency and crown discoloration has resulted in the neglect of a number of other indices that could be of considerable value. These include a variety of visual measures of crown condition and also several non-visual bioindicators. Some of these techniques are objective, reducing the present reliance on observer standardisation. A large number of potential techniques are currently at the research stage and have yet to be adequately tested in field trials. This represents an area where a substantial amount of further research is required.

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Introduction

The forests of Europe form an important economic, aesthetic and ecological resource. Other papers in this volume deal with the nature and extent of this resource. In this paper, the assessment of the condition of this resource is reviewed, with particular emphasis on those studies that have arisen from the concerns generated by the issue of "forest decline".

In reviewing the subject, it is important to define exactly what is meant by terms such as health, condition and vigour. Tree health is best considered in the pathological sense. It is defined as the incidence of biotic and abiotic factors affecting the trees within a forest. Tree condition is less specific, referring to the overall appearance of the trees within a forest. Tree vigour is best restricted as a term to the growth of the trees in relation to a hypothetical optimum. Forest health, condition and vigour is a different issue. Instead of only trees being considered, the entire forest should be included. Some components of forest ecosystems are much more sensitive to stress than others and, for example, the trees may not be the first to respond when the ecosystem is disturbed. However, most studies that refer to forest health actually deal with tree condition, and it will be some time before there is widespread acceptance that forests actually consist of more than trees. In this paper, the assessment of both tree and forest condition is considered, rather than the assessment of forest health in its strict sense.

The emphasis on condition rather than health is necessary because most field assessments are concerned with condition, and not health. To assess the latter, diagnostic techniques are required. It is particularly useful to draw the distinction between the assessments of forest condition, as made in extensive surveys, and the diagnosis of forest health problems, as identified by the surveys. The surveys can point to the existence of an actual or potential problem, diagnostic techniques are required to identify the cause of the problem. Generally, it is difficult to incorporate anything but the simplest diagnostic techniques into surveys, and the diagnostic assessments should be seen as a different level of investigation. There are a number of guides which aid diagnosis (e.g. Sinclair et al. 1987, Hartmann et al. 1988), but these cannot replace the laboratory studies that are required to undertake many diagnoses.

International assessment of forest condition

A number of international protocols have been developed which deal with forest condition. The most important of these is the programme developed by the Economic Commission for Europe of the United Nations. Under the Convention for Long-Range Transboundary Air Pollution, the International Co-operative Programme on the Assessment and Monitoring of Air Pollution Effects on Forests was established. This programme "aims to assess, monitor and document the extent and development of forest damage in Europe and to investigate the causes of new type of forest damage recently observed, also known as forest decline" (Forest Damage ... 1991). The aims of the programme, as stated, are quite revealing. It is assumed that forest damage is present and developing and it is also assumed that a new type of forest damage is occurring. These assumptions, although widely held, are difficult to substantiate. While forest damage is, and always has been, present, there is very little evidence that it is more frequent today than in the past. There were a large number of reports of "forest decline" in the 1980s, but similar records are available for earlier periods and there is little to indicate that the reports in the 1980s were unprecedented.

The programme assesses the extent and development of forest damage by monitoring two indices: defoliation and crown discoloration. The principles for assessing these two variables have been described in a manual but, in practice, a number of problems have arisen. It is not clear exactly what is meant by defoliation. In some countries, it is interpreted as an increase in crown transparency, a measure of the amount of light passing through the crown. In other countries, it is taken more literally as a measure of the amount of needle or leaf loss. In both cases, there is the problem of reference standards. There is no theoretical optimum that can be universally applied. For example, Scots pine (*Pinus sylvestris* L.) retains its needles for six years or more in northern Finland, whereas two to three years is the norm in England. Consequently, any attempt to base defoliation estimates on needle retention must be based on a sound knowledge of how many years of needles should be retained. Such information is generally unavailable.

In conifers, the length of needle retention is fraught with uncertainty. Needle retention within a given species is dependent on a number of different factors, including tree age, altitude, latitude and provenance (Ewers and Skied 1981). This may make the detection of any stress effect difficult, although a number of studies have successfully related needle retention to external stresses (e.g. Miller and Van Doren 1981). Recent studies in Finland have revealed that needle retention can be quite variable through time (Jalkanen and Kurkela 1990, Kurkela and Jalkanen 1990), posing the question of what is normal. This remains an area where further work would be of considerable value.

Various visual standards have been proposed (e.g. Innes 1990, Müller and Stierlin 1990, Cadahia et al. 1991), based on the condition of trees in particular regions. These work well where the crown form of trees is reasonably uniform. However, the standards break down when the crown form of a tree differs significantly from the photographic standard. This was recognised in the Swiss guide (Müller and Stierlin 1990) with, for example, three different types of Norway spruce (*Picea abies* (L.) Karst.) crown being illustrated. By definition, the use of photographic standards implies that crown transparency is being assessed.

Discoloration is equally difficult to assess, principally because of the lack of adequate definitions. While discoloration might seem an easy index to determine, in practice it is not. Difficulties arise over what constitutes discoloration. This is because discoloration actually covers several different values, including degree and extent. The extent of discoloration covers the proportion of the foliage that is discolored. The degree reflects the intensity of the discoloration. In late summer, when many forest "health" inventories are undertaken, older Norway spruce needles often have yellow tips. Does this constitute discoloration? Similarly, should a tree with marginal chlorosis receive the same score as a tree in which a few branches are intensely chlorotic? These are questions that should have been resolved internationally at an early stage but which were not. Instead, most countries have derived their own solutions. Unfortunately, these are frequently incompatible.

With both crown transparency and crown discoloration, there is a problem of how the results of any inventory are interpreted. Both indices are non-specific. While yellowing in Norway spruce has been widely associated with magnesium deficiency, it can be caused by several other nutritional disorders. In addition, yellowing can be brought about by other factors, such as insect attack. Crown transparency is even more difficult to interpret, being the end result of almost any form of stress. Consequently, studies that have alleged that the degree of crown transparency reflects only, for instance, the impact of air pollution, are seriously in error.

