FOREST HEALTH ASSESSMENT AND MONITORING – ISSUES FOR CONSIDERATION*

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Abstract. Assessment and monitoring of forest health represents a key point for environmental policy and for the management of environmental resources. With the renewed interest in assessment and monitoring of forest health generated by the suspected occurrence of a widespread forest decline in Europe and North America, many activities have been undertaken: however, some questions should be considered and clarified when attempting to estimate forest health. Particularly, the objective(s) of the assessment and monitoring program should be carefully identified. Identification of a program's task has a number of implications and consequences: it implies a definition of what concept of forest health (forest ecosystem health, forest health or forest trees health?) is assumed, what will be the target entity to be monitored, and therefore the identification of the relevant assessment questions and assessment endpoints. Consequences concern the definition of the spatial scale (from international to landscape and plot scale monitoring) and ecological coverage (from single species population to population of ecosystems) of the program, which can have a considerable influence on the choice of the proper sampling strategy and tactic, as well as on the most suitable methods, indicators and indices to be used. Although much of the work in the field of forest health and air pollution has concentrated on surveys on crown transparency and discoloration, there is an entire range of methods, indicators and indices developed to assess the health status of forests. The decision as to which ones should be used will depend on the aim of the program and on economic and practical considerations. A further consideration concerns the time span of the program, but any decision in this field is subject to many limitations due to difficulties in predicting future monitoring needs. All these points should be carefully considered and implemented according to a rigorous Quality Assurance procedure since any decision will influence future work for many years.

Key words: forest health, indicators, indices, monitoring, requirements, strategies

1. Introduction

There are some important reasons which make the assessment and monitoring of forest health of critical importance. First, forests are an invaluable ecological, economic, aesthetic and cultural resource on which the Earth's homeosthasis relies. Second, as for any other environmental resource, a proper management of forests should be based on the knowledge of their status and should be able to recognize changes in their condition in order to provide adequate management answers. Forests are generally sensitive to biotic and abiotic stresses and a continuous surveillance would allow any problem arising to be identified, provided that

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appropriate indicators are used. Third, although forests have since a long time and almost in any continent experienced cases of decline due to a variety of causes (e.g. Ciesla and Donaubauer, 1994), there is a growing awareness that atmospheric pollutants, global change and their combination with traditional pests and pathogens, may result in a serious threat to forest ecosystems (Schlaepfer, 1993). Effects of direct pollution on forests were first recognized more than 100 years ago. More recently the health of forests was thought to be declining in parts of Europe and North America, and this apparent deterioration was often assumed to be linked (although inextricably) to chronic exposure to long range transmitted air pollution and/or acidic deposition. Although the concentration of many pollutants has considerably changed over the last century (Taylor *et al.*, 1994), and in some places anthropogenic immissions should be considered as a new ecological factor which may affect forest ecosystems (Zöttl, 1990), it is still unclear whether a general decline of forests exists and the role of air pollutants is now being seriously reconsidered (Ferretti *et al.*, 1995a; Kandler and Innes, 1995; Skelly and Innes, 1994). Effects of climatic changes should be considered according to prediction models for different geographical regions (Kraüchi, 1993) with temperature increase, increased summertime evaporation accompanying warming, decrease of soil moisture in summer, increase of precipitation in winter and spring (with an associated increase in soil moisture in spring) being effects that are likely to occur. Effects on health, species composition, structure and processes in forest ecosystems are expected since adaptative mechanisms could not be developed at the speed required by the new environmental conditions (Kraüchi, 1993), although these effects are likely to be species-specific. In the cases of both air pollutants and global change, early detection of changes in forest ecosystems is of considerable importance and a continuous, well-suited monitoring program may provide useful information and baseline data to detect future changes (e.g. Bruns *et al.*, 1991; Messer *et al.*, 1991).

Fourth, it has been recognized that experimental causal research studies are either impractical or unfeasible with forests (Schmid-Haas, 1991): for example, it is very difficult to conduct realistic experiments with large, long-living trees and/or with entire stands, although progresses in this area have been already made (e.g. Bredemeier *et al.*, 1995; Rasmussen *et al.*, 1993). On the other hand, it is also questionable and sometimes meaningless to extrapolate findings from experiments with young plants (e.g. seedlings) to older ones (mature trees) (Kelly *et al.*, 1995). Properly designed field surveys and careful analysis of the resulting data sets can be considered as a sort of non-experimental cause-effect researches since they may allow the identification of both factors that can be excluded from the analysis and factors that deserve further investigation (e.g. Innes and Whittaker, 1993; Schmid-Haas, 1991; Strand, 1995a,b; Thomsen and Nelleman, 1994).

Fifth, prediction of the response of forest ecosystems to changes in pollutant loads and environmental conditions are essential for both scientists and politicians (Pylvänäinen, 1993). Mathematical simulation models capable of describing the physical, chemical and biological relationships existing in ecosystems and their changes in response to external disturbance are the best tool (Hope, 1995), but their validity rests on the validity of the input data. Thus, comprehensive, well-suited monitoring is the way to provide adequate data for model calibration and to identify the critical system functions. In short, careful observation and detailed analysis of forest health status and trends can allow specific problems to be identified, predictive models to be calibrated, experimental cause-effect researches to be effectively managed and mitigatory actions to be undertaken (Innes, 1994). Although forests have been surveyed for some time (e.g. yield plots established since 1888 in Switzerland, Köhl *et al*., 1994b), in recent years the concern on their health status has led to the launch of an unprecedented series of assessment and monitoring programs. International (e.g., the joint program of the European Commission and the UN/ECE *International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests* – ICP-*Forests*; the North American Sugar Maple Decline Project – NASMDP), national (e.g. the U.S. National Acid Precipitation Assessment Program, NAPAP, and the Environmental Protection Agency – EPA – Forest Health Monitoring – FHM; the Canadian Acid Rain Early Warning System – ARNEWS; surveys in many European countries) and small scale surveys (e.g. Bussotti *et al*., 1992, 1995, 1996) have been undertaken to detect suspected changes in forest condition due to air pollution. Furthermore, different international activities have been proposed for intensive monitoring, the most important being the EC and UN/ECE ICP-*Forests* Level II strategy, the UN/ECE *International Cooperative Programme on Integrated Monitoring on Air Pollution Effects* – ICP-IM, the Terrestrial Ecosystem Monitoring Sites (TEMS) of the Global Terrestrial Observation System (GTOS) and the proposed sites of the International Union of Forest Research Organization (IUFRO). In this paper I will attempt to clarify some methodological questions concerning the assessment and monitoring of forest health with special emphasis placed on the activities generated by the supposed occurrence of a widespread forest decline in Central Europe and North America. It is not intended as an exhaustive review of all the available methods and techniques: rather, it will provide an overview on the possible approaches to forest health assessment and monitoring.

2. Definitions and Implications

Before embarking on any discussion it is important to define some terms that will be used in the following chapters.

