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.

Keywords: forest health, crown condition, bioindicators, indicator organisms, damage, monitoring, assessment.

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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 Eff ects on Forests, 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 developed, 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 interpretation. Both approaches 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 Skid 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 considerably valuable.

Various visual standards have been proposed (e.g. Innes 1990, Moller and Sterlin 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 (Moller and Sterlin 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 possible. In most countries, different approaches have been taken. Unfortunately, these are frequently incompatible.

With both crown transparency and crown discoloration, there is a problem of how the results of one investigation are interpreted. Both approaches 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 transparence 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. First, those that use the intensity of the discoloration, such as scores of index of 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 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 imaging, 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 be 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 (Scherr 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 transparence assessments achieved in such applications, 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 waveband lengths to be used, allowing detection of a variety of subtle changes in reflectance (Hoshiza-
ki 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 Ostaf, 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 index (LAI) (Lloyd 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 (Close 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 visible 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, non-specific 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, Ewel 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 (and 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.

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, Ekland, 1954), other factors also affect flowering and it does not occur in response to stress alone (Philipson 1960). It is important that the effects of any past flowering or fruiting are taken into account when making other assessments, as flowering 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), Grant (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), Thiebaut (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 Thiebaut (1988). However, hands-on examination of the branches enables the past history of shoot extension to be reconstructed, 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-visible indicators of crown condition

There are a considerable number of non-visible 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 non-specific 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 Huttuen 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 seeming being dependent on the degree of initial discoloration. For example, Oswald 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 (Baillie et al. 1988a, b). However, it is 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 Lunemark 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 Huppis 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 since 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 Ghosh 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). As in the case with those indices that have been proposed is insufficient 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 was 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 stress, 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. Mäkäräinen 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. Helmisarla 1990);
- the preceding weather conditions; and
- the analytical techniques used to determine the nutritional status (e.g. Jarvis 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 stages 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. Fenger 1987, Villanneva and Santee 1991),
but there 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 surprisingly 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 (Böhlm 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. McClougherty et al. 1982, Richard et al. 1990, 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 Kairiukstis 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). Currently, 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, the event leading to the damage is not always clear. The determination of 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 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 relate the combined observations to forest ecosystem health at the present time. However, much work is going on in this area, and rapid and substantial progress is likely in the near future.

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 indicators 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

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*Table 1. Different levels of monitoring.*

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<td>Increment analysis</td>
<td>Root disease evaluation</td>
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<td>Litterfall</td>
<td>Soils: biological activity</td>
<td>Contamination</td>
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<td>Root disease evaluation</td>
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<td>Soil analyses</td>
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field costs in extensive surveys are related to the plots, the increasing time spent on niche requirements, to develop highly effective methods, however, the time and costs rises dramatically when foliar sampling is required.

Another group of indices is based on non-

visual assessments of crown condition. These frequencies determine the detection, prescription, and 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 species 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 northern Scotland to southern Germany. In most cases, the studies have been specifically related to "forest decline" and comparisons have been made between vari-

ous 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.

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