Monitoring Forest Damage

Methods and Development in Sweden

Sören Wulff

Faculty of Forestry
Department of Forest Resource Management
Umeå

Doctoral Thesis
Swedish University of Agricultural Sciences
Umeå 2011

Acta Universitatis agriculturae Sueciae
2011:97

Cover: From left: defoliated Scots pine, fieldwork in the target-tailored inventory of resin top disease, damage by Spruce bark beetle.
(photo: S. Wulff)

ISSN 1652-6880
ISBN 978-91-576-7641-2

Print: Arkitektkopia, Umeå 2011

Monitoring Forest Damage: Methods and Development in Sweden

Abstract

The aims of the work this thesis is based upon were to assess past and current methods of monitoring forest damage in Sweden and to propose key components of a new monitoring system that would be better adapted to the information requirements. A utilitarian perspective is adopted in the thesis, thus forest damage is defined as anything that reduces the vitality of trees in a forest or their economic value. Similarly, the term forest condition is used to describe the extent to which damage has reduced the vitality of trees, as assessed (largely) through crown defoliation.

Evaluation of the accuracy of large-scale monitoring of forest condition showed significant differences between observer teams, although on average their assessments did not significantly differ from a national standard. The results indicate that the long-term development of forest condition is the most important information that can be obtained from these kinds of inventories. Short-term fluctuations are difficult to interpret, since they may be due to extreme weather events or assessment variability. Large-scale monitoring, such as that performed in national forest inventories, has good potential for estimating geographical distributions, areas, and causes of extensive damage outbreaks. In major outbreaks even gradual changes of damage levels can be estimated with relatively high precision.

However, large-scale monitoring also has limitations. To meet current information needs, assessments of forest damage must be timely and be made at several spatial scales. Thus, in addition to broad monitoring programmes that provide time-series information on specific type of damage and their causes, there is a need for local and regional inventories adapted to specific damage events. In this way data can be obtained to support not only general strategic decisions but also specific regional and local mitigation programmes which are likely to become increasingly important following anticipated climate changes.

To meet the information needs a new Swedish forest health assessment system is proposed that includes several interacting components targeting the information requirements for strategic and operational decision-making, and accommodates a mechanism for continuously expanding the knowledge base.

Keywords: forest condition, defoliation, visual perception, national forest inventories, accuracy, precision, tree disease, long-term monitoring, target-tailored inventories

Author's address: Sören Wulff, SLU, Department of Forest Resource Management,
SE-901 83 Umeå, Sweden
E-mail: Soren.Wulff@ slu.se

Dedication

To Anne-Maj, Jonas and Christoffer

Allt är möjligt. Det omöjliga tar bara lite längre tid.
Winston Churchill

Contents

List of Publications **6**

1 Introduction **7**
1.1 Background 7
1.2 Forest health and forest damage 8
1.3 Indicators 10
1.3.1 Crown defoliation 12
1.4 Forest damage 15
1.4.1 Biotic damage 16
1.4.2 Abiotic damage 18
1.4.3 Assessment of forest condition and forest damage 19
1.5 Monitoring 20
1.5.1 Information needs 20
1.5.2 Monitoring forest condition 20
1.6 Forest damage in Sweden 22
1.6.1 Spatial and temporal trends of forest condition 24
1.7 Needs for new approaches in monitoring forest damage 26

2 Objectives **28**

3 Material and methods **29**
3.1 Evaluation of the accuracy of forest condition assessments (Paper I) 29
3.2 Evaluation of systematic plot-based sampling designs (Papers II and III)31
3.3 A new system for assessing and monitoring damage (Paper IV) 34

4 Results **35**
4.1 Evaluation of the accuracy of forest condition assessments (Paper I) 35
4.2 Evaluation of systematic plot-based sampling designs (Papers II and III)36
4.3 A new system for assessing and monitoring damage (Paper IV) 40

5 Discussion **43**

6 Conclusions **49**

References **50**

Acknowledgements **65**

List of Publications

This thesis is based on work described in the following papers, which are referred to by the corresponding Roman numerals in the text:

I Wulff, S. (2002). The accuracy of forest damage assessments – Experiences from Sweden. *Environmental Monitoring and Assessment* 74: 295-309.

II Wulff, S., Hansson, P., and Witzell, J. (2006). The applicability of national forest inventories for estimating forest damage outbreaks – Experiences from a *Gremmeniella* outbreak in Sweden. *Canadian Journal of Forest Research* 36: 2605-2613.

III Wulff, S., Roberge, C., Hedström Ringvall, A., Holm, S., and Ståhl, G. On the possibility to assess and monitor forest damage within large-scale monitoring programs – a simulation study (manuscript).

IV Wulff, S., Lindelöw, Å., Lundin, L., Hansson, P., Axelsson, A-L., Barklund, P., Wijk, S., and Ståhl, G. (2011). Adapting forest health assessments to changing perspectives on threats – a case example from Sweden. *Environmental Monitoring and Assessment* DOI 10.1007/s10661-011-2130-7

Papers I, II and IV are reproduced with the permission of the publishers.

1 Introduction

1.1 Background

Forests provide many goods and services. In addition to being sources of economically important products and playing a key role in industrial activities they provide important recreational areas and tranquil, restorative sites (Pröbstl *et al.*, 2010). Further valued aspects of forests are their wildlife, preservation of biodiversity, carbon sequestration and provision of food, fuel and shelter (Voller & Harrison, 1998; Valentini *et al.*, 2000; Diaz *et al.*, 2006; Lindenmayer *et al.*, 2006). Sustainable management of forests is highly important to provide these goods and services. Damage and other disturbances naturally occur in forests and are important for many ecological processes, but an important element of sustainable management is to develop and apply silvicultural practices that restrict forest damage to acceptable levels (Breda & Badeau, 2008; Coulson & Stephen, 2008). Damage to forests has always been of great concern, and serious decline (described by expressions such as “forest death” or “waldsterben” in German) have raised alarm in recent decades (Hinrichsen, 1987; Liedeker *et al.*, 1988). Thus, there is a clear need for accurate information on forest damage to support decision-making**,** and for a long time inventories have been carried out to assess forest damage and the abundance of damaging agents (e.g., Thorell & Ostlin, 1931; Power, 1988; Innes, 1993; Ciesla & Donaubaur, 1994).

In Europe a fear of forest decline escalated during the 1980-1990s when substantial forest damage was believed to be associated with air pollution and acid rain (e.g., Nihlgård, 1985; Schütt & Cowling, 1985). This prompted the initiation of major monitoring programmes within the framework of the International Co-operative Programme on assessment and monitoring effects of air pollution effects on forests (ICP Forests) under the Convention of Long-Range Transboundary Air Pollution (CLRTAP) (Lorenz, 1995). Today this type of monitoring is wide spread (Lorenz & Mues, 2007; Tkacz *et al.*, 2008; Shin & Chun, 2011; Wulff *et al.*, 2011)

1.2 Forest health and forest damage

Numerous concepts are used to describe forest health, and the definitions vary, depending on both the perspective (e.g., utilitarian or ecosystem), and scale (which may range from individual trees through landscapes to regions; Kolb *et al.*, 1994). In the broadest sense, forest health is used synonymously with ecosystem health to describe conditional states of forest ecosystems (Coulson & Stephen, 2008). In this respect a healthy forest ecosystem has high resilience to respond to, and recover from, disturbances. However, the complexity of ecosystems complicates attempts to describe their health (Ferretti, 1997; Teale & Castello, 2011). Terms such as balance, function and sustainability have been proposed to describe it**,** but can tend to be difficult to define and measure (Kolb *et al.*, 1994).

Forest health in a more restricted sense is limited to the status of the trees. This can be considered as a utilitarian perspective and is the perspective adopted in this thesis (cf., Figure 1). However, even in this case the characteristics of a healthy (or unhealthy) forest are far from straightforward, due to the wide range of states of trees in any forest, and the diversity of factors that affect them. Solberg (1999b) suggests that a healthy tree can be defined as “a tree without symptoms or malfunctions due to biotic or abiotic stresses at present or in the past; it performs well in growth rate; has a good chance to further survival; and has a certain ability to defend itself against, to tolerate and recover from stress”. The related terms tree vitality and tree vigour, with slightly different definitions (Ferretti, 1997; Dobbertin, 2005), are also sometimes used in this context.

Forest health is affected by damage, which can be regarded as anything that adversely affects trees in the forest and interferes with timber production (Ostry & Laflamme, 2009), but may also be viewed holistically as anything that conflicts with the maintenance of functions, diversity and resilience of forest systems. In this thesis utilitarian perspective is adopted and forest damage is used to denote any factor that negatively affects the vitality of trees or their economic value (Figure 1).

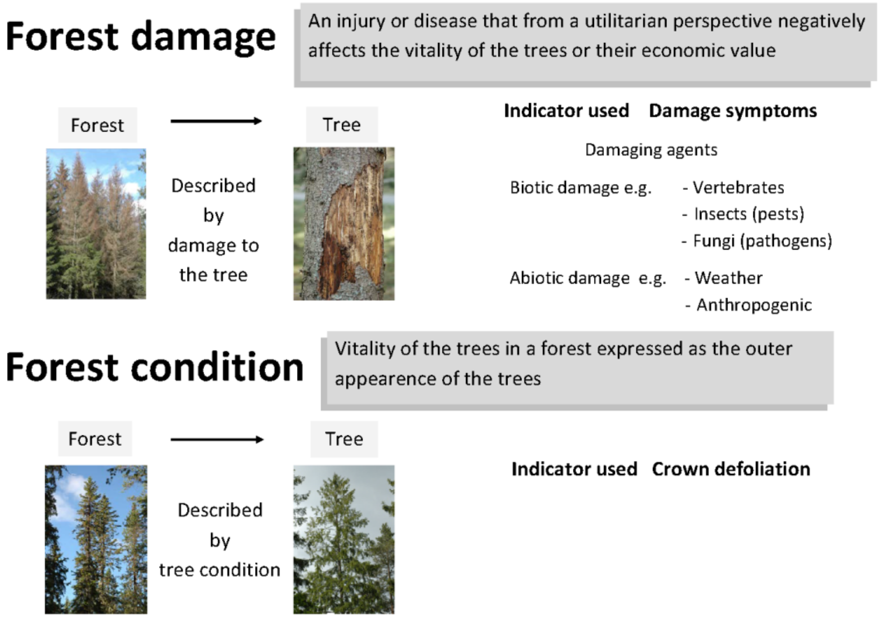


Figure 1. Main concepts used in this thesis to describe forest damage

Examples of causes of damage are climate change, anthropogenic pollution and silvicultural activities. Other damaging agents are biotic, e.g., insects and fungi; their effects on trees and forest ecosystems depend on interactions between them, the trees and ecosystem processes, which may be synergistic or antagonistic, as discussed by Lovett *et al.* (2006) and Witzell *et al.* (2009); an illustration is given in Figure 2.

Tree (or crown) condition is used in this thesis to describe the effect of forest damage on the vitality of trees, and refers to the outer appearance of the tree (Figure 1) (Ferretti, 1997; Solberg, 1999b; Eichhorn *et al.*, 2010). It has evolved as a general concept to address the problems that causes of forest damage may be difficult to assess and that the links between damage and health are often unclear (Ferretti, 1997; Moffat, 2002; Percy & Ferretti, 2004). Thus, assessment of forest condition is less subjective than assessment of forest health.

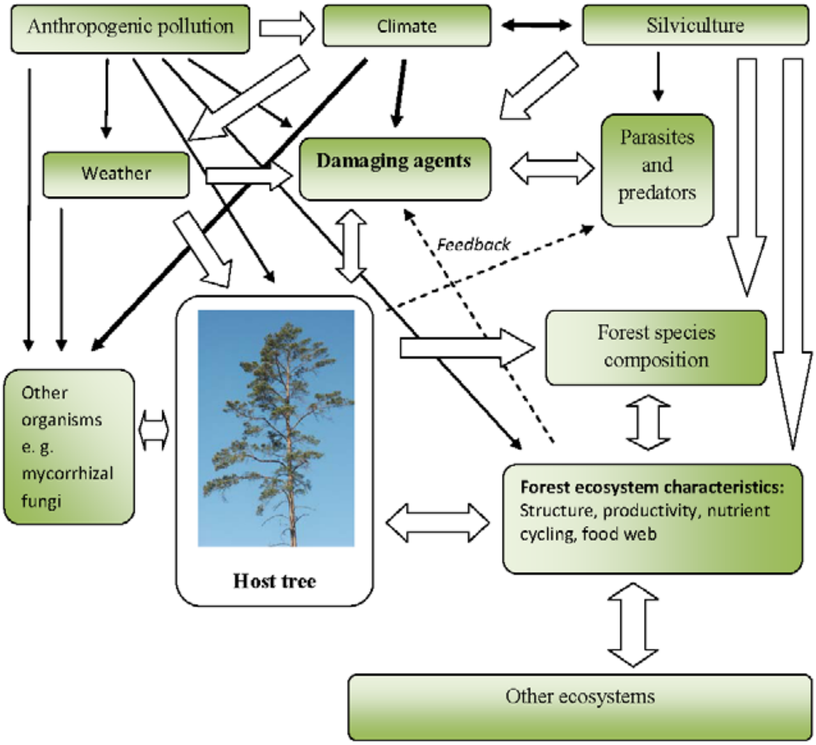


Figure 2. Impact of damaging agents on forest ecosystem processes. (Modified after Lovett *et al.* (2006) and (Witzell *et al.*, 2009).