2.1. TREE HEALTH, FOREST HEALTH, FOREST ECOSYSTEM HEALTH

Unfortunately, different terms and concepts are used as synonymous in this context, and this can generate confusion when attempting to discuss this point. As far as trees are concerned, it is important to stress the differences between health, condition and vigour (Innes, 1993a), although some relationship does exist among them. Tree health should be considered in a pathological sense, since it is defined as the incidence of biotic and abiotic factors affecting trees. Tree condition is a more general term which refers to the outer appearance of trees. Tree vigour refers to the growth of a tree in relation to a hypothetical optimum. Tree vitality and crown vigour are also terms sometimes used (e.g. Jukola-Sulonen *et al.*, 1990; Strand, 1995a,b) as synonymous of condition and/or health. There are considerable differences between tree health, forest health, and forest ecosystem health. Although in principle the same concept of health defined for trees can be used for a forest (a population of trees within a forest ecosystem), it is still unclear what can be considered as healthy or unhealthy (e.g. Kolb *et al.*, 1994), or even if it is possible for a forest to be perfectly healthy as the term 'health' is defined; 'death of trees is inevitable as birth and growth to the vitality of forests' (Manion and Lachance, 1992), and, for example, if just one of the tree species of the forests is declining, can we make assertions about poor forest health? (e.g. Skelly, 1992). Approaching the forest ecosystem health concept is even more difficult, and one can argue about whether health can be either an appropriate descriptor or a property of an ecosystem (e.g Suter, 1993; Wicklum and Davies, 1995). In this paper it is assumed that a single definition of forest ecosystem health is impossible given the nature of ecosystems themselves and given the fact that the concept of health depends strongly on an *a priori* definition of the point of view from which the concept is developed and of the time and spatial scale considered. Other concepts have been proposed (Suter, 1993; Wicklum and Davies, 1995): sustainability, quality, integrity and status. Although it has been already criticized (Wicklum and Davies, 1995), a possible concept to be adopted as a framework for the discussion of monitoring air pollution effects on forests can be ecosystem integrity: ecosystem integrity can be considered as preserved when changes in the ecosystem are not affected by air pollution. Note that this definition needs to be referred to a specific (real, supposed or suggested) causal factor. With this definition an ecosystem can experience different kind of stressors (insects, diseases, climatic events) without being unhealthy or impaired (e.g. Hall, 1995). A conceptual model of a forest ecosystem can be helpful (Figure 1): a forest ecosystem includes a number of biotic and abiotic components and processes: trees are the most obvious, but poor tree health does not mean *per se* either poor ecosystem health or pollution impact. Single species tree mortality could be an integral part of forest ecosystem dynamics (Ciesla and Donabuauer, 1994; Mueller-Dombois, 1992). A problem is that no single measurement or group of measurement of ecosystem performance exists: to assess forest ecosystem status it is perhaps important to search for suitable indicators (e.g. ecosystem level processes, Grodzinski and Yorks, 1981). Plant community structure, biodiversity, primary productivity, decomposition rates, interactions of consumers/producers, chemical balance can be used in estimating status and trends of a forest ecosystem. For example, accumulation of trace metals, sulphur and nitrogen in the foliage does not automatically result in tree health deterioration:

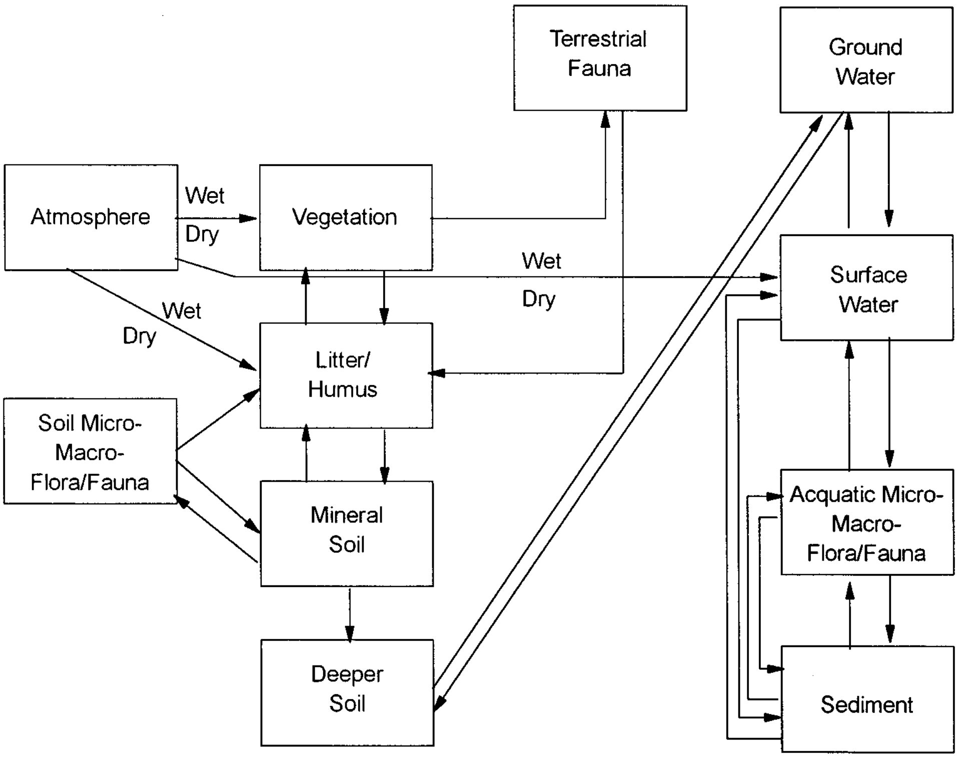

Figure 1. Conceptual model of a forest ecosystem (redrawn after Bruns *et al.*, 1991).

however, it can result in an accumulation of toxic materials on the forest floor following foliage shedding, and this can affect soil biota and decomposition rates. Simultaneously, contamination of grasses can affect rumen digestion of animals (e.g. deer, Moir, 1970, in Grodzinsky and Yorks, 1981) because rumen microbes are sensitive to N/S ratio, and this can have an effect on plant community and primary production through plant selection by grazers. Thus, an ecosystem may be impacted by pollutants through subtle processes and even when trees do not show any observable changes in their health yet.

2.2. ASSESSMENT AND MONITORING

In ecology, assessment means a quantitative or qualitative estimate or measurement of the status of a given environmental entity at a given time. This is generally accomplished by an organized group of activities the aim of which is to fulfil political, legal, societal, ecological, and statistical requirements. Monitoring can be broadly defined as a series of subsequent assessment of the status of the same target entity over time, i.e. ‘a process of detecting whether change has occurred, establishing its direction and measuring its extent’ (Ferris-Kaan and Patterson, 1992, p. 1). An operational definition of monitoring is given by Stevens (1994, p. 1): ‘monitoring is ... construed ... as tracking a particular environmental entity through time, observing its condition, and the change of its condition, in response to a well-defined stimulus’.