Comparisons of forest condition

One of the main reasons for undertaking the international inventories of forest "health" is to compare the condition of forests across Europe. This requires that the estimates of forest condition in different countries are based on the same principles and that they are comparable. Increasingly, this has been shown not to be the case. Several studies have made comparisons between field observers from different countries, working under realistic conditions (e.g. Innes et al. 1993). These have clearly indicated that observers from different countries produce different results when assessing the same trees under identical conditions. This effectively means that the results produced by different countries cannot be compared.

Other indices of crown condition

The problems surrounding the visual assessment of crown transparency and discoloration have led to a search for other indices that might be more objective and easier to interpret. These can be broadly divided into three different groups. Firstly, there are several more objective measures of crown transparency and crown discoloration. Secondly, there are a number of other visual indicators of tree condition. Lastly, there a range of techniques which rely on non-visual detection methods.

Objective methods of assessing crown transparency and crown discoloration

A frequently used method of detecting defoliation and discoloration is the use of remote sensing. While there has been a great deal of interest in the possible use of satellite imagery, this is of insufficient resolution to detect the condition of individual trees. However, it is useful when large areas of forest affected, and it can provide good estimates of forest health over large areas when entire stands have been affected. Airborne imagery, on the other hand, has proved extremely valuable in some situations. One of the biggest advantages of imagery is that a permanent record of the forest is obtained, enabling objective comparisons to made in the future.

Early applications of remote sensing in the field of forest health generally involved the use of colour infrared photography. These have a number of limitations, principally the amount of information that can be obtained from them. Scales of photography have varied and it seems that a scale of 1:9000 is sufficient to provide information on the condition of trees in a stand (Scherrer et al. 1990). However, more detail may be required to adequately define and assess damage in the crowns of individual trees. The use of colour infrared photography appears to have considerable potential where damage differentiation is clear, but it may be less valuable when the differences in condition among trees are very subtle. Under suitable conditions, aerial photography can be used to make much more comprehensive assessments of stand condition than can be made by ground assessments, as the latter are restricted by visibility. However, it is usually not possible to obtain the 5 % resolution for transparency assessments achieved in ground assessments, most applications having been limited to the categorical system (0–10 %, 11–25 %, 26–60 %, > 60 % transparency) initially used in forest damage inventories.

Airborne multispectral imagery appears to have considerable potential, although this is only just being realised (Elvidge et al. 1989). Airborne fluorescence line imagery enables 288 wavelength bands to be used, allowing detection of a variety of subtle changes in reflectance (Hoshizaki et al. 1988). However, such techniques are extremely expensive for routine assessments and less detailed information may be sufficient for many forest health applications (Koch et al. 1984, Leckie and Ostaff, 1988). Many of the problems with multispectral data are still being evaluated and the high costs of the equipment, flights and subsequent data handling currently limit its application.

Another source of objective information on tree crown transparency is the use of leaf area indices (e.g. Lang and Xiang 1986, Campbell and Norman 1989). This has been largely ignored in assessments of forest condition, although it is widely used in a number of other contexts. One of the biggest problems with the method is that ground-based estimates of leaf area are relatively time-consuming, and substitutes, such as sapwood-area, have only limited value (Coyea and Margolis 1992). However, with the widespread availability of suitable cameras (Chen et al. 1991) and the increasing use of image analysis, it is likely that there will be a number of developments in this area in the near future.

Other visual indicators of crown condition

A wide range of possible indices, in addition to crown transparency and discoloration, have been suggested for the assessment of forest health. These can be divided into two categories: research techniques and routine assessment techniques. The former are frequently used by pathologists when investigating specific problems, whereas the latter are intended for repeated, nonspecific assessments. Only routine assessments have been considered here.

Detailed assessments of foliar discoloration

In the international protocol, assessments of discoloration consider the overall discoloration of the crown, without determining the nature of the discoloration. However, the nature of the discoloration may provide critical information. At the very least, it is important to distinguish between chlorosis (yellowing caused by the loss of chlorophyll), necrosis (browning caused by the death of tissue) and other forms of discoloration. In conifers, the needle years that are affected are important, and the extent of discoloration on leaves/needles is important on both conifers and broadleaves. However, detailed assessments require the foliage to be examined closely (i.e. in the hand) as assessments made from the ground using binoculars may miss important symptoms (Muir and Armentano 1988).

There are several problems with the assessment of discoloration. Foliage may lie anywhere along a continuum between green, yellow and brown, and assigning it to a particular category may be very subjective. There is a problem with the definition of what constitutes discoloration: the discoloration of the tip of a needle may be intense but may only affect a very small fraction of that needle. Different parts of the crown may be affected to different extents, again calling for a subjective judgement. It seems likely that either multiple observations or a composite index will be the most useful approach (Pronos et al. 1978, Ewell et al. 1990).

Foliage size and shape

Foliage size and shape provides several types of information. The size of foliage often indicates the general nutritional status of the tree, particularly in relation to the allocation of assimilates from the previous year. In both conifers and broadleaves, foliar size can be used as an index of stress (Nihlgård 1985, Glavac 1988), provided that the normal size of the foliage is known. When the normal size of foliage is unknown, detailed analyses may be necessary (Riederer et al. 1988). However, with the aid of modern image analysis techniques, these are much less time-consuming than in the past.

Foliage shape is also important, with distortion often indicating insect, fungal or viral problems. Generally, when a high incidence of foliar distortion is seen, expert help should be sought as there are a wide range of possible causes, depending on the species and the environment.

Patterns of foliage flushing and senescence

Generally, assessments of forest health occur at a single time in the year. However, to establish cause-effect relationships, it may be necessary to undertake more detailed sampling. For example, the Canadian ARNEWS programme involves multiple visits to each plot (Magasi 1988). When this is done, it may be possible to date the occurrence of the flushing of the new foliage. In Switzerland, the date of flushing (and senescence) of beech is undertaken as part of meteorological monitoring, although there are plans to undertake similar studies in the forest monitoring. Similarly, the date of flushing is recorded in some of the more intensive forest monitoring programmes in the United States, such as at the Vermont Monitoring Cooperative site at Mount Mansfield, Vermont.