1.3 Indicators

Although the focus in thesis is primarily on forest damage and forest condition, a broad overview of indicators related to the subject area is first provided. When considering tree health indicators, such as biochemical variables or stress responses must be used since, no straightforward measures are available (Dobbertin, 2005). Notably, numerous analyses have examined putative relationships between nutrient deficiencies and stress (Cape *et al.*, 1990; Ericsson *et al.*, 1993; Solberg *et al.*, 2002), and although there are major uncertainties about threshold nutrient levels, there is no doubt that nutrient deficiencies adversely influence the vitality of trees (Horsley *et al.*, 2000). While it is difficult to obtain biochemical data from large-scale monitoring programmes, such indicators can be valuable for extending knowledge regarding processes related to tree health.

Tree growth can serve as a vitality or stress indicator, depending on the type and extent of the stress factor (Dobbertin, 2005). Several studies have found negative correlations between tree growth and defoliation (Söderberg, 1993; Solberg, 1999a; Dobbertin, 2005). Annual tree-ring widths are obtained in many national forest inventories (NFIs), but as bore cores are typically taken during the growing season such data can only be used retrospectively. Another important aspect is that no absolute reference values are available (Dobbertin, 2005)**,** partly because weather conditions inevitably influence tree growth. For example, summer droughts (such as those that occurred in Europe in the mid-1970s, early 1990s, and 2003) strongly affect tree growth (Bengtsson & Lindroth, 1991; Solberg, 1999a; Breda *et al.*, 2006). However**,** the strength of forest growth measurements lies in their ability to detect long-term changes, for instance effects of tree rot. Although tree growth and defoliation of tree crowns are related, the indicators might not reveal the same stress symptoms and are not exchangeable, but may be more useful when used in a complementary fashion. Other variables, such as sapwood content and growth, are also correlated with defoliation (Eckmüllner & Sterba, 2000)**,** but are less practical to use in large-scale monitoring.

Tree mortality is the definitive measure of tree vitality, and hence has been monitored in forest surveys from the start as in the Swedish NFI in the 1920's (e.g., Thorell & Ostlin, 1931). The results have been used to quantify extensive forest damage resulting from causes such as storm felling and insect attacks. Models of tree mortality rates have also been used to simulate and characterize damage caused by wind (Blennow & Sallnäs, 2004; Valinger & Fridman, 2011), drought (Bigler *et al.*, 2006) and outbreaks of insects such as the spruce bark beetle (Jönsson *et al.*, 2009). Clearly, knowledge of the effects of any agent on mortality rates, and hence frequencies of dead trees, will be useful. The abundance of dead trees has also traditionally been used for estimating quantities of fuel wood and, more recently, as a biodiversity indicator (Anon., 2007). However, for monitoring forest damage and identifying threats there is a need for indicators that are more sensitive to specific insects, fungi and abiotic causes.

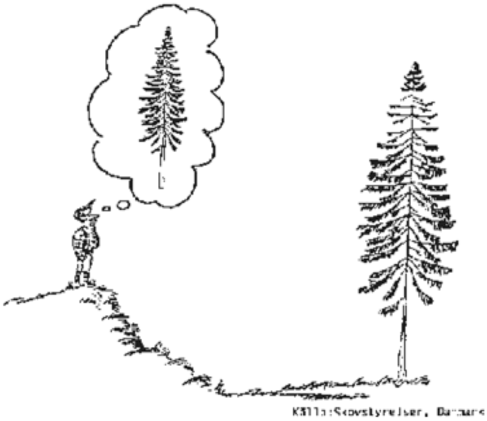
The most widely used indicators for assessing tree condition are defoliation and foliage transparency (commonly used in Europe and North America, respectively). There is no clear difference in the utility of these variables, and the geographical distinction has a traditional basis. Defoliation is defined as foliage loss in relation to a reference tree (see section 1.3.1), while foliage transparency is defined as the additional amount of skylight visible through an observed crown compared to the amount visible through a fully foliated crown

(Eichhorn *et al.*, 2010). Transparency assessments are similar to two-dimensional assessments of photo images.

Numerous other indicators have also been used in attempts to obtain more thorough descriptions of forest condition, but most of them have been of minor interest since they have shown poor reliability or made little contribution to forest condition assessments. Discolouration was a mandatory assessment variable in the European cooperation programme up to 2009, but for the conditions in boreal forests the results have been difficult to interpret in large-scale inventories carried out throughout the whole summer (Solberg, 2004). Defoliation types in Scots pine and Norway spruce trees, and amount of secondary shoots in Norway spruce**,** were also assessed during a 15-year period in the Swedish monitoring programme (Lesinski & Landmann, 1985; Westman & Lesinski, 1986; Lesinski, 1989; Wulff, 2006). However, since the results had poor reproducibility it was difficult to separate the symptoms from changes associated with natural developmental processes, such as ageing. The apical shoot architecture of beech (*Fagus sylvatica*) and other crown architecture parameters of oak (*Quercus* sp.) and birch (*Betula* sp.) trees have also been used in forest condition monitoring programmes (Roloff, 1990; Sonesson, 1999; Wulff, 2006; Eichhorn *et al.*, 2010). However, most reports on the condition of broadleaved trees have focused on defoliation and correlated patterns of biotic damage and acidification (Eichhorn *et al.*, 2005; Drobyshev *et al.*, 2007).

1.3.1 Crown defoliation

Defoliation was introduced in the ICP Forests monitoring programmes in 1986, and since then has been used as the major indicator of forest condition (Lorenz, 1995). Defoliation is defined in the ICP Forests manual as **"**needle/leaf loss in the assessable crown as compared to a reference tree. Defoliation is assessed regardless of the cause of foliage loss" (Eichhorn *et al.*, 2010). Despite harmonization efforts within the co-operation programme over the years slightly different definitions have been applied in different countries. The differences relate to the assessable crown and reference (absolute reference tree or local reference tree) used (Eichhorn *et al.*, 2010). Local reference trees, which may be either fully foliated trees in the near vicinity or imaginary trees with full foliage (Figure 3), are generally used. In Sweden, defoliation refers to needle/leaf loss and degradation of branches in the crown of an assessed tree, relative to the full foliage of a visualized tree under the same conditions in terms of the genetic range of variation, site and stand conditions (Anon., 2011). Further, only defoliation on Scots pine and Norway spruce trees is assessed.



Defoliation assessments have, in the NFI, since 2010 been recorded in 1% classes (Figure 4).

Defoliation assessments can be obtained cost effectively and relatively quickly in field surveys (Dobbertin, 2005). However, the utility of defoliation assessments for monitoring forest condition has been criticized for being non-specific, not revealing health status, inconsistent and producing unreliable data (Innes, 1993; Ferretti, 1997; Johnson & Jacob, 2010). Defoliation was introduced in monitoring activities to reveal damage symptoms caused by anthropogenic pollution, but the acquired data have been difficult to interpret in this respect. Nevertheless, monitoring the sum total of a non-specific symptom, such as defoliation, together with complementary assessments of symptoms of specific damage causes, provides possibilities to detect both specific and overall changes in forest condition.

Figure 3. Imaginary reference tree concept. (Skovstyrelsen Denmark).

As defoliation assessments are subjective, and highly variable due to differences in perceptions, substantial measurement errors may occur (Solberg & Strand, 1999; Wulff, 2002), and their applicability depends on diverse factors. Crucially, the methods used must be consistent over time and the assessments must be sufficiently accurate (Wulff, 2002). Otherwise, substantial changes must occur before one can safely conclude that change has really occurred (Ringvall *et al.*, 2005). Hence, considerable work was done to improve the quality of data and harmonize assessments in the European cooperation programme during a long period in the 1980s and 1990s. Further, greater efforts have been made recently to strengthen the quality test in the cooperation programme (Ferretti, 2010), and in Sweden quantifiable control tests have been carried out annually since 1995 during national training courses (Wulff, 2002).

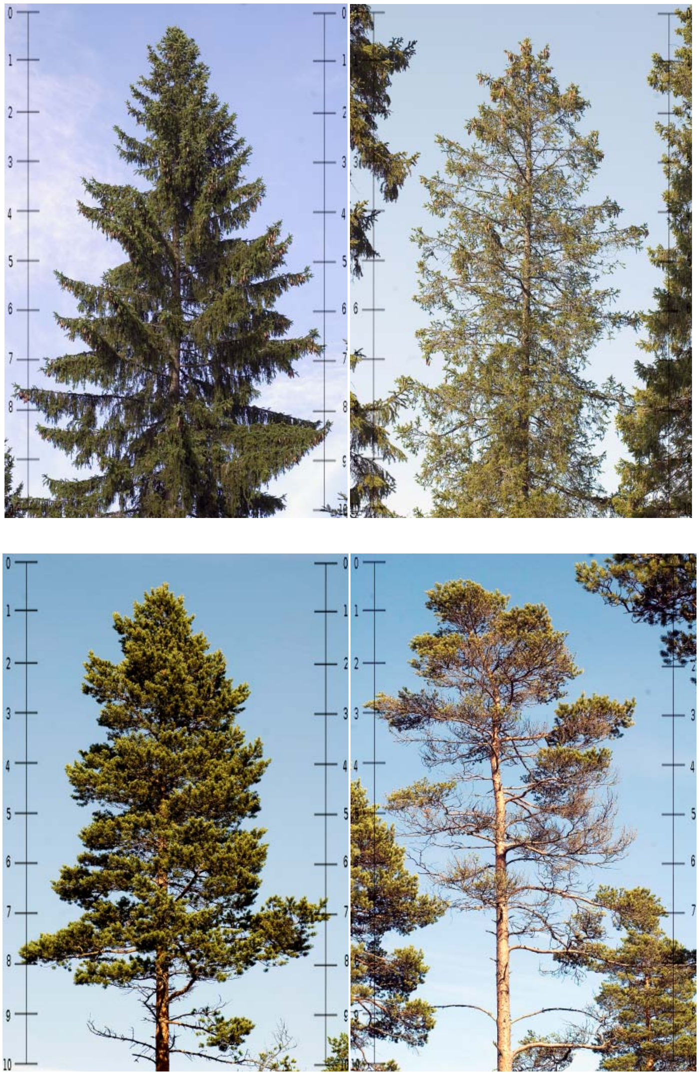


Figure 4. Defoliation of conifers. The upper photos show Norway spruce (*Picea abies*) trees with 5 % (left) and 65 % defoliation (right), while the lower photos show Scots pine (*Pinus sylvestris*) with 5 % (left) and 55 % (right) defoliation.

Both the definitions of assessable parts of trees and reference trees, which are essential for standardized assessments, differ to some extent between countries participating in the European cooperation programme. This complicates interpretation of data gathered on forest conditions in Europe (Innes *et al.*, 1993; Fischer *et al.*, 2010a). However, for regions with similar forest types, for instance Scandinavia, the assessments are fairly well standardised. Further, the reliability and consistency of the assessments are tested during international calibration courses (Wulff, 2002; Mues, 2006; Lindgren & Pouttu, 2010). Recently photos have been introduced to improve calibration of the assessments, using both photographic tests and a number of photographic guidelines for absolute reference trees in different parts of Europe (Aamlid *et al.*, 1991; Bauer *et al.*, 2007).