2.3. INDICATORS AND INDICES

An indicator is a characteristic or an entity that can be measured or assessed to estimate status and trends of the target environmental resource. This is almost the same definition given by Hunsaker (1993). This is however a general definition and further specification is needed. For example, if the target resource is a forest ecosystem, then trees can be one of the possible indicators. However, if the target resource is a population of trees, then foliage, branches and stem can all be considered as indicators. Therefore indicators can be defined only in relation to the resource to be monitored. An index is a characteristic that describes the status of the given indicator. For example, crown transparency is frequently used as an index to describe tree condition in forest condition surveys, the trees being assumed as indicators of forest condition. Usually an index is reported as a score which quantifies the status of the indicator under investigation.

The definitions given above have several operational consequences that should be considered when designing a forest health assessment and monitoring program. The consequences imply that the program should

(i) define exactly its target entity,
(ii) identify carefully its objective(s) and its assessment question(s),
(iii) define its spatial and/or ecological coverage,
(iv) identify the indicators and indices to be used in the program – which in turn
(v) define the intensity level of monitoring,
(vi) select the appropriate sampling strategy and tactic,
(vii) cover an adequate time span and
(viii) incorporate rigorous Quality Assurance (QA) procedures.

Stohlgren *et al.* (1995) identify additional critical attributes of reliable long-term monitoring studies: secure long-term funding, proper information management, peer-review and periodical program evaluation, integration with larger and smaller scale research, inventory and monitoring programs will undoubtedly improve the whole program.

3. Definition of the Target Entity

Although it seems quite easy to define the target resource in a forest health assessment and monitoring program, it is not so when considering the question from an operational perspective. This point deserves consideration since it has practical consequences. It could be relatively easy to assess the health status of a population of trees within a forest ecosystem, provided adequate expertise is involved in the program (e.g., entomologists and pathologists); also, the health status of a forest stand can be estimated provided that a representative sample of the concerned population is considered and provided that a clear definition of health is given, e.g. within the objectives of the forest management (it is not clear however how this definition can be achieved when health itself is the management objective, e.g. Kolb *et al*., 1994). It is much more difficult to assess the status of the ecosystem on the whole since a large number of ecosystem components (and therefore indicators) need to be incorporated in the program surveys (Innes, 1994). Thus, beside its task(s), a monitoring program should define exactly its target entity: a generic definition like e.g. 'European forests' would be infinitely vague since any operative definition of the forest resource to be monitored should detail aspects like size limits (surface, height, canopy coverage, ...), origin (natural versus artificial forests), management (managed or unmanaged forests), forestry practice (coppices, high forests, ...), level of ecological hierarchy to be investigated (trees, ground vegetation, fungi, mosses, lichens, soil; population or comunity, entire ecosystem). For example, the EC regulations 3528/86 and 1696/87 concerning 'the protection of forests against atmospheric pollution' provided some reference parameters for large-scale monitoring of forest health: forest size cannot be less than 0.5 hectares, canopy coverage should be 20% (this limit can drop to 10% for *Quercus ilex* and *Q. suber* forests), and all tree species can be considered and included in the assessment; only predominant, dominant and co-dominant trees higher than 60 cm should be assessed. However, no indication is given either about the origin of the forest, or about its management. In addition, dominated trees are excluded, as well as regeneration. Many of these conditions are the same as those adopted by the UN/ECE ICP-*Forests* (Anon., 1994b). Although recent amendments of the EC Regulations (e.g. 926/93 and 836/94) have incorporated new monitoring activities in large-scale surveys (soil and foliar analysis) which represent a considerable improvement of the international program, emphasis on trees rather than on forest ecosystems is obvious from these definitions. Different criteria are used by the U.S. EMAP Forest Health Monitoring (FHM). Forest land is 'a land that is at least 10% stocked with tree species, or currently nonstocked but formerly having such stocking; and not developed for use other than growing trees' (Tallent-Halsell, 1994). Commercial trees and plantations are classified as forest as well as stands that have recently been clearcut, but not developed to another land use. The site in question should be attached to a forest land 0.4 hectares in area and 36.6 m wide. Unlike the EC and UN/ECE program, U.S. FHM also considers seedlings (>30 cm in height or 2.54 cm at root collar).

Table I
Example of different assessment questions leading to different indicators

Assessment question	Assessment endpoint	Measurement endpoint	Indicator category
What is the integrity of oak forest ecosystems in Tuscany, Italy?	Tree health: diagnosis		Damage to trees
	– affected by pests		
	– affected by pathogens and other organism (MLOs)		
	– nutritional status		Foliage chemistry
	– affected by anthropogenic disturbance	Same but sample	
	– affected by other abiotic damage		
	– mortality rate		
	– regeneration frequency		
	Ground vegetation		Ground vegetation
	– species composition		
	Biodiversity		Vegetation species composition, animal abundance
	– threatened species		
	Soil		Soil physical and chemical parameters
	– chemical status		
	– soil biota: species		Soil biota, species abundance
	– mineralization		
	– soil solution chemical status		
	Input/output balance		Chemical parameters of deposition, biomass estimates, allocation and storage
	– deposition chemistry		
	– litterfall fluxes and chemistry		
	– streamflow chemistry		
	– runoff chemistry		
	– internal cycling		
	Nutrient turnover		
What is the condition of trees in oak forests in Tuscany, Italy?	Overall tree appearance		
	– crown transparency		
	– foliar symptoms		
	– flowering		
	– fruiting	Same but sample	Tree outer appearance
	– obvious damage		
	– ramification status		
	– stem and butt status		
What is the vigour of trees in oak forests in Tuscany, Italy?	Standing volume/area		
	DBH		
	Stem density		
	Increment	Same but sample	Tree growth efficiency
	Crown length		
	Crown width		