The date of senescence is also critical as several experimental studies have suggested that one effect of certain pollutants is to bring about premature senescence of foliage. However, it is normally impossible to allocate any cause to premature senescence, as it may be brought by a number of different factors. Even when a stress such as pollution is suspected, interacting factors often make it difficult to determine the actual cause of the premature senescence. For example high levels of ozone and drought conditions often occur together, and both can cause premature senescence of foliage.

Flowering and fruiting

The significance of flowering and fruiting patterns in relation to forest health is still uncertain. While it has been known for some time that flowering responds to climate (e.g. Lindquist 1931, Eklund, 1954), other factors also affect flowering and it does not occur in response to stress alone (Philipson 1990). It is important that the effects of any past flowering or fruiting are taken into account when making other assessments, as fruiting can have effects on factors such as foliage density and crown architecture (Lüscher 1989a, b, 1990).

Patterns of shoot growth and development

The pattern of growth and development of the crown can be an important indicator of the health of a tree, but indices involving branch structure have not been used as often as they should have been. The indices are specific to individual species or species groups and cannot all be summarised here. Instead, further information can be obtained from Colin and Houllier (1992), Gruber (1986, 1990), Lesinski (1991), Lesinski and Westman (1987) and Lesinski and Landmann (1988) for Norway spruce, Niehaus (1989) for Scots pine and Roloff (1989), Dobler et al. (1988), Thiébaut (1988) and Westman (1989) for broadleaves.

Some of the indices used to describe crown architecture are in need of refinement. For example, Athari and Kramer (1989) had considerable difficulties applying some of the scores developed by Roloff (1985) to beech, finding that crown architecture was often rather poorly correlated with shoot extension. Similar results were obtained by Thiébaut (1988). However, hands-on examination of the branches enables the past history of shoot extension to be constructed, providing important information on the response of the trees to external forcing factors (e.g. Lonsdale et al. 1989). While this has been done for beech, the technique does not yet appear to have been fully exploited for other species.

Non-visual indicators of crown condition

There are a considerable number of non-visual techniques that can be used in the assessment of tree health. Many of these are still at a developmental stage or have only been applied within the research context. They have only been described briefly here. Fuller descriptions can be found in Cape and Mathy (1988), Innes (1993a) and in a U.S. National Academy study (Biologic Markers...1989).

Foliage surface properties

Given that the foliage surface is the location of the first impact of many different types of stress, it is here that the first indications of an effect might be seen. However, it is precisely because so many different stresses affect the surface properties of the foliage that difficulties have been encountered allocating specific types of stress to specific forms of damage.

There have been numerous studies of the surface wax structures of tree foliage, some examining the structure directly by electron microscopy and other studies using indirect techniques, such as the contact angles between water droplets and the wax surface. The studies have generally indicated that the wax structures deteriorate with foliage age and that they can be adversely affected by climatic conditions. When a nonspecific index of wax degradation is being sought, then it is possible to recognise a number of stages of degradation (e.g. Barnes et al. 1988).

In some cases, it has been possible to use the condition of surface waxes as indicators of pollution impact (e.g. Karhu and Huttunen 1986, Tuomisto 1988). The success of such studies has been rather variable, mainly because of the large number of potential confounding factors. It remains to be seen whether a convincing application of the technique can be made within the more general context of forest health assessment.

Foliar pigment concentrations

Foliar pigment concentrations provide a quantitative backup to the visual observations of discoloration. Field measurements in this area have been quite successful (e.g. Hoshizaki et al. 1988, Wolfenden et al. 1988), although there are a number of outstanding problems. Not all studies have been successful, the degree of success seemingly being dependent on the degree of initial discoloration. For example, Osswald et al. (1987) recorded similar chlorophyll concentrations in Norway spruce with and without discoloration, and similar results were obtained by Hotz et al. (1990) for beech. Kandler et al. (1987) found no change in the chlorophyll to carotene ratios in Norway spruce with progressive chlorosis.

Some of the problems may be the result of the marked seasonal differences in chlorophyll concentrations in some species (Köstner et al. 1990). These changes appear to be both site- and species-specific, so a considerable amount of work will be required before they can be fully evaluated. As with many other tests, it seems that the value of the technique has been determined on the basis of a very small number of rather inadequate studies. Before it can be adopted routinely, much more work will be required.

A related technique concerns chlorophyll fluorescence. This is effectively a measure of the efficiency of the photosynthetic apparatus (Baillon et al. 1988a, b). However, it a number of different environmental factors affect the fluorescence, limiting its use as a specific tool. For example, the weather conditions before and during the measurements have a significant impact on the values (Strand and Lundmark 1988). Until the various factors affecting the measurements can be controlled, the use of the technique will be restricted to research applications.

Cellular structure

Many different types of damage can be diagnosed on the basis of the cellular damage. Most stresses affect foliage in different ways, providing an opportunity for cause-effect studies. Several studies have been successful in this area (e.g. Soikkeli and Tuovinen 1979, Kärenlampi and Houpis 1986), and detailed descriptions of different types of cellular damage have been produced by Carlson and Gilligan (1983) and Fink (1988). However, to be useful, detailed descriptions, based on field evidence and experimental replication, are required for each species to be investigated. To date, a suitable atlas of symptoms has not been produced, although progress in being made on symptom description (e.g. Günthardt-Georg et al. 1993).

Photosynthesis

While photosynthetic rates have been proposed as a means of assessing tree health, the techniques that have been used to date have all been derived from research environments. Two methods have generally been used, one based on measuring the photosynthesis of intact foliage *in situ* and the other based on measurements taken from detached foliage. The latter technique, although widely used (e.g. Amundson et al. 1992), is open to question as there has been insufficient research on the potential impact of the stress caused by foliage detachment. The use of portable gas exchange systems seems to offer some potential, but it is not clear how they could be used in a cost-effective manner to measure the photosynthesis of shoots in the upper crown areas of mature trees.

Respiration

As with photosynthesis, measurements of shoot respiration are still mostly in a research phase. The main problem is that the quantities of gases are so small that very sophisticated equipment is required to detect them. There has been some progress in the measurement of respiration of mature trees (e.g. Cropper and Gholz 1991) but, again, the use of a tower is required, making it difficult to use the technique in extensive investigations. Those studies which have been done suggest that the efficiency of water use in unhealthy trees may be lower than that in healthy trees. However, from transpiration measurements alone, it may be difficult to attribute a cause to any observed changes.