1.4 Forest damage

Fungi, insects, game browsing, and abiotic agents such as fire, wind, and drought are the major causes of forest damage (e.g., Edmonds *et al.*, 2000). In addition, large-scale damage has been strongly associated with anthropogenic air pollution (e.g., Schulze, 1989). Direct visible damage caused by high levels of air pollution has been known for more than a century, but has mainly been detected in the vicinity of soot-emitting industries (Hartig, 1889; Butin, 1995). However, the effects of acid rain and air pollution have also typically included acidification of surface water and forest soils (e.g., Ulrich, 1986; Likens *et al.*, 1996). Although several experimental studies have shown a negative correlation between plant growth and acidification of forest soils (e.g., Sverdrup *et al.*, 1994) it is less apparent that these effects significantly affect forest condition (e.g., Innes, 1993; Kandler & Innes, 1995; Binkley & Högberg, 1997; Solberg, 1999b). On the contrary, few field studies have found clear indications of negative effects of long range air pollution on forest condition (see Solberg *et al.*, 2009).

Forest damage can be seen as an injury or a disease that has biotic or abiotic causes. Manion (1991) defines three different types of diseases that may cause forest damage: (i) biotic (insects, fungi, etc.), (ii) abiotic, and (iii) decline. Unlike the first two, involving specific causal agents, the decline type involves an interacting set of factors, and the exposure of trees to long-term factors that predispose and contribute to the decline. This concept was further developed by Larsen (1995) in a discussion of ecological stability of forests. Predisposing factors including genetic potentials, site conditions, climate, and air pollution can destabilize the forest. Inciting factors, such as insect and fungal attacks, frost, and drought, may cause degeneration of an unstable ecosystem and evident damage. Canker and rot-decay fungi are considered to be factors that have long-term effects on forest ecosystems.

Although the perspectives on forest condition have changed since the tree disease concept was proposed by Manion (1991), it is still considered adequate and in accordance with different views of forest damage. In the following sections, types of damage caused by biotic and abiotic damaging agents are considered in more detail.

1.4.1 Biotic damage

Exposure to stress and/or exotic insects and fungi makes forests more susceptible to epidemics, which can have considerable economic consequences (e.g., Ciesla & Donaubaur, 1994; Edmonds *et al.*, 2000; Dale *et al.*, 2001). Serious outbreaks of insects occur in all major forested areas. The most well-known example is probably the ongoing outbreak of the mountain pine beetle (*Dendroctonus ponderosae*) in British Columbia, Canada. The heavily infested area is increasing annually, and covered about 13 million ha in 2008 (Westfall & Ebata, 2009). Most bark beetles are secondary scolytids, i.e. they select weakened trees or trees that have recently died as hosts, but when their populations increase some species can overcome the defences of healthy trees and kill them (Edmonds *et al.*, 2000). However, only a few of the ca. 6000 species of bark beetles in the world are outbreak-prone and known as pests. Nevertheless, major outbreaks of bark beetles of the *Ips* genus (Lindelöw & Schroeder, 2008; Santos & Whitham, 2010) have been observed in the US and Europe following extreme weather conditions**,** such as drought and severe storms. Beside the bark beetles few insects are known as pests of trees. However, defoliators such as the spruce budworm (*Choristoneura fumiferana***)** in North America, and the Siberian moth (*Dendrolimus sibiricus*) in Russia and China**,** can strip conifer trees and cause extensive tree death (Boulanger & Arseneault, 2004; FAO, 2009). Other defoliating insects may be common in single years, but they seldom cause extensive forest damage. Exceptions include eruptive outbreaks of *Lymantria* spp., in both North America and Eurasia (EPPO, 2005), and cyclic outbreaks of geometrid moths**,** such as *Epirrita autumnata* and *Operophtera brumata* (Jepsen *et al.*, 2008). Although foliage losses caused by defoliators do not directly cause tree mortality, they may trigger colonization (and ultimately death) of the weakened trees by secondary bark beetles and other wood**-** and bark-living beetles. Similar phenomena are observed with fungi such as *Armillaria* spp. Insects also often act as vectors, by transmitting diseases. For example, there are several known examples of bark beetles transmitting blue-stain fungus and wilt disease. Dieback caused by Dutch elm disease (*Ophiostoma novo-ulmi*) and pinewood nematode (*Bursaphelenchus xylophilus*) are examples of wilt diseases vectored by bark beetles (*Scolytus* spp.) and longhorn beetles (*Monochamus* spp.).

Many important damaging agents are fungi. Rot fungi**,** which are also the main decomposers of dead organic material, are clearly among the most serious. Other serious pathogens include species of honey fungi (*Armillaria* spp.), which are distributed in all temperate and tropical regions of the world. They can live as saprophytes in the soil for decades**,** but can also be severe pathogens of weakened conifer and broadleaved trees. *Armillaria* decay is generally less severe than *Annosum* root rot, but the fungi can also kill cambium (and indeed are also known as cambium killer). *Armillaria* fungi are often involved in spruce and oak diseases (Wahlström, 1992). Among conifers, spruces (*Picea* spp.) are more sensitive to rot fungi than pines (*Pinus* spp.), but the latter are more susceptible to fungi that affect tree crowns**,** such as rusts and cankers or shoot blight. The rust fungi include several aggressive pathogens**,** *inter alia* white pine blister rust (*Cronartium ribicola*) (Hunt *et al.*, 2010), resin top disease (*Cronartium flaccidum* and *Peridermium pini*) (Kaitera, 2000) and fusiform rust (*Cronartium quericum f. sp. fusiforme*) (Brown II & Coder, 2009). *Scleroderris*/*Gremmeniella* canker (*Gremmeniella abietina*) and *Diplodia pinea* (which causes diplodea shoot blight) are two of the most aggressive shoot blight. Major outbreaks of *Gremmeniella* have been recorded both in North America (Skilling, 1981; Laflamme & Lachance, 1987) and in the Nordic countries (Hansson, 1996; Nevalainen, 1999; Wulff *et al.*, 2006).

The factors that trigger outbreaks in a given area are of great interest, but knowledge of these factors and their interactions is still scarce, and few studies have addressed them at the landscape level. Clearly, the weather plays an important role in the initiation of outbreaks (Karlman *et al.*, 1994; Allen & Breshears, 1998; Breshears *et al.*, 2009). Adverse weather conditions**,** such as severe drought and heavy storms**,** can cause serious damage. However, weather conditions that favour a disease can also intensify an attack, and climatic warming could lead to increases in insects' reproductive rates and their ability to complete more generations per year (Bale *et al.*, 2002). Outbreaks are often activated by a disturbance to the host. Thus**,** disturbances that weaken hosts or increase the availability of suitable substrates (e.g., windthrown trees) increase risks of damage outbreaks. Silvicultural practices leading to the creation and maintenance of even-aged mono-species stands also enhance risks of escalating forest damage. Enhanced risks of outbreaks of native agents can also arise when alien tree species are introduced (Hansson, 1996; Karlman, 2001). Apart from outbreaks of native agents**,** anthropogenic introductions of alien fungi or insects to areas where endemic hosts have little or no resistance pose high risks of widespread damage (Welsh *et al.*, 2009). Widespread or rapid dispersion of new types of damaging agents have been observed in Europe and other continents, such as: sphaeropsis blight (*Diplodia pinea*) (Jeger & Pautasso, 2008) and red band needle blight (*Dothistroma septosporum*), which affect pines all over the world (Barnes *et al.*, 2008); Dutch elm disease, which originated in Asia where it slightly affects endemic elm trees, but after several mutations is now a severe pathogen of elm trees in Europe and America (Brasier, 2001); and the common pine shoot beetle (*Tomicus piniperda*), a Eurasian bark beetle that has an early swarming season and was introduced to

North America, where it faced less competition and has caused growth losses in pine trees (Czokajlo *et al.*, 1997). The latest example is the pinewood nematode, which is a threat for long-term heavy economic losses in forestry in Europe and America (Mota *et al.*, 1999).

In addition to insects and fungi, mammals and birds may also cause substantial damage to trees. Well known examples include ungulates such as the elk in boreal forests (e.g., Edenius *et al.*, 2002), and rodents which may cause substantial damage to tree plants during periods of high population levels (e.g., Sullivan & Sullivan, 2008).

1.4.2 Abiotic damage

Air pollution has substantially affected the condition of forests in heavily polluted areas in central Europe and the Kola Peninsula (Matzner & Murach, 1995; Rigina *et al.*, 1999). In the Nordic countries, areas where air pollution has been a major concern include south-eastern Norway, south-western Sweden and southern Finland (Sverdrup *et al.*, 1994; Binkley & Högberg, 1997; Lindgren *et al.*, 2000; Solberg *et al.*, 2004). The main concerns are related to acidifying sulphur and nitrogen deposition, and in some areas ozone (O_3). In recent years sulphur deposition has decreased dramatically. In contrast, nitrogen deposition levels have remained high (Fenger, 2009), but potentially adverse effects of acidifying nitrogen deposition on tree condition appear to be outweighed by the positive effects of the deposited nitrogen on forest growth (Solberg *et al.*, 2009). Emissions of O_3 and their effects on forest conditions in northern Europe have been discussed very little, but they are of greater concern in North America and southern Europe. Further, following anticipated climate changes greater attention to ozone levels may be required in northern Europe too (Oksanen *et al.*, 2009).

Like air pollution during the 1980-1990s, effects of actual or anticipated climate changes on forest condition have been key concerns during the beginning of the 21st century. Extreme weather conditions have also caused extensive forest damage in recent decades. Severe storms have frequently struck Europe**,** such as the autumn storm Lothar, in 1999**,** and the winter storms Gudrun and Per in 2005 and 2007**,** respectively (Hartebrodt, 2004; Valinger & Fridman, 2011). The storms, and the felling they caused, had huge effects on forests, forestry and the wider society. In addition, hurricanes regularly strike the south-eastern USA and cause substantial forest damage (Kupfer *et al.*, 2008). Major episodes of drought- and heat-related forest damage have also been reported globally, e.g., the severe droughts in Europe in 2003 (Rebetez *et al.*, 2006) and North America in the early 2000s (Ganey & Vojta, 2011; Michaelian *et al.*, 2011) and elsewhere (Allen *et al.*, 2010). The numerous and extensive drought episodes have been associated with climate change (Overpeck & Udall, 2010), and increasingly severe forest fires. One of the most exposed areas is the Mediterranean region, where fires annually cause serious damage to forests (Moriondo *et al.*, 2006). Frequent fires can also cause soil erosion and impair plant regeneration (Lindner *et al.*, 2010).

1.4.3 Assessment of forest condition and forest damage

Defoliation is a key variable when monitoring forest condition. However, for assessments of forest condition to be valuable for decision-making, data on damaging agents are required and thus they are also generally assessed. In ICP Forests, various types of damage symptoms and causes of damage are included (Eichhorn *et al.*, 2010). In the Swedish NFI a comparable set of damage symptoms is recorded and the damaging agents included are those that are most common or cause most damage to Sweden's forests (Table 1).

Table 1. Damage symptoms and damaging agents recorded in the Swedish NFI. From Wulff et al. (2011).

TREE DAMAGE SYMPTOMS		CAUSE OF DAMAGE	
Affected part	Symptom	Agent group	Agent/factor
Stem / Collar	Fallen Tilted Broken Wounds (debarking, cracks, etc.) Necrotic parts Resin flow Signs of fungi Signs of insects Decay/rot Planting damage Spike knot Multiple stems	Abiotic/climate	Wind/Snow; Frost; Other
		Anthropogenic	Forestry; Other
		Mammals	Elk; Reindeer; Roe deer; Wild boar; Other large mammals; Beaver; Rodents; Other mammals.
		Insects	*Tomicus sp.*; *Ips typographus*; Other bark beetles; *Pityogenes*; Other insects
		Fungi	Resin top disease; Rot or cancer; *Gremmeniella abietina*; Needle cast; *Melampsora pinitorqua*; Unspecified rust fungi; Other fungi
Tree crown	Dry top Defoliation Discolouration	Competition	Physical interactions
		Fire	
		Other	

1.5 Monitoring

1.5.1 Information needs

Relevant, accurate, and timely information is required for supporting decisions, not only to meet commercial objectives but also (*inter alia*) to enhance environmental protection, biodiversity and recreational services. The emergence of these additional forest objectives, and their interactive requirements, have increased the demands for information (Barth, 2007). Information regarding forest condition is needed by diverse decision-makers, ranging from governmental organizations responsible for mitigation strategies and law enforcement, to landowners trying to avoid severe damage to their forests (e.g.,Davis *et al.*, 2001).

Monitoring, defined as “keeping under surveillance”, should ideally be carried out regularly over long periods (Brydges, 2004). Thompson (1992) concludes that observations for monitoring purposes require suitable sampling designs and reliable methods for measurement and assessment. A wise choice of methods simplifies compilation of the data. In the large-scale monitoring of forest condition**,** time series of damage symptoms and damaging agents are of core interest. Hence, assessments of strictly defined damage symptoms and damaging agents are needed. A programme for monitoring forest condition should, besides having a basic robust structure, also include forest damage impact assessments.