4. Identification of the Objective(s) and of the Assessment Question(s)

It is important to recognize that objectives should be clearly stated when attempting to design a monitoring program. Since multiple objectives must always be combined in a finite time and money horizon, priorities should be established taking into account political, legal, societal, and ecological aspects (e.g. Schmoldt *et al.*, 1994). Furthermore, since it is always difficult to identify long-term objectives (>10 years), it is best to concentrate on the short and medium term, where it is important to the managers to avoid ambiguous and generic objectives. Long-term objectives can be progressively identified as a result of an iterative process where the results provided by the program can help considerably (Stout, 1993). The explicitation of the assessment question is therefore important since it should drive the definition of the assessment and measurement endpoints and of the choice of the indicators to be used. Hunsaker (1993) defines the assessment endpoint as ‘an explicit expression of the environmental value to be protected’ and the measurement endpoint as ‘a measurable ecological characteristic that is related to the valued characteristic chosen as the assessment endpoint. Measurement endpoints are often expressed as the statistical or arithmetic summaries of the observations that comprise the measurement’. According to these definitions, it is obvious that different assessment questions lead to different assessment endpoints and different measurement endpoints. For example, the considerable difference existing between tree health and forest ecosystem health, and between tree health, condition and vigour results in different assessment questions and endpoints (Table I). Operational consequences should be considered when designing a program or planning a survey: to assess tree health, diagnostic techniques are required which are difficult to incorporate into large-scale extensive surveys, since they are time consuming and require adequate expertise. However, some easy observation could be done which may help in data interpretation. If the term health is correctly used, almost none of the surveys carried out in Europe can be considered as forest health surveys. Tree condition is rather easier to assess as it is based on the appearance of the tree. A well-trained surveyor can collect a relatively large number of data on the status of the target trees with the aid of binoculars and manuals including properly defined Standard Operating Procedures (SOPs). Most of the available data on the status of forests actually concerns condition rather than health. Tree vigour assessment should include measurements of growth, such as radial and longitudinal increment. These measurements are difficult to be incorporated in large-scale extensive surveys, but they can be done in individual intensive monitoring plots (see Section 8, Intensity level of monitoring). However, even when the topic (health, condition or vigour), the ecological hierarchical level (population, community, ecosystem) and the target entity (trees, ground vegetation, soil biota, ...) are defined, the aim of the monitoring program should be clearly stated. For example, there are three kinds of surveys that can be considered when attempting to estimate forest health (Innes, 1988a): first, surveys whose aim is *to establish the condition* of forests within a region in a given year (the assessment question would be: ‘What is the condition of forests in Italy in the year x?’) without wishing to determine any trend over time. Second, surveys whose aim is aimed *to detect changes in forest condition over time* in order to establish whether any trend is occurring (the assessment question would be: ‘Is the condition of forests changing in Italy?’). Third, surveys whose aim is aimed *to identify the cause* of any detected spatial and temporal pattern (the assessment question would be: ‘What are the causes of the spatial distribution of poor forest condition and/or of the temporal changes of forest condition observed in Italy?’). The different aims will influence the design the sampling strategy of a monitoring program.

5. Spatial and/or Ecological Coverage and Sampling Strategy

5.1. GENERAL REMARKS

The sampling strategy is closely related to the assessment question and to the main problem that any monitoring program has to face: the distinction between real directional trends (‘signals’) to random elements (‘noise’) (Eberhardt and Thomas, 1991; Hurlbert, 1984; Palmer, 1993). This is particularly important since political and management decision-making processes need to be found on a strong body of evidence (e.g. Power, 1995). Basically there are two main approaches that can be considered when designing a monitoring program. One emphasizes the regional population of the target resource; with the other, emphasis is placed on individual ecosystems. Each of these approaches has its own implications, since the sampling strategy and regional inferences can be considerably influenced by the choice. When emphasis is placed on regional population of forest resources, sites can be selected according to one of the two following procedures (Stevens, 1994): by a *model-based* approach, with sites being selected according to their particular characteristics (i.e. physical characteristics, spatial pattern, species composition, exposure levels, ...) or by a statistical (*design-based*) approach which utilizes a probability sample.

Obviously, when the focus is on individual ecosystems the selection of monitoring sites is mainly based on the first approach, i.e. their expected ability to reflect regional characteristics. For example, large-scale surveys aimed at evaluating the condition of a forest in a given region and in a given year require a design-based approach. Conversely, when surveys are aimed at establishing causal relationships, or when intensive studies have to be done, a model-based approach would offer considerable advantages, although inferences cannot be extrapolated to sites other than those being monitored (Innes, 1995). Stevens (1994) clearly illustrates how the two approaches for site selection lead to different methods for making regional inferences. Regional inferences can be made following a non-statistical (model-based) approach which use models (conceptual, statistical or mathematical; explicit or not) which specify the relationship between the sites and the regional population: therefore the validity of the population inferences rests on the validity of the model. This is the case of site selection according to the site's characteristics. On the other hand, regional inferences with a statistical (design-based) approach rest on the ability of the design to produce a regional representative sample and information. This is the case of the statistical approach. In principle, the main advantage of a probability sample is that inferences are free of subjectivity, spatial patterns can be detected and both design- and model-based data analysis can be performed.

5.2. LARGE-SCALE SURVEYS

Many of the national large-scale monitoring programs implemented in Europe have been designed according to a systematic sampling strategy. The joint EC-UN/ECE large-scale monitoring program is based upon a 16 × 16 km grid, with the centre of the sample plot located on the grid intersection. National programs have different grid densities: for example, France has a 16 × 1 km grid net, Germany has a 4 × 4 km grid and Italy has a 3 × 3 km grid. The common European sample is based on a subsample of these national grids: thus, the nominal 16 × 16 km grid has a different practical meaning, in Italy being a 15 × 18 km grid. The U.S. EMAP FHM is based upon a triangular grid of 40 km^2 hexagons all over the US (Tallent-Halsell, 1994). The blanket application of the systematic sampling has been criticized by Innes (1988a): he argues that the sampling strategy should be designed according to the extent and distribution of forests's cover, to the phenomenon to be investigated, to the hypothesis being tested and to the type of survey to be undertaken. He provides convincing arguments that different sampling strategy can be more effective when monitoring air pollution effects on forests. Similar conclusions have been reached by Clauser *et al.* (1988). The inflexibility of systematic sampling design has important consequences in cases of scattered and fragmented forest cover, since a considerable number of grid intersections may fall outside forests, thus resulting in a loss of data on forest condition in certain areas. This can be a drawback in studies aimed at detecting the effects of air pollution on forests in those cases where there is a spatial pattern of pollutants since the distribution of plots may result in an oversampling of a certain situation (e.g., high or low pollution levels). Further questions concern the grid density to be adopted: Köhl *et al.* (1994a) provide convincing evidence that a 16 × 16 km grid can yield in high variability in the resulting data set, with data concerning subpopulation (e.g. subregions or minor species) being totally unreliable. When studying air pollution effects on forests, different sampling strategies can be more effective: to ensure a certain degree of uniformity, and to contain the possible source of variation, a systematic stratified unaligned sample or multifactor sampling are more suitable (Innes, 1988a). They allow for the selection of sites that can be chosen and located according to the hypothesis being tested. Sites with particular problems can be excluded from the sample. However, there might be some problems with regional inferences (Stevens, 1994), and conclusions cannot be generalized.