Biochemical substances

There are a large range of biochemical substances that might of use in the assessment of forest health. There are several reviews of these, including those by Jäger (1982), Jäger et al. (1986), Schulte-Hostede et al. (1988) and Innes (1993a).

In most cases, the difficulty with those indices that have been proposed is insufficent field testing. In some cases, indices have been derived from experimental work, without adequate checking to see whether different types of stress produce the same effects. In other cases, biochemical (and other) markers have been derived by comparing the biochemistry of trees with and without crown transparency (often only one tree in each class). The assumption is made that trees with higher levels of crown transparency are more "affected" (by air pollution) than those with lower levels. However, it is quite possible that all the trees in an area could be affected. Given the very small sample sizes that are usually involved, very little confidence can be placed on the results of such studies.

Transpiration

Although the transpiration of trees responds to a number of different stimuli and can probably be related to the health of the trees, there have been few attempts to assess transpiration as an index of tree health. Measurements are quite widely taken (e.g. Benner et al. 1988, Ellsworth and Reich, 1992), but information is still required on the transpirational responses to specific stresses, and the normal ranges of transpiration values in individual tree species.

Mineral nutrition

Mineral nutrition is one of the more useful methods of assessing forest health. However, it is also one of the most abused. It is relatively easy to collect foliage and to analyse its mineral content. However, there are many difficulties over the interpretation of the resulting data. The nutritional status is dependent on a wide range of factors, including:

- the nutritional status of the soil (e.g. Bell and Ward 1984);
- the age of the foliage (e.g. Mälkönen 1974);
- the age of the tree (e.g. Miller et al. 1981);
- the position of the foliage within the crown (e.g. Will 1957);
- the time of year (e.g. Helmisaari 1990);
- the preceding weather conditions; and
- the analytical techniques used to determine the nutritional status (e.g. Jarva and Tervahauta 1989).

With care, it is possible to control some of these although they are not all straight forward. For example, while the time of year can be stated precisely, trees at different latitudes will be in different phenological states on the same calendar date. Even at the same site, there are differences in the phenology of individual trees which mean that the foliage of two adjacent trees may be of different age on the same calendar date.

The best way to overcome some of these problems appears to be through the adoption of adequate sample numbers. The variation between trees differs according to the element being investigated, with some having much wider ranges than others. Consequently, the sampling design must be based on the collection of an adequate sample for the most variable element being considered. For very variable elements, such as calcium, the sample size required to obtain a reasonably precise estimate of the nutritional status of the stands may be more than 50 trees.

The interpretation of foliar analyses is also difficult. Most work has been concerned with relatively young trees, where remedial fertilisation of nutritional disorders is likely to produce useful results. However, forest health assessments are normally concerned with mature stands. It is not clear just how far the results obtained from young stands can be applied to older stands and, although there have been a huge number of studies, the critical levels for many of the elements are still rather vague. Consequently, many more recent studies have looked at the relative contents of elements, particularly in relation to nitrogen. This appears to offer potential, but the techniques have still to be fully evaluated for mature trees of most species.

Transport and allocation of photosynthate

Studies of the transport and allocation of photosynthates offer a number of possibilities for the assessment of forest health but, as with many other physiological indices, the work is still mainly at the research level. Several studies have looked at the processes in relation to forest health (e.g. Fengel 1987, Villanueva and Santerre 1991), but there are appear to be a number of unresolved questions. In particular, the daily and seasonal dynamics of the photosynthates in trees growing in forest environments are only beginning to be investigated (e.g. Gholz and Cropper 1991, Paynter et al. 1992). A great deal of research is going on this area, and progress is likely in the near future.

Root condition

Most forest scientists are aware of the importance of roots but there is surprisngly little information available on the assessment of root health. One problem is that such assessments invariably involve destructive sampling. However, the use of the ingrowth core method (Böhm 1979, Neill 1992) may limit such destruction. There is always a danger of infection, either by inadvertently introducing a pathogen or by allowing a pathogen entry to the root via damage caused by the sampling.

There a number of techniques available for looking at fine root turnover (e.g. McClaugherty et al. 1982, Richards 1989, Hendrick and Pregitzer 1993). However, various studies have indicated that the rates are extremely variable and detailed sampling (with the associated problems) may be required before any reliable estimates of turnover can be obtained. The sampling requirements for extensive assessments have still to be determined, but they are likely to be dependent on a number of factors, including forest type, soil type and and stand age.

Tree-ring analysis

The analysis of past growth provides an extremely valuable indication of the health of a tree or stand. Past disturbances can be seen and the relationship between any current change in growth can placed in the context of past changes. There are a wide variety of techniques available, too many to examine here. Instead, reference should be made to the various reviews that are available (e.g. Fritts 1976, Hughes et al. 1982, Cook and Kariukstis 1990). Although a number of problems exist, these have been the subject of detailed investigation and have now been largely resolved.

Expert systems

Several expert systems are available for the assessment of the crown health of trees. One of the best appears to be ForestHealth, which was developed in the United States (Nash et al. 1992). Currenty, this system has only been designed for a limited number of hardwoods present in the northeast United States, but its potential for expansion to other species in other areas is considerable. In particular, it offers help with the identification of common insects, diseases and abiotic disorders, an area which otherwise requires considerable skill. Herein lies one of the biggest questions in the assessment of forest health. On the one hand, most traditional pathologists and entomologists would insist that diagnosis was required before any assessment of forest health was made. On the other hand, most field surveys concentrate on identifying the presence of an actual or potential problem, rather than seeking to ascertain its cause.

It is actually not clear whether a full diagnosis can be made during the course of an assessment. While the direct causes of damage can often be identified, ill health is rather more complicated. Determining the presence of many pathogens involves sample collection and subsequent laboratory work. When a pathogen is identified, it is often unclear whether it is a primary or secondary problem. Many fall into the latter category, and the identification of the factors leading to the infection may be much more difficult to identify. This is particularly true in situations where trees are predisposed towards biotic or abiotic damage by an independent factor.