Forest damage can appear in various forms, ranging from distinct symptoms to diffuse decline. Thus, to meet information demands, assessments of forest condition need to cover both specific**,** known damage causes as well as the general state of the forest.

1.5.2 Monitoring forest condition

In Sweden**,** the monitoring of forest conditions is integrated with the NFI (Axelsson *et al.*, 2010). Due to its multiple objectives, the structure and design of the NFI is not optimized for collecting data on events that occur sparsely and at irregular points in time. However, the advantages of such integration often outweigh this drawback.

In general terms, the objectives of NFIs are to describe the state of**,** and changes in, forests (e.g.,Tompoo *et al.*, 2010). In the Nordic countries, NFIs started in the 1920s to meet needs for information on diminishing forest resources. Today**,** NFIs are carried out in many countries and have broader objectives, embracing the collection of data concerning timber supply as well as biodiversity, etc. A brief description of the design and the data collected by the Swedish NFI can be found in NFI (2011).

Data on forest damage were included from early stages of the inventories and focused on the main damaging agents. For boreal forests in northern Europe these include easily detectable biotic agents (such as the spruce bark beetle and resin top disease) and abiotic agents such as wind and snow (Anon., 2011). It is essential that the inventories generate reliable results, hence the damage and damaging agents covered must be accurately assessed (Ferretti *et al.*, 2010). To maximize the consistency of data acquisition in the Swedish NFI the types of damage included are limited to those with rather common and easily detectable causes, and attempts are made to maintain the quality of the collected data by continuous training of the field crews as well as check surveys.

In 1979 CLRTAP was launched, by the United Nations Economic Commission for Europe (UNECE), to promote measures to reduce emissions of air pollutants (Sliggers & Kakebeeke, 2004; CLRTAP, 2011). In addition to develop the required international cooperation in research on, and monitoring of, pollutant effects, the Working Group on Effects (WGE) was established (WGE, 2011). Under the effects part of the Convention, there are six International Cooperative Programmes (ICPs), a Task Force on Health, and a Joint Expert Group on Dynamic Modelling. The monitoring system, introduced in 1986 to study the effects of atmospheric deposition on forests, was coordinated in Europe by ICP Forests (2011). Today, 41 countries participate in this programme. To meet the information needs of the WGE, ICP Forests has two main objectives (Lorenz, 2010): to provide (i) a periodic overview of the spatial and temporal variation of forest condition by means of large-scale representative monitoring (level I), and (ii) a better understanding of the cause-effect relationships between the condition of forest ecosystems and stress factors by intensively monitoring a number of selected permanent observation plots spread over Europe (level II). The diverse aspects covered by the programme are described in the ICP Forests (2010) manual. The European Union and ICP Forests have collaborated throughout the years in these tasks. The European Commission co-financed the forest monitoring during 1987-2006. From 2009 to June 2011 the project 'Further Development and Implementation of an EU-level Forest Monitoring System (FutMon)' under Life+ funding was charged (*inter alia*) with harmonizing and linking together existing inventories (FutMon, 2011). Although there is no longer any financial support from the European Commission a forest condition monitoring system is still important, and thus is included in the EU's Green Paper on Forest Protection and Information (EU, 2010).

Environmental concerns have also led to the launch of programs for monitoring and reporting forest conditions in North America. In the USA, the national Forest Health Monitoring (FHM) program has been established, and fully integrated with the USDA Forest Service Forest Inventory and Analysis program (FIA) (Shaw, 2008), to carry out this task (USDA, 2011). The monitoring program includes several connected components, which can be classified as: detection monitoring (standardized aerial and ground surveys to evaluate the status of and changes in forest condition); projects focusing on problem areas to determine the extent and severity of wide-scale forest damage; and intensive site monitoring (ecosystem process studies of cause-effect relationships and research on monitoring techniques). Expected outcomes of the program (besides providing required information) are improvement of the efficacy of new and existing regulations.

In Canada**,** the Canadian Forest Service (CFS) coordinates research and monitoring in the forest sector (CFS, 2011). The Canadian NFI involves systematic sampling using a combination of ground, photographic and remote sensing techniques in permanent plots (Gillis *et al.*, 2005). Key variables monitored include the area and severity of insect attacks, disease infestation**,** fire damage and disturbance. In addition to the data collected by the NFI**,** the occurrence of native and exotic forest pests and pathogens in Ontario´s forests are summarized in annual reports (Ontario, 2011).

Another, acid deposition monitoring, network (EANET) was established in East Asia in 1998. The situation in East Asia differs from that in Europe and North America (Schreurs, 2011). The acid deposition is more severe and there are currently no agreements on reducing acid emissions in the region. Work is, however, in progress and emissions have begun to decrease (Lu *et al.*, 2010).

1.6 Forest damage in Sweden

Many types of regional forest damage may affect Swedish forests, but generally only a few damaging agents have major economic implications. During the last decade a few damage events have strongly influenced Swedish forestry. Storm events regularly affect Swedish forests, but the winter storms in 2005 and 2007 were exceptionally severe. In January 2005**,** trees with an estimated volume of 75 million m^3sk blew down and a further 12 million m^3sk two years later in January 2007 (Jonsson, 2008). Due to logistic difficulties in managing all the storm-felled trees**,** large amounts of timber (and hence large amounts of suitable substrates for bark beetles) were left in the forest. The populations of spruce bark beetle (*Ips typographus*) were low before the storms**,** but they subsequently increased dramatically (Lindelöw & Schroeder, 2008) due to high reproduction in wind felled trees in 2005 and 2006. A second generation in 2006 contributed substantially to the tree mortality. The estimated volume of standing spruce trees killed by the beetle in 2006-2010 amounted to ca. 3 million m^{3}sk (Långström *et al.*, 2010). Another insect that regularly causes substantial forest damage and high mortality in young forest plantations (on average, losses of ca. 2.9 % of planted trees in southern Sweden; (Nordlander & Hellqvist, 2008) is the pine weevil (*Hylobius abietis*).

Grazing by deer, particularly elk (Am. moose), can cause severe damage in young forests, and damage caused by elk and other mammals is often distinguished from damage caused by other biotic agents. The impact of the damage caused by grazing is intensively debated and described in different ways by different interested parties, such as land owners, managers and hunters (Apollonio *et al.*, 2010). However, elk browsing can certainly cause substantial destruction in young Scots pine forests, which inevitably affects forest owners financially. Data from the elk-browsing inventory (ÄBIN) carried out in the Swedish NFI show that nearly half of the Scots pines in young stands with average heights of 1-4 m are affected by elk grazing (Skogsstyrelsen, 2010). Fresh damage (i.e. damage that occurred during the preceding season) is found, on average, on about 10 % of surveyed pines (NFI data); more than four times the frequency that the Swedish forestry industry considers to be acceptable.

Annual economic losses of 50-100 million € due to timber and growth losses make the root rot caused by *Heterobasidion annosum* the most severe type of damage (Oliva *et al.*, 2010). In total, 110 million m^{3}sk of spruce trees in forests of thinning or clear cutting age are affected by rot at breast height (NFI 2005-2009). This is a slight increase in volume, from 7.4 % to 9.2 % of the total volume of spruce trees, since the 1980s (Swedish NFI).

Massive damage was also caused in an epidemic outbreak of *Gremmeniella* in 2001-2003 affecting an estimated total area of pine forest of 484 000 ha (Wulff *et al.*, 2006). According to Hansson *et al.* (2005) the monetary losses caused by the outbreak of *Gremmeniella* in Sweden during this period, excluding effects of reduced growth, amounted to 1.2 billion SEK.

Other types of damage that occur have less serious economic implications in Swedish forestry, but may have substantial regional economic and/or ecological impact. Regional damage events observed in recent years include outbreaks of European pine sawfly (*Neodiprion sertifer*) in south-eastern Sweden, and neighbouring countries (Lindelöw, 2011) and an outbreak of resin top disease on younger Scots pine in northern Sweden and Finland (Wulff *et al.*, 2011). Increasing decline of ash (*Fraxinus excelsior*) has also been observed in recent years in southern Sweden, and attributed to attacks by the fungus *Chalara fraxinea*. The disease has previously caused major damage in Poland and Lithuania, and is rapidly spreading north-westwards (Johansson *et al.*, 2010). An adopted inventory of ash in southern Sweden, in 2009 and 2010, showed that about 25 % of the trees were severely damaged or dead (Wulff & Hansson, 2011). Reductions in numbers of ash trees will result in reductions in biodiversity and the disappearance of highly valuable forests (Skovsgaard *et al.*, 2009). Although tree species such as ash and elm cover less than 1 % of the total standing volume in Sweden they are significant in the landscape of agricultural areas. Both elm and ash are now declining rapidly and have been placed on the red list (Gärdenfors, 2010).

1.6.1 Spatial and temporal trends of forest condition

During almost 30 years of monitoring, trends of defoliation in Sweden have shown large temporal variations (Figure 5). This is probably mainly due to variations in occasional stress factors, especially weather conditions, but partly to uncertainties introduced by the observation methods (Innes, 1988; Köhl, 1991; Solberg & Strand, 1999; Wulff, 2002). Consequently, long-term development of the forest condition is the most important information from the inventories. The drought in the early 1980s clearly seems to have contributed to the observed forest condition (Innes, 1993; Kandler & Innes, 1995). In the beginning, the attention of the assessments was focused on inexplicable damage symptoms (Lindroth, 1984), which could explain the weaker consistency of the results in the initial years. However, from the late 1980s onwards, the assessments were broadened to include all causes of defoliation (Anon., 2011). On Scots pines the large outbreak of *Gremmeniella* in the early 2000s is clearly manifested in increased defoliation (Wulff *et al.*, 2006). Otherwise there are no clear long-term trends in the data collected on pine tree defoliation. A slight decline in the condition of Norway spruce is apparent since the mid-1990s, peaking in 2006 after the severe winter storms in 2005 and 2006 and the following outbreak of spruce bark beetle. In contrast, for Europe in total little changes are shown in defoliation on Scots Pine and Norway spruce over the past 10 years after an improvement during the 1990ties (Fischer *et al.*, 2010b). During the same period oak and beech trees have deteriorated, and reductions in vitality after the summer drought in 2003 are also apparent. These long-term trends are unlikely to be due to the effects of occasional phenomena. However, calamities such as severe storms and major outbreaks of damaging agents certainly temporarily influence the results.

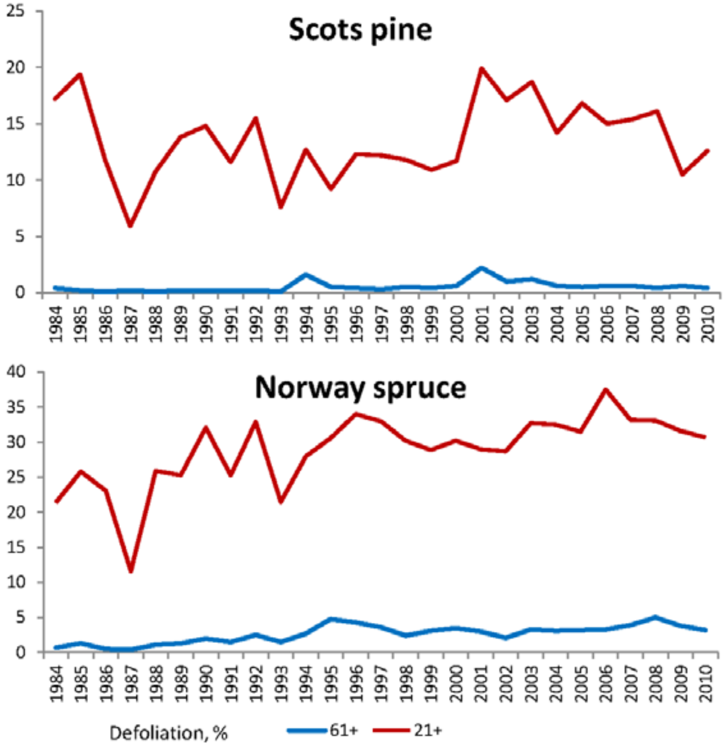


Figure 5. Proportions of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) trees with >20% and >60% defoliation in middle-aged and old forests in Sweden, 1984-2010.