5.3. INTENSIVE MONITORING

Intensive long-term monitoring sites need a different approach since their main aim is to provide data for the description of forest ecosystems and for causal inferences. According to Köhl *et al.* (1994b) the scientific value of a permanent intensive monitoring plot rests on the approach used for data evaluation. They distinguish three kind of plots: plots set up as experiments, as case studies and sample surveys. If causal inferences are the goal of the data analysis, the design of an intensive monitoring network should be set up as an experiment and it should be characterized by randomization, replication and homogeneity. This means that for example the same tree species, represented by even-aged plots located on the same soil type, should be tested under different treatments (i.e. different environmental conditions) to allow causal relationships to be established. However, the frequent non-random nature of the natural pattern of the involved variables, the heterogeneity of ecological conditions and the cost of data collection on intensive monitoring plots all make a large number of sample units unsustainable, thus precluding any statistical approach (probability sample) to site selection. For example, 71 site types have been identified in Switzerland and financial constraints prevented the location of plots in all site types with sufficient replication (Innes, 1995). Thus, site selection for plot establishment becomes an even more critical step which should be carefully addressed since the decision will have consequences on future work for many years. Although sites are usually selected subjectively, in the sense that no probability sampling design seems suitable, different approaches can be used to prevent ‘excessive’ subjectivity (e.g. Ferretti *et al.*, 1996; Innes, 1995; Stohlgren *et al.*, 1995; Herrmann and Stottlemayer, 1991). Theoretical, ecological and practical criteria are usually involved in site selection: theoretical criteria should consider the needs related to the hypothesis being tested (when experiment plots should be established), the basic knowledge of the forest ecosystem within the region being considered, the knowledge of mechanism acting in a forest ecosystems, and any available mathematical model needed to evaluate coupled temporal and spatial variability. Ecological criteria are mainly related to site homogeneity, although it has been criticized (e.g. Palmer, 1993); decision should be taken on the spatial scale (landscape to plot level) and nature (e.g. potential or actual vegetation) of homogeneity. Practical criteria include plot accessibility, availability of local staff, availability of data for the concerned site, presence of local monitoring stations, willingness of the local managers to host a monitoring plot, possibility of incorporating existing activities in the program (Innes, 1995; Ferretti, 1994a; Ferretti *et al.*, 1996; Stohlgren *et al.*, 1995;). Priorities among criteria should be established in order to facilitate site selection. When certain ecosystems are selected to host a limited number of plots a drawback is that there are limitations to any causal infer-

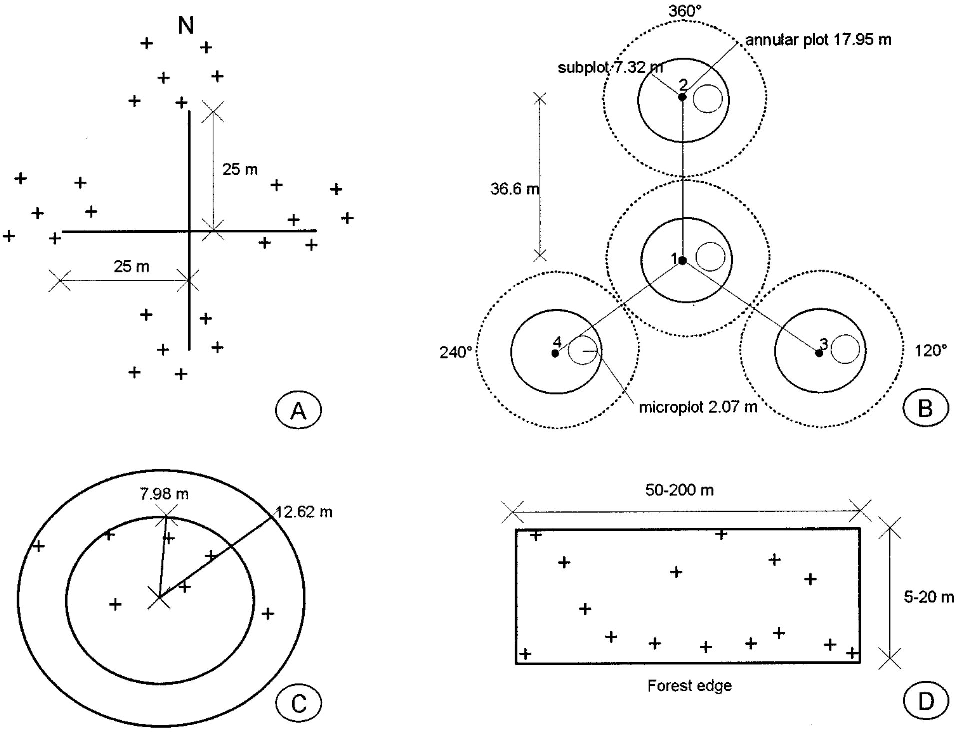

Figure 2. Different kinds (shape and size) of sample plot used in forest health surveys: (A) the cross-cluster stem-distance method plot recommended by the EC Regulation 1696/87; (B) the cluster-plot used by the FHM in U.S.: most tree measurements are performed in the subplots; saplings and seedlings are assessed on the microplots. The different radii are reported; (C) the fixed-area plot used in the Swiss survey; (D) the 'visibility' plot used in some Italian local surveys: mimimum and maximum side sizes are reported. Crosses indicate the hypothetical position of sample trees (redrawn after Clauser *et al.*, 1988; Stierlin and Walther, 1988; Tallent-Halsell, 1994; Cenni *et al.*, 1995).

ence; any cause–effect relationship found cannot be generally applied. In many cases, however, intensive monitoring plots are not established to provide representative data; rather data can be used to generate or calibrate models to predict forest development at the site concerned (Innes, 1995).

6. Sampling Sites Characteristics

6.1. LARGE-SCALE SURVEYS

Many of the large-scale surveys currently being implemented in Europe use a cross-cluster plot with the centre being located on the grid intersection (Figure 2). Other sampling units shape include circular ones like in Italy (national survey) and Switzerland, or subrectangular ones (like in some Italian regions) (Figure 2). In the U.S.A., each FHM plot consists of a series of circular subplots tied to a cluster of four points (Figure 2). Sample plots can have a fixed number of trees selected according to the stem distance method (with a variable plot surface), as in most of the countries, or a fixed plot surface (with a variable number of trees), as in Switzerland. There are some consequences with these two different methods (Köhl *et al.*, 1994b): using a fixed area plot, measured or estimated attributes can be related to the plot area, which keeps constant, while the number of trees may change as a consequence of mortality, growth and new trees. Therefore the sample is statistically dependent over time. On the other hand, with the stem distance method (fixed number of trees, variable plot area), attributes are related to trees. Since dead trees and felled trees have to be replaced by new ones, this is likely to generate samples not strictly dependent over time. In both cases a major problem is the visibility of the crown of the target trees, especially when dense broadleaved forests are concerned. A statistically sound selection method of plots and trees has the consequence that trees with poorly visible crowns are selected and this affect strongly any visual assessment. Poorly visible trees may result in an unquantifiable random error, since the observer tries to imagine what the condition of the crown may be based on the view of one or two branches, or on the view from the bottom of the tree which is a particularly misleading viewing point. To overcome these problems a shifting procedure for sample plots selection has been adopted in Tuscany, Italy (Clauser *et al.*, 1988; Cenni *et al.*, 1995). Plots have been established along forest trails and/or along forest edges, and the edge-effect is quantified (and subsequentely mathematically managed) by recording the relative width of the openness in the canopy and other relevant site conditions. Another question concerning the sample unit is its size and/or the number of trees to be selected for each site. Usually the plots of the large-scale surveys include 24–30 trees. EC Regulations indicate 24 trees per plot and the ICP *Forests* manual requires 20 trees as minimum. However, the optimal number of trees to be sampled at each sample plot has yet to be found, even if there are suggestions that a sample size of 24 trees is inadequate. Innes and Boswell (1990) demonstrate that significant variations exist within each subplot and amongst the 4 sub-plots of each plot, even when considering quite homogeneous sample plots (located in even-aged, single-species stands), as the one in the U.K. Forestry Commission's main survey, and this places a serious question on the representativeness of the sample size usually adopted to extrapolate data on forest condition. Things would be much more difficult in assorted-species and uneven-aged stands that are quite common, e.g. in low-altitude forests in Italy. The inadequate sample size adopted at plot level – together with the existing doubts on the grid density – make any assertion on 'forest condition' questionable: rather then on forest, the surveys implemented over the last decade in Europe seem to provide data on trees.