"Level 2 monitoring" and the intensive monitoring of forest ecosystems

The above discussion has concentrated on the assessment of the health of forest trees, rather than the forests themselves. The assessment of the health of forest ecosystems is an entirely different issue. While all the techniques described above can be used to assess the health of the tree component within forest ecosystems, there are many other components to the ecosystem. There has been increasing interest in assessing these, although there has been some confusion over how intensive or extensive such investigations should be. In most cases, the high costs of mounting routine assessments of forest ecosystems precludes any extensive investigations, although some measurements in addition to tree health are often made. For example, soils are often assessed on an extensive basis (e.g. in Finland – Tamminen and Starr 1990), although this seems to be the only parameter that is assessed regularly.

A range of potential indicators is given in Table 1. This has been taken from the Swiss intensive monitoring programme (Innes, 1993b), and all the indices are believed to represent measures of forest ecosystem health. Many of these are still in an early stage of development, but the range of potential indices is clear. Three levels of monitoring are identified, each more detailed than the last. The different levels are not strictly compatible with the levels proposed by the International Co-operative Programme on forest monitoring, nor are they strictly compatible with the International Co-operative Programme on integrated monitoring. However, they do provide much of the information required by these two separate programmes. In addition, the scheme covers the likely information requirements of other monitoring schemes, such as the Global Terrestrial Observation System.

How the information from a such an assessment scheme will be integrated remains an open question. Various forest models exist, but most of these are based on rather limited data, and the data collected as part of the assessment will be required to properly initialise the models. Given our poor understanding of forest ecosystem processes, it is unlikely that we will be able to specifically related the combined observations to forest ecosystem health at the present time. However, much work is going on this area, and rapid and substantial progress is likely in the near future.

Table 1. Different levels of monitoring.

Level 1	Level 2	Level 3
Disturbance	Air quality	Aquatic biology
Forests:	Bulk precipitation	Breeding birds
crown class	Epiphytes	Butterflies
foliar composition	Heavy metal deposition	Contamination
fruiting	Increment analysis	Gauging station
regeneration	Litterfall	Mammals
structure	Root disease evaluation	Moths
tree damage	Soils: biological activity	Other insects
tree growth	Throughfall	Stream chemistry
tree health	Tree foliage (hands-on)	Water quality
tree phenology	Tree genetic structure	
Ground flora		
Meteorology		
Site description	**+ Level 1**	**+ Levels 1 and 2**
Soil analyses		

Conclusions

While a variety of different methods exist to assess forest health, international efforts have concentrated on only two indices: crown transparency and crown discoloration. Both of these were associated with "forest decline", although their precise relationship with any new phenomena that may be occurring in forests remains unclear. Neither are particularly useful as indices of forest health. Both are non-specific, being brought about by a number of different factors. Crown transparency in particular cannot be readily equated with tree health, although there is clearly a relationship in some cases. Crown discoloration is more useful but, to be of any value, different types (colours) should be distinguished and, in conifers, the needle year classes that are affected should be indicated.

A number of other indices of forest health exist. Many of these have yet to be applied in a rigorous fashion to routine assessments, but some have already produced useful results. Estimates of crown architecture have proved useful, as have estimates of dieback and shoot death. In most cases, such assessments can be made relatively simply, without spending an undue amount of time on site. As a substantial proportion of the field costs in extensive surveys are related to travel to the plots, increasing the time spent on site relative to travel is highly cost-effective. However, the time and cost rises dramatically when foliar sampling is required.

Another group of indices is based on non-visual assessments of crown condition. These frequently involve the destructive sampling of foliage, followed by laboratory analysis. In most cases, such techniques have been developed from experimental studies, when the seedlings or young trees were already in the laboratory. However, a number of techniques have been developed following limited field investigations. In all cases, there has been relatively little field investigation of the viability of the techniques, severely restricting their application. Even the most extensive study (Cape et al., 1988) only involved 12 purposefully selected sites spread across an area extending from north Scotland to southern Germany. In most cases, the studies have been specifically related to "forest decline" and comparisons have been made between various characteristics of trees with and without crown transparency. Such a procedure is rather questionable when it is uncertain whether or not the transparency can be related to the health of the trees.

References

Amundson, R.G., Hadley, J.L., Fincher, J.F., Fellows, S. & Alscher, R.G. 1992. Comparisons of seasonal changes in photosynthetic capacity, pigments, and carbohydrates of healthy sapling and mature red spruce and of declining and healthy red spruce. Canadian Journal of Forest Research 22: 1605–1616.

Athari, S. & Kramer, H. 1989. Beziehungen zwischen Grundflächenzuwachs und verschiedenen Baumparametern in geschädigten Buchenbeständen. Allgemeine Forst- und Jagdzeitung 160: 77–83.

Baillon, F., Dalschaert, X., Grassi, S. & Geiss, F. 1988a. Spruce photosynthesis: possibility of early damage diagnosis due to exposure to magnesium or potassium deficiency. Trees: Structure and Function 2: 173–179.

— 1988b. Possible use of chlorophyll fluorescence in early detection of forest damages: influences of different criteria. In: Mathy, P. (ed.). Air pollution and ecosystems. Reidel, Dordrecht. p. 590–595.

Barnes, J.D., Davison, A.W. & Booth, T.A. 1988. Premature degradation of epicuticular wax on Picea abies needles induced by ozone. In: Cape, J.N. & Mathy, P. (eds.). Scientific basis of forest decline symptomatology. Air Pollution Report 15. Commission of the European Communities, Brussels, p. 245–251.

Bell, D.T. & Ward, S.C. 1984. Foliar and twig macronutrients (N, P, K, Ca and Mg) in selected species of Eucalyptus used in rehabilitation. Sources of variation. Plant and Soil 82: 363–376.

Benner, P., Sabel, P. & Wild, A. 1988. Photosynthesis and transpiration of healthy and diseased spruce trees in the course of three vegetation periods. Trees: Structure and Function 2: 223–232.

Biologic markers of air-pollution stress and damage in forests. (1989). National Academy Press, Washington DC. p. 363. ISBN 0 309 04078 7.

Böhm, W. 1979. Methods of studying root systems. Ecological Bulletin 33. Springer-Verlag, Berlin. 188 p.