The main causes and effects of regional forest condition spatial patterns are associated with variations in growing situations, including site and stand conditions, such as forest types and tree age. In this context, it should be noted that application of the local reference tree concept will only partly account for the effects of natural factors (Solberg, 1999b). Increases in stress due to harsher climate conditions explain the higher mean defoliation seen in northern Sweden (Anon., 2007), and the higher observed mean defoliation of spruce trees, compared to pine, is probably due to greater stress induced by drought and wind arising from spruce's relatively shallow root systems and greater susceptibility to infection by rot fungi. Needle or shoot fungi, which more commonly affect pine, generally result in high defoliation. Epicentres of heavy damage, such as the *Gremmeniella* outbreak and severe storm felling also contribute to regional patterns (Schlyter *et al.*, 2006; Wulff *et al.*, 2006). Higher defoliation levels in south-western Sweden have been discussed since the 1980s and were recognized in early versions of distribution maps (Wulff, 1994).

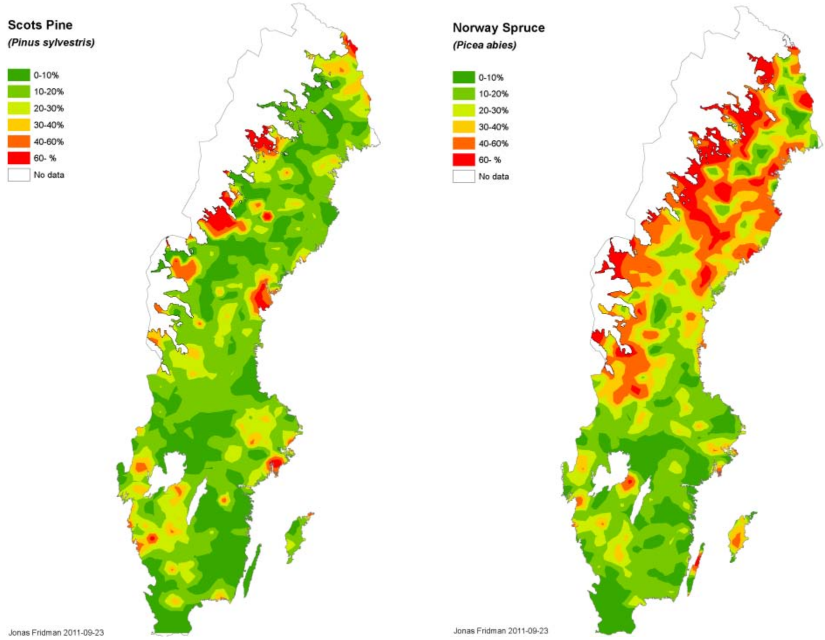


Figure 6. Defoliation distribution maps, showing proportions of Scots pine (Pinus sylvestris) and Norway spruce (Picea abies) trees with >25% defoliation in older forests (mature forest ready for final felling). Data from the Swedish NFI 2006 – 2010.

Increases in defoliation were also recorded in this area in the late 1980s, but subsequently the decline weakened (Schlyter & Anderson, 1997). Later defoliation distribution maps show no other clear regional pattern apart from increased defoliation in areas with harsh climate conditions (Figure 6). Distribution maps are also published annually by the European cooperation programme (Fischer *et al.*, 2010a). However, interpretation of spatial patterns across Europe is difficult due to variations in the methodologies applied (Innes *et al.*, 1993; Seidling & Mues, 2005).

1.7 Needs for new approaches in monitoring forest damage

Today, monitoring plays a crucial role in environmental science, policy development, and implementation. In the future, the demands for reliable monitoring are likely to increase due to the increased pressures on ecosystems, the changing climate, and a growing human population that needs to manage resources more intensively for producing renewable raw materials. Although there is a demand for durable long-term surveys, monitoring schemes must continuously be adapted to meet the societal demands. Lovett *et al.* (2007)

conclude that a combination of good foresight and understanding of the monitored system can produce monitoring data with high information value.

To meet information requirements, the assessment of forest condition needs to cover specific damage symptoms, agents, and effects, as well as the general state of the forest. Further, the methods applied in the inventories should be reliable, practical and cost-effective. Large outbreaks of insects and fungi can be detected in extensive crown condition monitoring programmes (Wulff *et al.*, 2006; Nevalainen *et al.*, 2010). However, in many cases, damage occurs only at limited points in time and space, and such outbreaks may have severe economic implications while they are difficult to detect with sparse monitoring networks. Further, although the focus during recent decades on defoliation assessments has contributed to our understanding of forest condition and damage, it has not been fully successful in capturing emerging needs and demands for data that can assist in timely mitigation of forest damage (Dale *et al.*, 2001; Requardt *et al.*, 2009; Blennow, 2010).

Thus, recognition of the limitations of the past and current inventories is essential for gauging their reliability, interpreting the results, and considering possibilities for introducing new approaches that are better adapted to today's information needs.

2 Objectives

The over-all objective of the work underlying this thesis was to assess past and current forest condition monitoring in Sweden and to propose key components of a future monitoring system. The studies evolved from intensive discussions in Europe and Sweden about forest health and the need for forest condition monitoring.

The specific objectives of the studies described in the appended papers were:

- To evaluate the accuracy and surveyor variability of defoliation and discolouration assessments of Norway spruce and Scots pine (Paper I).
- To evaluate the usefulness of the kind of systematic plot-based sampling designs used in National Forest Inventories for assessing different real (Paper II) and simulated (Paper III) forest damage outbreaks. In Paper II, the background was the large *Gremmeniella* outbreak in pine forest in 2001-2003 and the objective to assess its extent using existing NFI and ICP Forests level I data. In the study reported in Paper III, a simulation method was developed to evaluate large-scale monitoring of forest damage.
- To propose a new system for assessing and monitoring damage in Swedish forests that would meet the requirements of the major stakeholders (Paper IV).

3 Material and methods

3.1 Evaluation of the accuracy of forest condition assessments (Paper I)

Six observer teams, each consisting of two observers, carried out assessments according to Swedish National Forest Damage Inventory (NFDI) protocols annually, from 1995 to 2006. Defoliation was assessed in 1-% classes and discolouration in the international damage classes, i.e. 0-10%, 11-25%, 26-60%, and 61-100%. Defoliation data were compiled into the damage classes for comparisons with control survey data. Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) trees with defoliation exceeding 25% were referred to in this study as damaged.

The consistency of forest damage assessments was evaluated in several calibration courses and control surveys. During annual national training courses results obtained by single observers or observer teams were compared to those obtained by a national reference team. In the international North European intercalibration courses in 1995 and 1997-1999, assessments of defoliation by national teams from Estonia, Finland, Norway and Sweden were analysed. Control surveys were carried out by control teams. An overview of the material used in the study is given in Table 2.

Table 2. *Numbers of trees assessed in: national calibration* courses *(1), control surveys (2), and international calibration courses (3) during 1995-1999 (Paper I).*

Year	Data set	No. of observers	No. of observer teams	No. of Norway spruce trees	No. of Scots pine trees
1995	1	15	-	10	10
	2	-	6+1 control	271	399
	3	-	4	20	20
1996	1	20	-	10	
	1	19	-		10
	2	-	6+2 control	217	169
	3	-	4	30	30
1997	1	-	9	20	20
	2	-	6+2 control	352	361
1998	1	-	8	20	20
	2	-	6+1 control	294	145
	3	-	4	20	20
1999	1	12	-	10	
	1	13	-		10
	2	-	6+1 control	275	342
	3	-	4	25	20

For the assessment of defoliation (in 1% classes), the following general model for an observer's assessment of the damage on a tree was applied:

where Obs_{it} is the assessment by observer i of tree t; μ_t is the true, but unknown, damage of tree t; δ_i is the observer bias for observer i, and ε_{it} the random error of observation by observer i of tree t. The same model was used for all types of trees, i.e., the observers' bias was assumed not to depend on tree type or level of defoliation. In the national training courses defoliation by the national reference team was set as standard, although not considered as being the true defoliation, and the difference between the mean defoliation registered by observers and the national reference standard was recorded. Statistical tests were carried out to evaluate the consistency of the assessments, assuming that the observations by the national reference team and the observers had the same precision.

Assessment of discolouration and the compiled defoliation assessments in damage classes were compared with data from the control surveys. In this case the data were categorical, so the above approach could not be applied. Instead, the agreement (A) between assessments, estimated by calculating the percentage of the registrations that shared the same classification**,** was studied. However, for skewed distributions with many observations in few classes (and thus high levels of agreement by chance), as in many forest damage inventories, the agreement measured can be misleading and a better estimate is the kappa statistic (Cohen, 1960; Fleiss *et al.*, 1969); a measure of the extent to which agreement across categories is greater than that expected by chance.

3.2 Evaluation of systematic plot-based sampling designs (Papers II and III)

Area estimates and disease development were estimated along with sampling errors for the outbreak of Gremmeniella in 2001 – 2003 (Paper II). The data used originate from the Swedish NFI 2002-2003, and the Swedish NFDI 1999-2003. In total, 7500 sample plots in pine forests (stands with pine accounting for at least 65% of the basal area) from the NFI and 4500 sample trees in 535 sample plots from the NFDI were used (Table 3). The tree species included were Scots pine (*Pinus sylvestris*) and lodgepole pine (*Pinus contorta*).

Table 3. *Number of trees and plots used in this study from the Swedish National Forest Inventory (NFI) and the Swedish National Forest Damage Inventory (NFDI), 1999-2003*

Year	Data set	All forest		Pine forest plots
		Trees	Plots	
1999	NFDI	4472	535	
2000	NFDI	4492	533	
2001	NFDI	4530	535	274
2002	NFI			2434
2002	NFDI	4520	535	271
2003	NFI			2311
2003	NFDI	4544	542	276

The Swedish NFI uses a stratified systematic cluster sampling design, with a combination of temporary and permanent plots that are sampled in a 5-year cycle (Ranneby *et al.*, 1987; Axelsson *et al.*, 2010). The plot clusters are square-shaped and the distances between clusters and between plots within clusters vary in accordance with the spatial variation of the forest landscape. Distances between clusters range from 2 km in southern Sweden to 5 km in northern Sweden. The lengths of the sides of the square clusters range from 300 m in the south to 1800 m in the north, with six or 12 temporary plots, and from 300 to 1200 m with four or eight permanent plots (Anon., 2011).

Plots of different sizes are used for different measurements; the temporary and permanent plots used for acquiring tree data have 7 and 10 m radii, respectively. Plots with 20 m radii are applied for area estimates of stand and site variables (Axelsson *et al.*, 2010). More detailed descriptions of the estimates used in the Swedish inventories can be found in Fridman and Walheim (2000) and Toet *et al.* (2007).

The Swedish NDFI is based on a two-stage sampling design and the primary units (sample plots) are selected using systematic sampling stratified in three regions and three forest maturity classes (Wulff, 1996). In the second stage, sample trees are selected. A sample of the larger trees in a stand (dominant and codominant; Eichhorn *et al.*, 2010) is selected with a probability that increases with the diameter of the tree. For details of the NFDI design, see Wulff *et al.* (2006).

Gremmeniella shoot blight was examined visually by binoculars and recorded if blighted pine shoots had dead buds and if Norway spruce trees in the understory had dead tops. Dead shoots with remaining needles were classified as fresh damage. Based on the amounts of shoot blight, trees were assigned to one of three classes: class I (lightly damaged), trees with shoot blight symptoms covering >10% of the crown; class II (moderately damaged), trees with shoot blight covering >25% of the crown; and class III (severely damaged), trees with shoot blight covering >60% of the crown.

The proportion of damaged trees on each plot was calculated from the frequencies of sample trees in the NFDI and all trees in the NFI. Plots were classified according to disease occurrence as follows: slightly diseased if more than 10% of the trees were moderately damaged and severely diseased if more than 60 % of the trees were moderately damaged and at least 20% severely damaged.

Using Monte-Carlo simulation (Paper III) the possibilities to estimate various damage scenarios together with different inventory designs are multi-fold (e.g., Gregoire & Valentine, 2008). In our simulation study, we focused on a large landscape covering 50,000 km^2 of forest land, comparable to the forest area in the southernmost Swedish region, Götaland, representing the size of a region for which precise estimates from NFIs are commonly required. For this landscape, we were interested in evaluating the precision of estimates of state and change in the number of damaged trees ha^{-1}. Generally, such landscapes have many land cover types, but only forest land is of interest when estimating numbers of forest trees with certain types of damage. In practice this difference is handled by using ratio estimators (Thompson, 1992), taking the number of plots falling on forest land into account, and estimators of variance based on the variation in number of trees on plots falling on forest land.

Due to the large size of the area of interest in this study and the consequently large numbers of damaged trees, simulation of a systematic layout of sampling locations covering the total area was unfeasible. Instead, we divided the study area into equally sized non-overlapping squares with sides corresponding in length to the distance between sampling locations in an imaginary systematic design, in which the area of each square corresponded to the area within exactly one sampling location. This type of design is used, for example, in the FIA, the US national forest inventory (McRoberts *et al.*, 2010). At each sampling location, one cluster of eight fixed area plots was selected in the simulations, and the dimensions of the squares was set to 10*10 km, resulting in a study area of N=500 squares in total. All plot clusters were supposed to be permanent, i.e., remeasured at certain time intervals.