6.2. INTENSIVE MONITORING

EC regulation 1091/94 provides some guidelines for the configuration of the intensive monitoring plots. These guidelines include the size of the plot and its locational criteria: a 0.25 hectare plot is suggested, with an indicative dimension of 50 × 50 m. A surrounding buffer zone (10 m width) should be present. Plots should represent the most common forest ecosystem in a country and homogeneity is required as far as species composition, aspect, slope and forest management. These criteria are almost the same as those adopted by the ICP *Forests* for its Level II strategy. Different and more strict criteria have been adopted by the International Cooperative Programme on Integrated Monitoring of Air Pollution Effects (ICP-IM), which however focuses on several ecosystems rather than just on forests. Two kinds of sites are considered: intensive monitoring sites and biomonitoring sites. According to Pylvänäinen (1993) desirable ICP-IM intensive monitoring sites characteristically:

- are located in protected areas, far away ($>$50 km) from pollution sources,
- are located in small catchments (10–1000 ha) which should be hydrologically isolated and geologically homogeneous,
- allow input/output measurements,
- include different habitat types, and
- are close to sites where scientific researches related to modeling are carried out.

Although desirable, many of these characteristics can be matched only in a very limited number of sites. For example, it is not easy to find a site located 50 km away from any pollution source in Italy, which at the same time has all the other desired characteristics. The appropriate plot size is an open question. For example, a dimension of 2 ha has been adopted by the Swiss program (Innes, 1995) and it contrasts markedly with the minimun size proposed by the Regulation of the European Union. As for many other aspects, any decision on the dimension of the plot depends on the aims of the program: for example, any investigation on bird populations is impossible on a 0.25 ha plot; on the other hand, most of the forest ecological studies have been conducted at the plot to stand level with a spatial scale of 10 m^2 to 100 m^2 of homogeneous forest condition (Kareiva and Anderson, 1988 in Stohlgren *et al.*, 1995). The existing well-known relationship between diversity and sample area (e.g. Arrhenius, 1921) in establishing monitoring points in different patch types is discussed by Innes (1995) and it should be considered in relation to the characteristics of the geographical region under consideration.

7. Indicator(s) to be Used

The choice of indicators to be used in the program depends largely on the tasks of the program and represent a critical decision to be taken. Indicator is a term that can include organisms, population, communities and ecosystem components, processes and characteristics related to the assessment endpoints. Although analytical processes for the selection of the most suitable indicators can be used (e.g., Hunsaker, 1993), indicator performance and goodness are subject to change for example, if the monitoring needs change over time, or to accommodate new perspectives, approaches and techniques. For example, although it is often assumed that through protecting the most sensitive species in an ecosystem it is possible to inadvertently protect all the others, there is a considerable debate about the use of single indicators (even the most sensitive ones) to extrapolate effects on ecological systems (e.g. Cairns and Pratt, 1993). Thus the definition of suitable sensitive indicators at forest-ecosystem level is difficult, and no single measurement can be considered as an indicator of ecosystem performance. For example, four indicator categories have been adopted by the EPA's Environmental Monitoring and Assessment Program (EMAP):

Response indicators, which quantify the biological condition of the ecosystem.
Exposure indicators, which are measures of ecosystem exposure to chemicals, radiations, climatic extremes, physical disturbances, etc.
Habitat indicators, which should represent the conditions on a local or landscape scale (extent, spatial and vertical pattern of the vegetation cover).
Stressor indicators are those which reflect activities or occurrences that determine changes in exposure or habitat conditions like episodes of acute pollution, introduction of exotic species.

In principle, all of these indicator categories might be considered in a program that would concern the integrity of a forest ecosystem. However, considerable work is required to find out the most suitable indicators within each category (e.g., Muir and McCune, 1987). For example, desirable indicators characteristically (Hunsaker, 1993):

- correlate with changes in processes or other unmeasured components such as stressor of concern,
- are appropriate for regional monitoring and apply to a broad range of resource classes,
- can integrate effects over time,
- are unambiguously and monotonically related to an endpoint, a relevant exposure or habitat variable, or a stressor,
- can be quantified by synoptic monitoring (low natural variability) or can be cost-effectively monitored,
- can be related to the overall structure and function of ecosystems,
- are responsive to stressors of concern for management strategies,
- should have a standard measurement error,
- have a low measurement error,

- have an historical data base or accessible data for development of a data base, and
- are cost effective.

Although an entire range of visual, non-visual, and objective indicators and indices exists to estimate forest health (e.g. Innes, 1993b), in Europe much work in forest health monitoring has been concentrated on assessment of just one indicator (trees) and two indices (crown transparency and discoloration): despite the fact that they lack many of the reported requirements, they have almost universally been assumed to be the appropriate indicator of forest health and their assessment formed the basis for a series of international reports (e.g. Anon. 1987, 1988, 1989, 1990, 1991, 1992, 1993a, 1994a, 1995) on what was previously called ‘forest damage’ and subsequently ‘forest condition’. However, a series of problems have been identified with these indicators and indices (e.g., Skelly, 1993; Innes, 1988a,b): the basic assessment method (i.e., a visual estimate of crown transparency and discoloration performed by surveyors with the aid of binoculars) (i) provide the basis for subjective evaluation, thus making it difficult to compare data collected by different field crews (Bohuot *et al.*, 1992; Bussotti *et al.*, 1990; Ferretti *et al.*, 1994, 1995b; Gertner and Köhl, 1995; Ghosh *et al.*, 1995; Innes, 1988 a,b; Innes *et al.*, 1993; Köhl, 1991, 1992; Mahrer, 1989; Mauser, 1991; Montoya *et al.*, 1992; Neumann and Stowasser, 1986; Schadauer, 1991), (ii) makes detailed observations of foliar symptoms difficult, which implies (iii) poor attention being paid to ascertain the cause of any observed deviation from ‘nominal’ conditions. A further consequence is that emphasis on defoliation and discoloration assessment have often resulted in poor attention being paid to ramification, stem and butt status, although it can provide useful information for explaining the actual condition of the trees concerned (e.g. Skelly, 1993; Innes and Schwyzer, 1994). In addition an unanmbiguous relationship between crown transparency and objective measurement of tree vigour (e.g. increment) has yet to be found (e.g. Kenk, 1990; Schmid-Haas, 1989; Konnert and Mettendorf, 1990), and if such a relationship exists, than it would probably vary with species and site.