Cadahia, D., Cobos, J.M., Soria, S., Clauser, F., Gellini, R., Grossoni, P. & Ferreira, M.C. 1991. Observation of damages to Mediterranean forest species. MAPA, Madrid and Commission of the European Communities, Brussels. 96 p.

Campbell, G.S. & Norman, J.M. 1989. The description and measurement of plant canopy structure. In: Russell, G., Marshall, B. & Jarvis, P.G. (eds.). Plant canopies: Their growth, form and function. Cambridge University Press, Cambridge. p 1–19.

Cape, J.N., Paterson, I.S., Wellburn, A.R., Wolfenden, J., Mehlhorn, H., Freer-Smith, P.H. & Fink, S. 1988. Early diagnosis of forest decline. Institute of Terrestrial Ecology, Grange-over-Sands. 68 p.

— & Mathy, P. (eds.). 1988. Scientific basis of forest decline symptomatology. Air Pollution Report 15. Commission of the European Communities, Brussels. 410 p.

Carlson, C.E. & Gilligan, C.J. 1983. Histological differentiation among abiotic causes of conifer needle necrosis. Research Paper INT-298. USDA Forest Service, Intermountain Forest and Range Experiment Station. 17 p.

Chen, J.M., Black, T.A. & Adams, R.S. 1991. Evaluation of hemispherical photography for determining plant area index and geometry in a forest stand. Agricultural and Forest Meteorology 56: 129–143.

Colin, F. & Houllier, F. 1992. Branchiness of Norway spruce in northeastern France: predicting the main crown characteristics from usual tree measurements. Annales des Sciences Forestières 49: 511–538.

Cook, E.R. & Kariukstis, L.A. (eds.). 1990. Methods of dendrochronology. Applications in the environmental sciences. Kluwer, Dordrecht. p. 394.

Coyea, M.R. & Margolis, H.A. 1992. Factors affecting the relationship between sapwood area and leaf area of balsam fir. Canadian Journal of Forest Research 22: 1684–1693.

Cropper, W.P. & Gholz, H.L. 1991. In situ needle and fine root respiration in mature slash pine (Pinus elliottii) trees. Canadian Journal of Forest Research 21: 1589–1595.

Dobler, D., Hohloch, K., Lisbach, B. & Saliari, M. 1988. Trieblängen-Messungen an Buchen. Allgemeine Forst Zeitschrift 43: 811–812.

Eklund, B. 1954. Årsringsbreddens klimatiskt betingade variation hos tall och gran inom norra Sverige årea 1900–1944. Meddelelser fra den Statens Skogsforsknings institutt 44(8): 5–150.

Ellsworth, D.S. & Reich, P.B. 1992. Water relations and gas exchange of Acer saccharum seedlings in contrasting natural light and water regimes. Tree Physiology 10: 1–20.

Elvidge, C.D., Vogelmann, J.E. & Fox, C.A. 1989. Comparisons of aircraft and satellite sensors for monitoring air pollution effects on forests. In: Olson, R.K. & Lefohn, A.S. (eds.). Effects of air pollution on western forests. Air and Waste Management Association, Pittsburgh. p. 337–349.

Ewell, D.M., Mazzu, L.C. & Duriscoe, D.M. 1990. Specific leaf weight and other characteristics of ponderosa pine as related to visible ozone injury. In: Olson, R.K. & Lefohn, A.S. (eds.). Effects of air pollution on western forests. Air and Waste Management Association, Pittsburgh. p. 411–418.

Ewers, F.W. & Skied, R. 1981. Longevity of needle fascicles of Pinus longaeva (bristlecone pine) and other north American pines. Oecologia 51: 107–115.

Fengel, D. 1987. Chemischanalytische Untersuchungen am Holz erkrankter Bäume. Gelöste Substanzen im frischen Splintholz. Holz als Roh- und Werkstoff 45: 501–507.

Fink, S. 1988. Histological and cytological changes caused by air pollutants and other abiotic factors. In: Schulte-Hostede, S., Darrall, N.M., Blank, L.W. & Wellburn, A.R. (eds.). Air pollution and plant metabolism. Elsevier Applied Science, London. p. 36–54.

Forest damage and air pollution. Geneva, Global Environment Monitoring System. (1991) 117 p. + append.

Fritts, H.C. 1976. Tree rings and climate. Academic Press, London. p. 567.

Gholz, H.L. & Cropper, W.P. 1991. Carbohydrate dynamics in mature Pinus elliottii var. elliottii trees. Canadian Journal of Forest Research 21: 1742–1747.

Glavac, V. 1988. Blatt-Verkleinerungen in immissionsgeschädigten Buchenwäldern. Allgemeine Forst Zeitschrift 43: 813–814.

Gruber, F. 1986. Beiträge zum morphogenetischen Zyklus der Knospe, zur Phyllotaxis und zum Triebwachstum der Fichte (Picea abies (L.) Karst) auf unterschiedlichen Standorten. Beiträge Forschungszentrum Waldökosystemen/Waldschäden A25. 215 p.

— 1990. Verzweigungssystem, Benadelung und Nadelfall der Fichte (Picea abies). Birkhäuser Verlag, Basel. 135 p.

Günthardt-Georg, M.S., Matyssek, R., Scheidegger, C. & Keller, T. 1993. Differentiation and structural decline in the leaves and bark of birch (Betula pendula) under low ozone concentrations. Trees: Structure and Function 7 p. 104–114.

Hartmann, G., Nienhaus, F. & Butin, H. 1988. Farbatlas Waldschäden. Diagnose von Baumkrankheiten. Verlag Eugen Ulmer, Stuttgart. 256 p.

Helmisaari, H.-S. 1990. Temporal variation in nutrient concentrations of Pinus sylvestris needles. Scandinavian Journal of Forest Research 5: 177–193.

Hendrick, R.L. & Pregitzer, K.S. 1993. Patterns of fine root mortality in two sugar maple forests. Nature 361: 59–61.

Hoshizaki, T., Rock, B.N. & Wong, S.K.S. 1988. Pigment analysis and spectral assessment of spruce trees undergoing forest decline in the NE United States and Germany. GeoJournal 17: 173–178.