Different damage scenarios were specified, corresponding to different simulated damage types and levels. To enable both estimation of state and changes in numbers of damaged trees per ha, the simulations provided positions of damaged trees at two time points (TP1 and TP2). The difference between the time points is the change; in this study we did not allow trees to recover and thus the intensity of damage always increased from TP1 to TP2. The simulations of damaged trees aimed at imitating two main event scenarios:

1. Sparsely but evenly distributed damage. The damage is always present and mainly dispersed slowly and randomly with low aggregation. Positions of damaged trees were simulated as a Poisson point process (e.g., Stoyan & Penttinen, 2000) with specified upper and lower bounds for the intensity (number of trees ha^{-1}). Positions of new trees at TP2 were simulated independently of the position of trees at TP1.
2. Local or regional outbreaks with accumulated centres. The damage is often present at low level but can rapidly increase if provoked by favourable conditions (e.g., the weather). The dispersal is mostly rapid with varying degrees of aggregation. The positions of damaged trees were clustered with specified upper and lower bounds for the number of cluster centers ha^{-1}. Cluster centers were not allowed to fall closer than 50 m from each other. A cluster radius was simulated and within this radius the positions of damaged trees were randomly distributed. The radius of clusters was increased with a given probability and the intensity of damaged trees within this radius was also increased with a given probability (independently of the increase in radius). Hence, certain clusters were exactly the same at both TP1 and TP2 whereas others grew considerably.

With a cluster sample of circular fixed area plots, the number of possible sampling locations is infinite, and the variance of the estimator within each square cannot be calculated analytically. Hence, this variance was determined by Monte-Carlo simulation (e.g., Gregoire & Valentine, 2008) with 10 000 repetitions. In relation to the actual number of damaged trees ha^{-1} varying subscenarios and proportion of squares with damaged trees were tested. The latter was set to low and medium levels (1.5 and 12 damaged trees ha^{-1}, respectively) in scenario 1 and to a high level (75 damaged trees ha^{-1}) in scenario 2.

Finally, the variance of the estimator of number of damaged trees ha^{-1} across the whole studied landscape was calculated for each scenario and damage level. To investigate the possibility to estimate the extent of outbreaks based on a subset of the full sample, we derived the variance of an estimator based on a subsample of squares by assuming a simple random sub-sampling of squares, which then constituted one year's panel.

3.3 A new system for assessing and monitoring damage (Paper IV)

An information needs assessment was conducted in order to review the decision-making requirements of forest damage information. Different stakeholders' needs for data were assessed and an overview of available inventory programmes etc. was carried out.

Several sources of data on forest damage and condition in Sweden are available including, at strategic level, the NFI data and information obtained from long-term monitoring of insect populations. In the NFI information is collected on tree, stand and site variables, as well as damage observations (Axelsson *et al.*, 2010). The ICP forests level I plots have been completely integrated in the NFI since 2007. The spruce bark beetle (*Ips typographus*) is monitored in four regions. Beetle activity and density are assessed using pheromone traps during the flight period (Lindelöw & Schroeder, 2001). An internet-based reporting system, "SkogsSkada", where the extent, nature and distribution of forest damage can be recorded, is also available. The system comprises a damage diagnosis function, fact sheets, reports, maps, and up-to-date information about recent damage (SLU, 2011). ICP Forests level II plots have been established aiming to examine correlative relationships between damage-causing factors and effect parameters, e.g., drought and tree growth or nitrogen deposition and insect damage.

Based on the information needs assessment, and the review of existing assessment and monitoring components, a new system for monitoring forest damage in Sweden was proposed.

4 Results

4.1 Evaluation of the accuracy of forest condition assessments (Paper I)

In almost all tests during the national training courses significant differences were found for at least one team (or observer). However, the observer average assessments of defoliation seldom differed significantly from the reference standard (Table 4).

Estimates from the control survey showed varying agreement of the assessments in the international damage classes (Table 5). Estimates of the Kappa statistic indicated that assessments of defoliation on Norway spruce was fairly good (0.30-0.58), and the agreement was weakest for discolouration assessments. The results from the international calibration courses revealed that in almost all tests assessment of defoliation by representatives of at least one of the four included countries significantly differed from the Swedish national reference values (Table 6).

Table 4. *Results of a t-test of the differences between the national reference team's and mean of all observers' assessments of defoliation in national calibration courses in 1995 – 1999.*

Year	Norway spruce (*Picea abies*)					Scots pine (*Pinus sylvestris*)				
	Average defoliation	Diff	SD_{diff}	df	$\lvert t_0 \rvert$	Average defoliation	Diff	SD_{diff}	df	$\lvert t_0 \rvert$
1995	32.8	-0.8	4.5	14	0.65	16.3	0.0	4.9	14	0.02
1996	35.3	-2.1	5.2	19	1.80	23.9	0.0	3.9	18	0.01
1997	28.7	0.2	2.8	8	0.20	18.4	0.2	2.0	8	0.31
1998	26.3	0.7	1.9	7	1.04	16.8	-0.9	2.0	7	1.23
1999	33.7	-0.5	7.2	11	0.25	18.3	-0.7	2.6	12	0.98

Diff is the mean of the differences between the observers' and the reference team assessments and SD_{diff} is the standard deviation of the differences. The hypothesis H_0:Diff= 0 was tested and rejected if $|t_0| > t_{\alpha/2, n-1}$.

Table 5. *Actual agreement coefficients (A) and Kappa statistics (K) for assessment of defoliation and discolouration between the ordinary teams and the control team during 1995 – 1999.*

Year	Norway spruce (*Picea abies*) Defoliation		Scots pine (*Pinus sylvestris*) Defoliation		Norway spruce (*Picea abies*) Discolouration	
	A	*K*	*A*	*K*	*A*	*K*
1995	0.51	0.30	0.61	0.20	0.79	0.23
1996	0.64	0.45	0.59	0.29	0.80	0.06
1997	0.66	0.48	0.52	0.18	0.88	0.28
1998	0.73	0.58	0.77	0.50	0.90	0.23
1999	0.68	0.51	0.59	0.30	0.75	0.28

Table 6. *Results of the t-test of differences between the Swedish national reference assessment and average assessments by representatives of other north European countries of defoliation in the international calibration courses during 1995 – 1999.*

Year	Norway spruce (*Picea abies*)					Scots pine (*Pinus sylvestris*)				
	Average defoliation	Diff	SD_{diff}	df	$\|t_0\|$	Average defoliation	Diff	SD_{diff}	df	$\|t_0\|$
1995	34.0	1.7	8.0	19	0.93	25.1	-3.4[a]	5.5	19	2.81
1996	26.4	1.1	5.8	29	1.04	25.3	-3.7[a]	6.3	29	3.15
1998	27.2	-1.8	6.5	24	1.41	24.4	-7.2[a]	7.6	24	4.76
1999	32.0	-4.0[a]	7.8	24	2.53	32.9	-0.8	5.8	19	0.64

[a] Significant difference at 0.05 level. Diff is the mean of the differences between the observers' and the reference team assessments and SD_{diff} is the standard deviation of the differences. The hypothesis H_0:Diff= 0 was tested and rejected if $|t_0| > t_{\alpha/2, n-1}$.

4.2 Evaluation of systematic plot-based sampling designs (Papers II and III)

The estimated total area of *Gremmeniella*-affected pine forest during 2001-2003 was 484 000 ha (Table 7), almost 6 % of the pine forest in Sweden, making this outbreak by far the largest reported in Sweden. Affected pine

Table 7. Estimated areas (ha), and coefficients of variation (CV %), of *Gremmeniella*-affected pine forest and sanitation cuttings due to shoot blight disease in Sweden during 2001 – 2003.

Area	Slightly affected	Severely affected	Total affected	Cuttings
1000 ha (CV%)	423 (8.9)	62 (25.8)	484 (5.8)	51 (13.3)

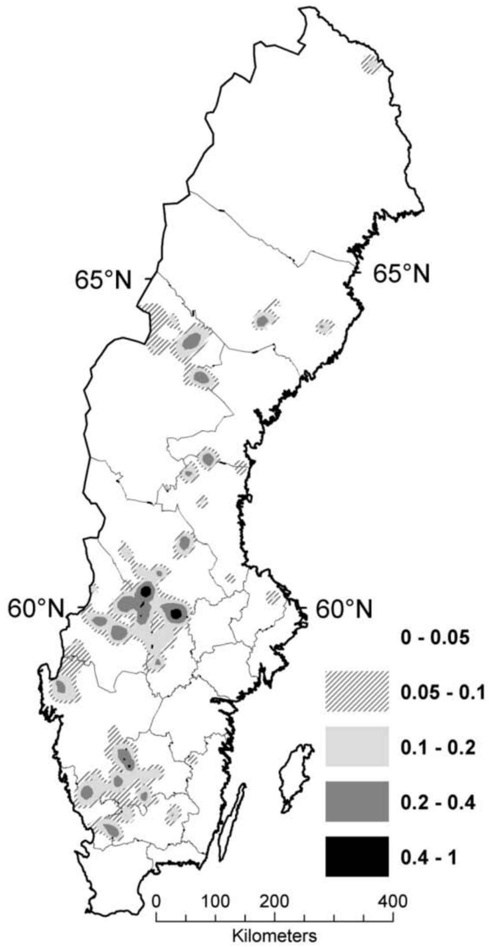


Figure 7. Proportions of *Gremmeniella*-affected pines in pine forests (where pine accounted for at least 65% of stand basal area) in 2002 - 2003. N=Norrland, S=Svealand, G=Götaland.

forest was found over almost the entire country, as shown in Figure 7. The map shows three epidemic centres at high altitudes in: (i) central Götaland, (ii) western Svealand, and (iii) central Norrland. In these three areas widespread damage was also found in 1999, which increased due to favourable weather conditions for the fungi during the summer of 2000 and winter of 2000/2001, resulting in further escalation in 2001.

The total area of diseased pine forest was estimated with a confidence interval of +/- 11.4 % of the area estimate (Table 7), and estimated proportions of pine trees with fresh shoot blight infection significantly increased ($p < 0.05$) from 2000 to 2001 (Table 8). The results indicate that despite a relatively sparse sample plot density, the NFI and the NFDI have good potential for estimating the geographic distribution, area, and development of extensive damage-causing disease outbreaks.

Table 8. Proportion (*R*) of pine trees with fresh shoot blight infection. Data from the Swedish National Forest Damage Inventory 1999 - 2003.

Degree of damage	Year									
	1999		2000		2001		2002		2003	
	R	CV %	*R*	CV %	*R*	CV %	*R*	CV %	*R*	CV %
Light	-[1]		-[1]		10.01	12.9	3.01	25.6	2.04	26.8
Moderate	0.11[2]	83.2	0.00[2]	0	3.59	19.0	0.67	66.2	0.31	69.4
Severe	0.00	0	0.00	0	1.28	26.8	0.30	56.2	0.00	0

[1] Data not available due to differences in classification.
[2] Amount of shoot blight exceeding 20%.

The simulation study (Paper III) revealed that for Scenario 1, with low levels of damage at TP1, the relative SE was never less than 10 % even when a full sample was utilized (Figure 8, to the left). However, with this starting intensity, the relative SE of the estimate of the increase in the number of damaged trees ha^{-1} was less than 10 % when utilizing the full sample size if the increase in the number of damaged trees ha^{-1} was 50 % or more, i.e., 0.8 new damaged trees ha^{-1}

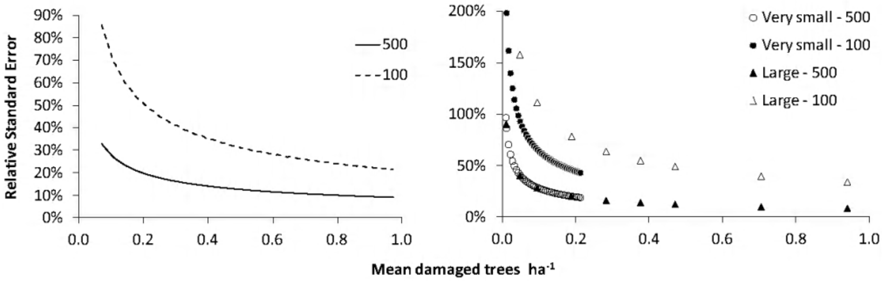


Figure 8. The relative standard errors of estimates at TP1 (left figure) and the increment to TP2 (right figure) in relation to the number of damage trees ha^{-1} with a full sample size (N=500) and one year panel (n=100). Results for scenario 1 and the low level of damaged trees in TP1.