8. Intensity Level of Monitoring

Many years of monitoring of crown condition of forest trees have failed to establish direct and general relationship between air pollution and crown density and discoloration. However, this does not mean that pollutants may not affect forest ecosystems: rather, it is likely that the pollutant concentrations typical of most forest ecosystem may cause less spectacular and much more subtle effects in ecosystem structure and functioning. As a consequence, if well-suited extensive surveys can provide valuable data of fluctuation on tree condition and even useful information for isolating some factors involved, only intensive, integrated studies and careful

Table II

Activities currently being implemented under the different intensity level of monitoring in the UN-ECE ICP-Forests strategy (Level I and II). Level III activities are yet to be specified within the ICP Forests program: the activities reported in the relevant column in the table are those defined by the subprograms of the UN-ECE ICP on the integrated monitoring of ecosystems

Level I	Level II	Level III
Crown condition assessment	Soil analysis	Inventory of birds and small rodents
Soil analysis	(more detailed)	Inventory of plants
Foliar analysis (optional)	Foliar analysis	Air chemistry
	Increment	Metal chemistry in mosses
	Deposition chemistry	Soil water chemistry
	Meteorology	Groundwater chemistry
		Runoff water chemistry
		Lake water chemistry
		Litterfall chemistry
		Hydrobiology of streams
		Hydrobiology of lakes
		Vegetation
		Trunk epiphytes
		Aerial green algae
		Microbial decomposition
		Forest stand inventory
		Plant cover inventory
	+ Level I	+ Level I and II

observation of the ecosystem's component and functioning can allow causal relationships to be established. Integrated or multimedia monitoring of an ecosystem means that physical, chemical, biological measurements should be performed at the same location, over time, for different ecosystem compartments (Bruns *et al.*, 1991; Pylvanainen, 1993; Wiersma and Otis, 1986): forest ecosystems are a suitable location for this purpose, since they offer on a small scale an entire set of organisms (producers – including long-living ones – primary and secondary consumers, decomposers), functions and processes (photosynthesis, mineral nutrition, hydrological balance) that can be sensitive to environmental changes. However, when approaching the design of a monitoring program it should be clear that there are some differences between what is *desirable*, what is *possible*, what is *practical* and effective (Innes, 1993a,b). For example, it would be desirable to measure and monitor any component and process of the target ecosystem. It is clearly impossible because of technical and therefore financial constraints. A selection amongst indicators should be done according to the hypothesis being tested and the current status-of-the art. Some international and national monitoring programs have been designed considering different intensity level of monitoring. Table II reports the indicator proposed by the UN-ECE ICP on forest monitoring.

Each monitoring level is more detailed than the last, since it includes a higher number of indicators: but, the more detailed the monitoring level, the less extensive the investigation, and only a few sites can be devoted to the most intensive monitoring level. Three monitoring levels are distinguished. Level I includes extensive survey on tree crown condition (defoliation and discoloration, readily identifiable damaging agents), and soil analyses. Foliar analyses is also an optional survey. Level I surveys should be undertaken on more than 4700 plots selected according to the nominal 16×16 km grid throughout Europe. Level II strategy is currently being implemented. It includes intensive monitoring plots selected in a more subjective way. The number of these plots (643 plots installed by the end of 1995, Anon., 1996) is dramatically lower than those pertaining to Level I: usually Level II plots are 10–20% of the total Level I plots. Investigations on Level II plots include crown condition, more detailed foliar and soil analyses than those performed on Level I, deposition chemistry, increment, meteorology. Discussions concerning a more detailed crown condition assessment and ground vegetation assessment on Level II plots have already started, and some countries (i.e. Spain, Switzerland, Italy-Tuscany, France) have already started with these investigations. Level III strategy should concern special ecosystem analysis: however, this strategy has yet to be implemented within the ICP-Forests and it is likely that it will be developed in cooperation with ICP-IM. Indicators considered by the UN-ECE ICP-IM are listed in Table II. Many and detailed investigations will probably be undertaken (e.g., soil water analysis, soil biota) and this makes the proper selection of monitoring sites and plots of critical importance. Large observational units ($>$1000 ha) have been proposed for the Swiss program, and this would allow the inclusion of several monitoring strategies and programs with the benefit of avoiding duplication of efforts (Innes, 1993a). However, only a very limited number of sites can usually be devoted to Level III monitoring because of the high costs of setting up and maintenance.

9. Time Coverage of the Program

Besides composition and structure, a forest ecosystem is characterized by biorhythms (Schirone, 1993). Plants have a number of functions which follow rhythmic courses, ranging from ultradian ($<$20 hours) to poliennial ($>$2 years) rhythms. It is well known to foresters and to scientists that there are cyclic pulsations in phenology and in growth, which vary according to the species and to the coenosis. For example, Kairiutskis and Dubinskaite (1990) report different growth rhythms for Scots pine (*Pinus sylvestris* L.) according to the coenosis's ecology. Growth rhythm of stands characterized by the *Carico-sphagnosum* type have a 9–12 years pulsation, while the *Vaccinium mirtillum-sphagnosum* stand type have 10–13.3 years. The same Authors also reported much longer cycles, 30 up to 192 years. It is also to be noted that some changes in health, species composition and structure are a natural occurrence in forest ecosystems and that those natural changes usually take place over a long period. In addition, it is known that many plants (e.g. geophytes) have prolonged dormancy (1–2 years) and this should be taken into account, since it can influence the strategy for selecting sampling sites (repeated random sampling vs. permanent monitoring plots), the time and the number of visits to the plot, the total length of the monitoring program and the interpretation of the results (e.g. Lesica and Steele, 1994). Furthermore, forest ecosystems usually experience a variety of stressors causing a variety of effects, which can in some cases be delayed for some time (Becker, 1989; Landmann, 1989; Gandolfo and Tessier, 1994).