Hotz, A., Bilger, W., Kaiser, W.M. & Lange, O.L. 1990. Chlorophyll-Fluoreszenz, Photosynthesekapazität, Chlorophyll- und Nährstoffgehalte der Blätter "ungeschädigter" und als "geschädigt" eingestufter Buchen (Fagus sylvatica L.) im Gebiet um Würzberg. Forstwissenschaftliches Centralblatt 109: 40–54.

Hughes, M.K., Kelly, P.M., Pilcher, J.R. & LaMarche, V.C. (eds.). 1982. Climate from tree rings. Cambridge, Cambridge University Press. 223 p.

Innes, J.L. 1990. Assessment of tree condition. Forestry Commission Field Book 12. HMSO, London. 96 p.

— 1993a. Forest health: its assessment and status. Commonwealth Agricultural Bureau, Wallingford. In press.

— 1993b. Design of an intensive monitoring system for Swiss forests. In: Beniston, M. (ed.). Mountain environments in changing climates. Routledge, London. In press.

— , Landmann, G. & Mettendorf, B. 1993. Consistency of observations of forest tree defoliation in three European countries. Environmental Monitoring and Assessment 25: 29–40.

Jäger, H.J. 1982. Biochemical indication of an effect of air pollution on plants. In: Steubing, L. & Jäger, H.J. (eds.). Monitoring of air pollutants by plants. Methods and problems. W. Junk, The Hague. p. 99–107.

— , Weigel, H.J. & Grünhage, L. 1986. Physiologische und biochemische Aspekte der Wirkung von Immissionen auf Waldbäume. European Journal of Forest Pathology 16: 98–109.

Jalkanen, R. & Kurkela, T. 1990. Needle retention, age, shedding and budget, and growth of Scots pine between 1865 and 1988. In: Kauppi, P., Anttila, P. & Kenttämies, K. (eds.). Acidification in Finland. Berlin, Springer-Verlag. p. 691–697.

Jarva, M. & Tervahauta, A. 1989. Neulasten rikkianalysivertailu. Summary: A comparison of sulphur analyses of conifer needle samples. Silva Fennica 23(2): 117–124.

Kandler, O., Miller, W. & Ostner, R. 1987. Dynamik der "akuten Vergilbung" der Fichte. Epidemiologische und physiologische Befunde. Allgemeine Forst Zeitschrift 42: 715–723.

Kärenlampi, L. & Houpis, J.L. 1986. Structural conditions of mesophyll cells of Pinus ponderosa var. scopulorum after SO_2 fumigation. Canadian Journal of Forest Research 16: 1381–1385.

Karhu, M. & Huttunen, S. 1986. Erosion effects of air pollution on needle surfaces. Water, Air, and Soil Pollution 31: 417–423.

Koch, B., Ammer, U., Kritikos, G. & Kubler, D. 1984. Untersuchungen zur Beurteilung der Vitalität von Fichten anhand multispektraler Scannerdaten. Forstwissenschaftliches Centralblatt 103: 214–231.