For scenario 1 with medium levels of damaged trees ha^{-1} at TP1, the relative SE was less than 10 % in almost all cases (Figure 9), and when utilizing the full sample even changes as small as 5 % of the initial value when damage was present in all squares could be estimated with good precision (e.g., 0.8 freshly infected trees ha^{-1} with less than 10 % relative SE). With a single panel, changes depended on the starting level of damage and the proportion of squares with damaged trees. Precision was lower (i.e. SEs were higher) when there were smaller increases in damage and fewer squares were used, and the relative SE was consistently greater than 10 %.

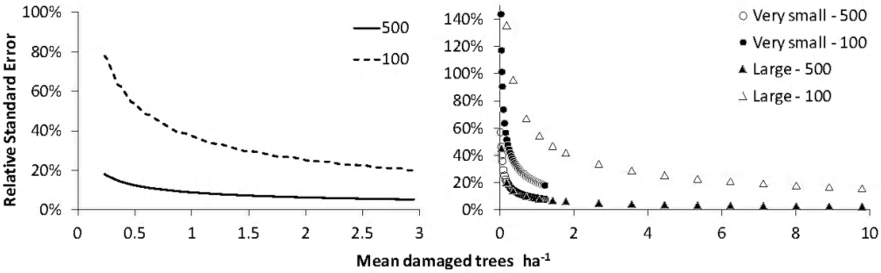


Figure 9. The relative standard errors of estimates at TP1 (left figure) and the increment to TP2 (right figure) in relation to the number of damage trees ha^{-1} with a full sample size (N=500) and one year panel (n=100). Results for scenario 1 and the medium level of damaged trees in TP1.

For the scenario 2 populations the precision was clearly poorer than for the population simulated in scenario 1; relative standard errors < 20 % were only obtained for simulations with a large level of damage at TP2 when using the full sample and a large number of damaged trees per hectare (Figure 10).

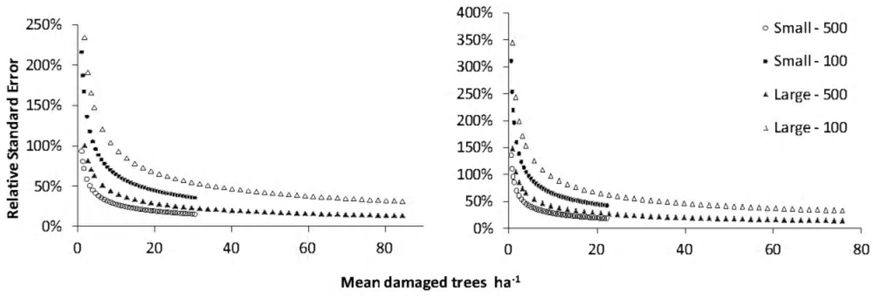


Figure 10. The relative standard errors of estimates at TP1 (left figure) and the increment to TP2 (right figure) in relation to the number of damage trees ha^{-1} with a full sample size (N=500) and one year panel (n=100). Results for scenario 2 and the medium level of damaged trees in TP1.

4.3 A new system for assessing and monitoring damage (Paper IV)

The information needs assessment and review of existing methods resulted in a proposal for a new Swedish monitoring system. The new system includes complementary components targeting different needs, intended to provide a broad spectrum of information needed for decision-making. The comprehensive monitoring system incorporates strategic monitoring, operational inventories of forest damage, and research-related monitoring (Figure 11). National Forest Inventories (NFIs) are primary sources of data for national and large area assessments of the state of forests (McRoberts *et al.*, 2009). However, the NFI design makes it difficult to monitor rapid changes, e.g., changes in insect populations during the vegetation period. Further, in order to maintain high-quality assessments there is a limit to the number of damage agents that can be included. Thus, in addition to measurements in the NFI, long-term monitoring of insect populations on separate plots would be conducted as part of the new Swedish system.

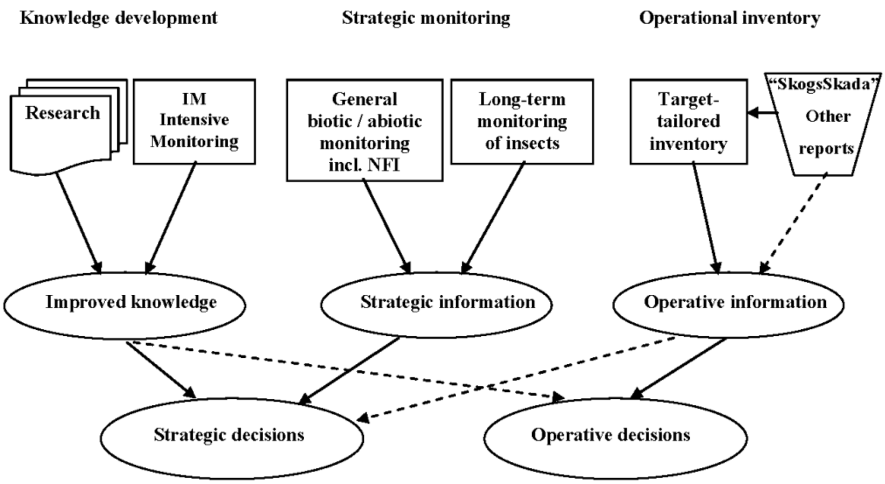


Figure 11. An overview of the new Swedish monitoring system.

Information for operational-level decision making needs to be adapted to the specific needs of a certain damage mitigation scheme. The first step is to identify locally important insect and fungus outbreaks. In this step an important role is proposed for the reporting and analysis system "SkogsSkada", to provide first assessments of the damaging agent, the amount of damage and geographic location.

Once damage is judged to have reached a degree where intervention is required, there is often a need to collect additional information to support specific mitigation decisions. At this stage specific inventories, tailored to provide information relevant for the specific scheme being elaborated, should be utilized. Such "target-tailored" inventories have already been carried out in some case studies (Table 9).

Table 9. Target-tailored inventories carried out in Sweden during 2006 – 2011.

Year	Damage	Area
2006 and 2007	Tree death caused by Spruce bark beetle	Southern Sweden
2007 and 2008	Resin top disease on young pine trees	Northern Sweden
2009 and 2010	Ash disease	Southern Sweden
2011	Tree death caused by bark beetles	Northern Sweden

In addition to the components focussing on providing information to support decision making, the system also include components that focus primarily on knowledge expansion. Besides research, these activities are mainly related to the Integrated Monitoring (IM) program under the Swedish implementation of CLRTAP (Lundin *et al.*, 2008).

5 Discussion

Monitoring forest damage often involves collecting data through ocular assessments. Visual observations of damage are affected by weather and visibility as well as the status of the target object (Innes, 1988). On the calibration courses several of the disturbance factors affecting the observations are constant. However, the quality of the assessments also strongly depends on the experience and visual perceptions of the observers. In a study of surveyor consistency in presence/absence sampling for monitoring vegetation (Ringvall *et al.*, 2005), significant differences were found more often between observers of a less experienced group than between members of an experienced group. Experience improves observers' skill to detect differences and changes, but other underlying conditions also affect visual perception ability. Expectations of what is seen, and what it is seen as, will also influence the assessments (Gordon, 1996).

The process of making observations can be broken down into three steps, as discussed by Stoerig (1996). The first step includes a vision; the observer becomes aware of what is seen, but not what it is. Secondly, he/she notices an object and finally recognizes the object as a certain object. In most cases assessments (observations) are influenced by presumptions about the observation and the situation. Notably, observers (and their observations) are influenced by the information given. For these reasons, guidelines for inventories must be as objective as possible.

Significant differences between observers indicate that observer bias also influence the results, in accordance with previous reports it affects assessments of forest damage together with both sampling error and natural variation (Innes, 1988; Strand, 1996; Solberg, 1999b). In addition to the bias component the observer variability has to be considered. This variability is important not only between observers but also among the observations made by a single surveyor, as indicated in Paper I and follow-up studies (Wulff, 2002; Wulff, 2004). These errors also affect any trend analysis based on the data, but the effects of the errors are reduced when the time series are long and several observers have been involved each year.

The control survey in 2001-2003 revealed that assessments of Gremmeniella damage with good agreement (kappa statistic 0.6) were obtained during the first two years. Although shoot blight is a distinct symptom, there are uncertainties regarding the best way to monitor it. In 2003, when frequencies of new infection decreased, the agreement was weaker (kappa statistic 0.3); similar results were obtained in later control surveys (Table 10), indicating difficulties in identifying the cause of damage and the assessable part of the tree crown. This highlights the importance of distinct descriptions, accurate assessments of damage symptoms, and stable identification of causal agents to improve estimates of forest damage (Ferretti, 1997; Nevalainen, 1999; Wulff, 2007).

Results from later tests of assessments of different damage symptoms and causes have shown poor reproducibility, especially for low degrees of damage symptoms (Table 10). This has led to the inclusion of threshold values in the inventory of forest damage in the NFI. Although this introduces risks of missing low degrees of damage, which may indicate initial phases of outbreaks, it is considered essential in order to ensure the reliability of the inventory data. The accuracy of the assessments should be regularly tested to evaluate the quality of the inventory, and thus obtain a better understanding of the results.

Our study of the applicability of national forest inventories for estimating forest damage outbreaks (Paper II) concludes that large-scale monitoring has good potential for estimating geographical distributions, areas, and the epidemiology of extensive disease outbreaks. This conclusion is supported by Nevalainen *et al.* (2010), who also found a clear correlation between changes in defoliation and the degree of damage caused by pathogens and pest organisms. In terms of sampling errors, accurate estimates can be obtained from the National Forest Inventory data (as shown in Table 3), indicating that NFI´s provide trustworthy time series, which is a core concern for strategic-level decision-making.

Table 10. Actual agreement coefficients (A) and Kappa statistics (K) for assessments of forest damage symptoms, extent and causes in the Swedish NFDI control survey during 2005. n = 675. Modified from Wulff (2007)

Damage Symptom / Causes	A	K
Wounds	0.92	0.63
Resin flow	0.95	0.53
Tilted	0.97	0.57
Dead branches	0.76	0.34
Broken branches	0.91	0.31
Discolouration	0.85	0.30
Needle/leaf loss	0.65	0.07
Fungi	0.78	0.27
*Gremmeniella**	0.70	0.27
Insects	0.83	0.38
Defoliator	0.87	0.37

*On pine trees only

A challenge in this context is to detect slight changes in forest damage over time. Results from our simulation study indicate that gradual changes of forest damage can be estimated with relatively low standard errors. Revealing general slow-degree changes in forest condition implies benefits from large-scale monitoring difficult to get from other inventories. Despite all the advantages of large-scale monitoring, accurate interpretation of data also requires knowledge of limitations. Many NFIs are based on permanent plots remeasured in intervals of 5-10 years (Lawrence *et al.*, 2010). A large total sample can be obtained and data on time-series can be presented in moving average. However, for certain damage outbreaks (short-time) full sample can be difficult to utilize. An outcome from our simulation study (paper III) was that the usability of large-scale inventories decrease for more scattered occurrence in the landscape and clustered outbreaks of damage. Notably, major regional outbreaks of damaging agents or sudden changes during the field season are difficult to survey in large-scale inventories (Wulder *et al.*, 2006). Normally, large-scale inventories, such as NFIs, cannot provide adequate information for identifying appropriate mitigation measures. Thus, in addition to broad monitoring programmes that provide time-series information on known damaging agents and their effects, there is also a need for local and regional inventories adapted to specific damage events.

Strenuous efforts are put into monitoring forest condition and health, but in many cases there is a need for thorough analysis of whether the objectives and methodology of monitoring programmes are in accordance with the present and future requirements (e.g., Percy & Ferretti, 2004). The effectiveness of such programmes, the significance of the results, and the suitability of the format (including analysis and interpretation) in which they are presented for intended decision-makers are discussed in several papers (Ferretti, 1997; Percy & Ferretti, 2004; Lovett *et al.*, 2007; Moffat *et al.*, 2008). At a strategic level (cf., Barth, 2007) there is a need for information to support assessments of general risks for damage outbreaks as well as actual damage caused by both biotic and abiotic agents. Short-term planning involves decisions for implementing specific mitigation schemes, such as when a major damage outbreak has occurred or is about to occur due to large insect populations. In such situations, forest agencies may be responsible for implementing coordinated mitigation schemes and the landowners may need to implement more than regular management (Lindelöw & Schroeder, 2008). In addition to information to support decision-making, there is a general need for increased knowledge of damage agents and damage-promoting factors. Such knowledge may also be crucial for successful implementation of mitigation schemes.