Therefore it is not easy to establish a suitable length for a monitoring program as it is highly dependant on the aim of the program, and as we have very few bases for a careful definition of long-term aims (Innes, 1994). A continuous and long-term monitoring program would probably be the best, although financial availability, scientific and technological progresses are likely to influence strongly the implementation and follow up of the program. For example, the program MONITO (MONitoraggio Intensivo delle foreste TOscane) in Tuscany is designed in a long-term perspective, but it is financed only up to 1997 (Ferretti *et al.*, 1996). On the other hand the French program RENECOFOR (RÉseau National de suivi a long terme des ECOsystèmes FORestiers) is planned to last 30 years (Ulrich, 1994), the main aim being the detection of fluctuation in forest health and impairment in ecosystem functioning. The Swiss program is designed taking into account both medium-term (<10 years) and long-term aims, although long-term aims can be formulated only in a general way (Innes, 1994). In any case, continuity and long-term seem to be the characteristics emphasized. The emphasis on continuity would enable the detection of rapid changes in some indicators caused by sudden stressors; the emphasis on long-term would enable the fainter trends that are expected in the perspective of a progressive and cumulative load (i.e. air pollution, climatic changes) to be detected. As reported in Pylvänäinen (1993, p. 11) ‘intermittent and short-term monitoring does not provide the information on temporal and spatial variations required to distinguish natural from anthropogenically induced effects’.

10. Quality Assurance

Although it is widely adopted as routine procedure in North America, Quality Assurance (QA) is still a relative new topic in forest monitoring in Europe. Loosely speaking, the quality of a given product is the degree to which it meets a need (Cline and Burkman, 1989). In practice, QA ‘is an organized group of activities defining the way in which tasks are to be performed to ensure an expressed level of quality’ (Millers *et al.*, 1994). In practice, this mean that any data produced by a monitoring program should be the result of a process in which all steps are carefully and correctly addressed, from the design of the survey to the data collection, processing and reporting. The main benefit of a QA program is the improvement of consistency, reliability and cost-effectivenness of the program through time. For example, long-term monitoring programs may last decades, and the time factor can impact strongly how the work is viewed and implemented by the personnel involved (Shampine, 1993). A QA procedure is critical from the early stages of monitoring programs, and a QA plan is fundamental, since it forces program managers to identify and evaluate the majority of factors involved in the program. In addition, the assessment of data quality permits a mathematical management of uncertainty and this could result in a more appropriate data presentation and use. Four main activities are considered in a QA program (Cline and Burkman, 1989):

Quality Management (QM). It concerns the proper design of the project and its documentation and it has the major benefit of ensuring that proper activities are performed in a proper way.
Quality Assurance (QA). It concerns the first steps of the evaluation of the quality of the data, including the use and documentation of Standard Operating Procedures (SOPs). It has the benefit of providing consistent methods with known and verified data quality.
Quality Control (QC). It mostly concerns the training, calibration and control phases. Its major benefit is to ensure that data are appropriately collected and quality assurance is carried out.
Quality Evaluation (QE). It mainly concerns the statistical evaluation of the data quality. It allows precision and accuracy of determinations to be evaluated, providing a basis to evaluate comparability of data.

Unfortunately, many of the basic points of QM are not oftenly properly considered in Europe. More effort has been spent on adopting SOPs and on evaluating the consistency of the data. For example, the UN/ECE ICP-Forests produced a Manual (Anon., 1994b) which attempted to introduce a standardization of methods. This Manual was first adopted in 1987 and it is continuously updated as new activities are incorporated in the program. However, some countries and regions have developed their own procedure for special situations not contemplated in the common Manual (Anon. 1993b; Ferretti, 1994b; Mathieu, 1994; Müller and Stierlin, 1990; Stierlin and Walther, 1988; Cenni *et al.*, 1995; Innes, 1990) and some considerable difference exist among countries (Ferretti, 1994c). Now there is a reasonable doubt that the differences reported in defoliation between countries can be at least partly caused by the different standards and references. That is why since 1992 the maps of the international reports have a caption in which the reader is warned about the limits of international comparisons. To assess the reliability and consistency of data collected in large-scale surveys two activities are fundamental: training of the personnel involved in data collection and field checks on reproducibility of data (Innes, 1988a; Innes and Boswell,1991; Millers *et al.* 1994; Ferretti *et al.* 1995c), but even the implementation of field checks activity can lead to other problems (e.g. Ghosh *et al.*, 1995). Some programs have established Measurement Quality Objectives (MQO; e.g. Millers *et al.*, 1994; Tallent-Halsell, 1994) and data are required to fit into these limits before thay can be processed further. Other QA activities within forest monitoring programs should include verification of data completeness, data plausibility, data trasmission, audits and data quality reporting. A report on data quality should be included among the results of a survey, since it helps nterpretation considerably, allows an estimation of the the limits of the survey itself, and provide the basis for improvements. Surprisingly it occurs only rarely and this is a principal cause of uncertainty of data and therefore a serious limit to the use of survey data for causal inference.

11. Conclusions

The invaluable importance of forests is obvious and great care should be devoted to preserve their health. Forests provide us with a number of benefits: the perpetuation of these benefits cannot however fail to consider the knowledge on how and at what rate forest health can be endangered either by ‘traditional’ (pests, pathogens, weather condition) and/or ‘new’ factors (air pollution, climatic changes). A number of programs have been implemented dealing with forest health in Europe and North America. Particularly, considerable work has already been done in monitoring the condition of forest trees, and millions of data have been collected on crown transparency and discoloration. Unfortunately these data suffer a number of limitations: they are non-specific, collected according to sampling designs not always appropriate to provide the desired information and liable to errors. Besides extensive surveys on transparency and discoloration, intensive monitoring programs have been established in many countries: even if in most cases emphasis is still placed on trees, assessment and measurements of other ecosystem compartments (ground vegetation, soil) and characteristics (deposition, meteorology) have been incorporated in the monitoring activities. Perspective for continuous and integrated, multimedia monitoring should consider that assessment of any change is impossible without baseline data and that remedial action cannot be undertaken without the evidence that change is occurring or has already occurred. This latter point implies that data collected should be as strong (statistically sound, reliable, consistent) as the political and management decisions are requested to be. This is a critical point for any monitoring program. The successive step is that remedial action needs further data to be calibrated and validated. A long-term well-suited assessment and monitoring program is the tool which allows a continuous evaluation of the ecosystems’ status and trends, the validation of remedial actions and the collection of basic information on natural resources. The build-up of predictive mathematical models and the mapping of critical levels and loads related to receptor sensitivity are closely linked to monitoring activities since they need reliable data with which to work (Chadwick and Kuylenstierna, 1991; Hunsaker *et al.*, 1993;

Strickland *et al.*, 1993; Hicks *et al.*, 1993; Holdren *et al.*, 1993). The concepts of critical loads and critical level are revealing about the need to collect reliable and integrated information (Anon., 1993c). In both cases, emphasis is placed on sensitivity of different environmental receptors – e.g. freshwaters, crops, forests – to establish critical thresholds of pollutant concentration (critical level) or critical exposure threshold (critical load); this requires a considerable amount of work to be done by scientists and resource managers to update the knowledge on sensitivity of environmental resources.

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