Köstner, B., Czygan, F.-C. & Lange, O.-L. 1990. An analysis of needle yellowing in healthy and chlorotic Norway spruce (Picea abies) in a forest decline area of the Fichtelgebirge (N.E. Bavaria). 1. Annual time-course changes in chloroplast pigments for five different needle age classes. Trees: Structure and Function 4: 55–67.
Kurkela, T. & Jalkanen, R. 1990. Revealing past needle retention in Pinus spp. Scandinavian Journal of Forest Research 5: 481–485.
Lang, A.R.G. & Xiang, Y. 1986. Estimation of leaf area index from transmission of direct sunlight in discontinuous canopies. Agricultural and Forest Meteorology 35: 83–101.
Leckie, D.G. & Ostaff, D.P. 1988. Classification of airborne multispectral scanner data for mapping current defoliation caused by the spruce budworm. Forest Science 34: 259–275.
Lesinski, J.A. 1991. Morphological vigour indicators in Norway spruce. Proc. IUFRO Workshop on Ecological Modelling, Usti nad Labem, Czechoslovakia, 1991. IUFRO, Usti nad Labem. p. 38–46.
— & Landmann, G. (1988) Crown and branch malformation in conifers related to forest decline. In: Cape, J.N. & Mathy, P. (eds.). Scientific basis of forest decline methodology. Air Pollution Report 15. Commission of the European Communities, Brussels. p. 92–107.
— & Westman, L. (1987) Crown injury types in Norway spruce and their applicability for forest inventory. In: Perry, R., Harrison, R.M., Bell, J.N.B. & Lester, J.N. (eds.). Acid rain: scientific and technical advances. Selper, London. p. 657–662.
Lindquist, B. 1931. Den Skandinaviska Bogskogens Biologi. Svenska Skogs-Foren. Tidskr. 3: 179–532.
Lonsdale, D., Hickman, I.T., Mobbs, I.D. & Matthews, R.W. 1989. A quantitative analysis of beech health and pollution across southern Britain. Naturwissenschaften 76: 571–573.
Lüscher D 1989a. Die Blütenbildung bei Bäumen und ihre Auswirkung auf die Struktur der Krone: II. Die Weisstanne (Abies alba Mill.). Schweizerisches Zeitschrift für Forstwesen 140: 239–245.
— 1989b Die Blütenbildung bei Bäumen und ihre Auswirkung auf die Struktur der Krone: III. Die Fichte (Picea abies [L.] Karst). Schweizerisches Zeitschrift für Forstwesen 140: 813–822.
— 1990. Die Blütenbildung bei Bäumen und ihre Auswirkung auf die Struktur der Krone: IV. Die Buche (Fagus sylvatica L.). Schweizerisches Zeitschrift für Forstwesen 141: 147–154.
McClaugherty, C.A., Aber, J.D. & Melillo, J.M. 1982. The role of fine roots in the organic matter and nitrogen budgets of two forested ecosystems. Ecology 63: 1481–1490.
Magasi, L.P. 1988. Acid rain national early warning system. Manual on plot establishment and monitoring. Canadian Forestry Service Report DPC-X-25. Forestry Canada, Ottawa. p. 16 + append.
Mälkönen, E. 1974. Annual primary production and nutrient cycle in some Scots pine stands. Communicationes Institutale Forestalis Fennica 84. 87 p.
Miller, H.G., Miller, J.D. & Cooper, J.M. 1981. Optimum foliar nitrogen concentration in pine and its change with stand age. Canadian Journal of Forest Research 11: 563–572.
Miller, P.R. & Van Doren, R.E. 1981. Ponderosa and Jeffrey pine foliage retention indicates ozone dose response. Proc. Symposium on the Dynamics and Management of Meditteranean-type Ecosystems, San Diego, California. United States Department of Agriculture Forest Service, Berkeley. p. 621.
Muir, P.S. & Armentano, T.V. 1988. Evaluating oxidant injury to foliage of Pinus ponderosa: a comparison of methods. Canadian Journal of Forest Research 18: 498–505.
Müller, E. & Stierlin, H.R. 1990. Sanasilva Kronenbilder mit Nadel- und Blattverlustprozenten. Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft, Birmensdorf. 129 p.
Nash, B.L., Saunders, M.C., Miller, B.J., Bloom, C.A., Davis, D.D. & Skelly, J.M. 1992. ForestHealth, an expert advisory system for assessing foliar and crown health of selected northern hardwoods. Canadian Journal of Forest Research 22: 1770–1775.
Neill, C. 1992. Comparison of soil coring and ingrowth methods for measuring belowground production. Ecology 73: 1918–1921.
Niehaus, G. 1989. Terrestrische Zustandserfassung von Kiefernkronen (Pinus sylvestris) – ein differenzierter Anspracheschlüssel. Forst und Holz 44: 200–206.
Nihlgård, B., Schlyter, P. & Stjernquist, I. 1985. Luftförorreningsskador på bok i Sydsverige. Skogen 7: 20–22.
Osswald, W.F., Senger, H. & Elstner, E.F. 1987. Ascorbic acid and glutathione contents of spruce needles from different locations in Bavaria. Zeitschrift für Naturforschung 42c: 879–884.
Paynter, V.A., Reardon, J.C. & Shelburne, V.B. 1992. Changing carbohydrate profiles in shortleaf pine (Pinus echinata) after prolonged exposure to acid rain and ozone. Canadian Journal of Forest Research 22: 1556–1561.
Philipson, J.J. 1990. Prospects for enhancing flowering of conifers and broadleaves of potential silvicultural importance in Britain. Forestry 63: 223–240.
Pronos, J., Vogler, D.R. & Smith, R.S. 1978. An evaluation of ozone injury to pines in the southern Sierra Nevada. US Department of Agriculture Forest Service Pacific and Southwest Region Forest Pest Management Report 78–1. 17 p.
Richards, J.H. 1989. Evaluation of root growth and functioning of trees exposed to air pollutants. In: Committee on Biologic Markers of Air-Pollution Damage in Trees (eds.). Biologic markers of air-pollution stress and damage in forests. National Academy Press, Washington DC. p. 169–181.
Riederer, M., Kurbasik, K., Steinbrecher, R. & Voss, A. 1988. Surface areas, lengths and volumes of Picea abies (L.) Karst. needles: determination, biological variability and effect of environmental factors. Trees: structure and function 2: 165–172.
Roloff, A. 1985. Schadstufen bei der Buche. Der Forst- und Holzwirt 40: 131–134.

— 1989. Kronenentwicklung und Vitalitätsbeurteilung ausgewählter Baumarten der gemäßigten Breiten. Schriften aus der Forstlichen Fakultät der Universität Göttingen und der Niedersächsischen Forstlichen Versuchsanstalt, 93 p. 258.
Schulte-Hostede, S., Darrall, N.M., Blank, L.W. & Wellburn, A.R. (eds.). 1988. Air pollution and plant metabolism. Elsevier Applied Science, London.
Sinclair, W.A., Lyon, H.H. & Johnson, W.T. 1987. Diseases of trees and shrubs. Cornell University Press, Ithaca. 574 p.
Soikkeli, S. & Tuovinen, T. 1979. Damage in mesophyll ultrastructure of needles of Norway spruce in two industrial environments in central Finland. Annales Botanici Fennici 16: 50–60.
Strand, M. & Lundmark, T. 1987. Effects of low night temperature and light on chlorophyll fluorescence of field-grown seedlings of Scots pine. Tree Physiology 3: 211–224.
Tamminen & Starr, M.R. 1990. A survey of forest soil properties related to soil acidification in southern Finland. In: Kauppi, P., Anttila, P. & Kenttämies, K. (eds.). Acidification in Finland. Springer-Verlag, Berlin. p. 235–251.
Thiébaut, B. 1988. Tree growth, morphology and architecture, the case of beech: Fagus sylvatica L. In: Cape, J.N. & Mathy, P. (eds.). Scientific basis for forest decline symptomatology. Air Pollution Report 15. Commission of the European Communities, Brussels. p. 49–72.
Tuomisto, H. 1988. Use of Picea abies needles as indicators of air pollution: epicuticular wax morphology. Annales Botanici Fennici 25: 351–364.
Villanueva, V.R. & Santerre, A. 1991. Contribution to forest decline studies; biochemical effects of atmospheric pollution (acid rain) in Picea trees. In: Longhurst, J.W.S. (ed). Acid deposition. Origins, impacts and abatement strategies. Springer Verlag, Berlin. p. 141–160.
Westman, L. 1989. A new method for assessment of visible damage to birch and other deciduous trees. In: Bucher, J.B. & Bucher-Wallin, I. (eds.). Air pollution and forest decline. Eidgenössische Anstalt für das forstliche Versuchswesen, Birmensdorf. p. 223–228.
Will, G.M. 1957. Variation in the mineral content of Radiata pine needles with age and position in the tree crown. New Zealand Journal of Science and Technology 38B: 699–706.
Wolfenden, J., Robinson, D.C., Cape, J.N., Paterson, I.S., Francis, B.J., Mehlhorn, H. & Wellburn, A.R. 1988. Use of carotenoid ratios, ethylene emissions and buffer capacities for the early diagnosis of forest decline. New Phytologist 109: 85–95.

Total of 94 references