In recent years much effort has been placed on harmonization and quality assurance of the monitoring systems. Continuous quality assurance work (calibration and tests), with updated manuals to provide clear and concise definitions, is essential (Ferretti *et al.*, 2010). Much work has been carried out within the framework of the EU´s FutMon (Clarke *et al.*, 2011) and Cost Action E43 (McRoberts *et al.*, 2009) programmes towards coordinating data collection in the ICP Forests Level I and NFI surveys, and developing harmonization techniques that facilitate common reporting (FutMon, 2011). However, the harmonization process at a European level has been questioned and there are uncertainties about its progress, although different perspectives may be considered at national level (Ferretti, 2010). For these (and other) reasons, forest condition monitoring activities have to be improved, further developed, and adapted to changing perspectives on threats.

Effective monitoring programmes require not only data collection and evaluation, but also clear awareness of the questions to be addressed, and they must provide appropriate, reliable and timely information for defined users. The new Swedish forest damage and health monitoring system proposed in Paper IV is well in line with these requirements.

Monitoring should also be integrated with research programmes to promote continuous knowledge development. Data provided for compliance with agreements such as CLRTAP and Forest Europe (MCPFE, 2011) need to be collected within stable long-term monitoring programmes that provide simplified but meaningful interpretations of time series. The most important results are provided by sustained monitoring of key variables in long-term studies, as many disturbances have a gradual influence on forests. However, the provision of information to support certain damage mitigation schemes needs to be flexible enough to adapt quickly to new situations. Irregularly occurring forest pests and pathogens are difficult to survey solely through large-scale monitoring programmes, which can only meaningfully include rather common and easily detectable types of damage, even with large sample sizes, as in the Swedish NFI (Table 11). Results from the simulation study in Paper III show that estimates of regional outbreaks of damage typically have poor precision.

Table 11. *Minimum numbers of plots required within the Swedish NFI (assuming simple random sampling of plots with proportional allocation) to obtain a certain precision within an area where outbreaks occur*

Size of area within which a damage outbreak occurs	Number of plots required within the NFI to obtain a certain coefficient of variation (CV) for the estimated disease-affected area		
	CV = 1%	CV = 5 %	CV = 10 %
Small (10 kha)	42,750,000	1,710,000	427,500
Intermediate (100 kha)	4,275,000	171,000	42,750
Large (1,000 kha)	427,500	17,100	4,275
Very large (10,000 kha)	42,750	1,710	428

In large, widespread outbreaks like the *Gremmeniella* epidemic in 2001-2003, which could act on 8.7 million ha of pine forest, useful information is available from large-scale inventories. In other cases there is a need for complementary tailored inventories to increase the possibilities for timely delivery of relevant information.

One of the most demanding tasks in monitoring forest damage is to establish an early warning system. Ideally the monitoring system should be able to detect both outbreaks of native insects or fungi and the dispersal of new diseases. Risk analysis can be improved, as proposed by Coulston *et al.* (2008), by applying sampling techniques providing known levels of precision to verify freedom from invasive damaging agents. Detecting future risks is also a major challenge for international cooperative efforts; currently there is no pan-European system for the early detection of forest decline triggered by insect or fungus outbreaks. Monitoring in sparse plot networks, such as CLRTAP forest condition surveys and NFIs, is used to provide outlines of the spatial and temporal variation of forest condition. However, the networks are not designed to detect rapid changes or alien invasive species threatening the forest.

The new Swedish forest health system is believed to be capable of detecting and monitoring incipient threats to the forest more robustly. A first forewarning should be obtained through the internet-based reporting and assessment scheme "SkogsSkada", which includes a damage diagnosis function, fact sheets, records, maps, and up-to-date information about recent damage. The reporting scheme is fully open, but of course for optimal results it needs to be generally known and used by forest officers. Further work is required to publicise its availability and encourage its use to report the occurrence of damage in the forest, but this should be facilitated by modern techniques based on use of GPS and "SkogsSkada" as an application on cell phones.

The proposed forest health system is comparable to corresponding national programs of forest health monitoring (FHM, 2011) and forest inventory and analysis (FIA, 2011) in the USA. Data on forest health indicators are collected on forest health plots integrated with the NFI (Tkacz *et al.*, 2008). Sound detection, evaluation, and intensive site monitoring, together with research on monitoring techniques, analysis and reporting, should lead to robust assessments of forests in changing environments, and thus contribute to future management and policy decisions (Woodall *et al.*, 2011). In the detection monitoring program remote sensing techniques are used.

Utilizing remote sensing and geographic information systems increases the possibilities to monitor forest damage. A prototype of an Early Warning System (EWS) was introduced in the USA in 2010, which in low-resolution (231-m) satellite images are used to produce maps showing potential forest disturbance (Hargrove *et al.*, 2009). New images are available every eight days and a change detection system is used to highlight areas of interest. Follow-ups by airborne and ground inspections of areas of potential interest will determine if signalled areas are affected by damage. Images from the MODIS satellite have also been used to detect outbreaks of European pine sawfly in south-eastern Norway (Eklundh *et al.*, 2009). The technique has good quality potential to detect large-scale outbreaks causing distinct damage at early stages, for instance those caused by insects feeding on needles, such as pine sawflies. The relatively frequent measurements also make it useful for covering changes over time. However, there are still less distinct disturbances and other threats to the forest posed by alien species which need additional attention.

6 Conclusions

In ocular assessments, as applied in many environmental monitoring programmes, observer errors together with sampling errors influence the reliability of results. Therefore, the accuracy of the assessments should be regularly tested to evaluate the quality of the inventory, and thus obtain a better understanding of the results.

Large-scale monitoring programmes, such as national forest inventories, have a good potential for estimating geographical distributions, areas, and the epidemiology of extensive damage outbreaks. Gradual changes in forest damage can also be estimated from data acquired by large-scale monitoring, with relatively low standard errors, which would be difficult to detect in data from other inventories. An assessment of the current Swedish forest damage monitoring system revealed advantages as well as shortcomings. To meet the information demands, assessments of forest damage and condition must cover both specific known damage causes and the general state of the forest. For optimal results, reliable, practical and cost-effective methods are required in assessments of tree responses to different causes of damage. Monitoring in sparse plot networks, such as CLRTAP forest condition surveys and NFIs, provides information on the general state and both spatial and temporal variation of forest condition. However, despite all the advantages of large-scale monitoring, accurate interpretation of the acquired data also requires awareness of the limitations. Thus, in addition to broad monitoring programmes that provide time-series information on known damaging agents and their effects, there is also a need for local and regional inventories adapted to specific damage events.

To meet the information needs a revised Swedish forest health assessment system is proposed, composed of several interacting components that target information needs for strategic and operational decision-making, and accommodates a mechanism for continuously expanding the knowledge base.

References

Aamlid, D., Solheim, H. & Venn, K. (1991). *Skogskader, Veiledning i overvakningen av skogsskader* Norsk Institutt for skogforskning, Ås. ISBN 82-7169-505-3. (In Norwegian).

Allen, C.D. & Breshears, D.D. (1998). Drought-induced shift of a forest-woodland ecotone: Rapid landscape response to climate variation. *Proceedings of the National Academy of Sciences of the United States of America* 95(25), 14839-14842.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.H., Allard, G., Running, S.W., Semerci, A. & Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* 259(4), 660-684.

Anon. (2007). *Forestry statistics 2007*. Umeå: Official Statistics of Sweden, Swedish University of Agricultural Sciences. ISSN 0280-0543.

Anon. (2011). *Fältinstruktion 2011, RIS Riksinventeringen av skog*. Umeå. (In Swedish).

Apollonio, M., Andersen, R. & Putman, R. (Eds.) (2010). *European ungulates and their management in the 21st century*. Cambridge University Press.

Axelsson, A.-L., Ståhl, G., Söderberg, U., Pettersson, H., Fridman, J. & Lundström, A. (2010). National Forest Inventories Reports: Sweden. In: Tomppo, E., *et al.* (Eds.) *National Forest Inventories: pathways for Common Reporting.* pp. 613-621 New York: Springer. ISBN 978-90-481-3232-4.

Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M., Brown, V.K., Butterfield, J., Buse, A., Coulson, J.C., Farrar, J., Good, J.E.G., Harrington, R., Hartley, S., Jones, T.H., Lindroth, R.L., Press, M.C., Symrnioudis, I., Watt, A.D. & Whittaker, J.B. (2002). Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. *Global Change Biology* 8(1), 1-16.

Barnes, I., Kirisits, T., Akulov, A., Chhetri, D.B., Wingfield, B.D., Bulgakov, T.S. & Wingfield, M.J. (2008). New host and country records of the Dothistroma needle blight pathogens from Europe and Asia. *Forest Pathology* 38(3), 178-195.

Barth, A. (2007). *Spatially Comprehensive Data for Forestry Scenario Analysis.* Diss. Umeå:Swedish University of Agricultural Sciences.

Bauer, A., Dammann, I., Gawehn, P., Schröck, H.W., Wendland, J. & Ziegler, C. (2007). *Waldbäume: Bilderserien zur Einschätzung von Kronenverlichtungen bei Waldbäumen*. 2nd. ed: Verlag M. Faste. ISBN 978-3-931691-50-9.

Bengtsson, G. & Lindroth, S. (1991). *Skogsskadeinventeringen i Blekinge år 1984*. Sveriges Lantbruksuniversitet, Institutionen för Skogstaxering Rapport 50. ISSN 0348-0496. (In Swedish).

Bigler, C., Braker, O.U., Bugmann, H., Dobbertin, M. & Rigling, A. (2006). Drought as an inciting mortality factor in Scots pine stands of the Valais, Switzerland. *Ecosystems* 9(3), 330-343.

Binkley, D. & Högberg, P. (1997). Does atmospheric deposition of nitrogen threaten Swedish forests? *Forest Ecology and Management* 92(1-3), 119-152.

Blennow, K. (2010). Risk management in Swedish forestry-policy formation and fulfilment of goals. *Journal of Risk Research* 11(1-2), 237-254.

Blennow, K. & Sallnäs, O. (2004). WINDA - a system of models for assessing the probability of wind damage to forest stands within a landscape. *Ecological Modelling* 175(1), 87-99.

Boulanger, Y. & Arseneault, D. (2004). Spruce budworm outbreaks in eastern Quebec over the last 450 years. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 34(5), 1035-1043.

Brasier, C.M. (2001). Rapid evolution of introduced plant pathogens via interspecific hybridization. *Bioscience* 51(2), 123-133.

Breda, N. & Badeau, V. (2008). Forest tree responses to extreme drought and some biotic events: Towards a selection according to hazard tolerance? *Comptes Rendus Geoscience* 340(9-10), 651-662.

Breda, N., Huc, R., Granier, A. & Dreyer, E. (2006). Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. *Annals of Forest Science* 63(6), 625-644.

Breshears, D.D., Myers, O.B., Meyer, C.W., Barnes, F.J., Zou, C.B., Allen, C.D., McDowell, N.G. & Pockman, W.T. (2009). Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements. *Frontiers in Ecology and the Environment* 7(4), 185-189.

Brown II, E.A. & Coder, K.D. (2009). *Fusiform Rust on Pines*. CAES, The University of Georgia. The Cooperative Extension, Circular 440.

Brydges, T. (2004). Basic concepts and applications of environmental monitoring. In: Wiersma, B.G. (Ed.) *Environmental Monitoring*. pp. 83-109. Boca Raton: CRC Press. ISBN 1-56670-641-6.

Butin, H. (1995). *Tree diseases and disorders: Causes, biology and controlin forest and amenity trees*. Oxford: Oxford University Press.

Cape, J.N., Freersmith, P.H., Paterson, I.S., Parkinson, J.A. & Wolfenden, J. (1990). The nutritional-status of Picea abies (L) Karst across Europe, and implications for forest decline. *Trees-Structure and Function* 4(4), 211-224.

CFS *Forest Research-Canadian Forest Service*. [online] Available from: http://cfs.nrcan.gc.ca/forestresearch.

Ciesla, V.N. & Donaubaur, E. (1994). *Decline and dieback of trees and forests: A global overview*. Rome. (FAO Forestry Paper; 120). ISBN 92-5-103502-4.

Clarke, N., Fischer, R., De Vries, W., Lundin, L., Papale, D., Vesala, T., Merilä, P., Matteucci, G., Mirtl, M., Simpson, D. & Paoletti, E. (2011). Availability, accessibility, quality and comparability of monitoring data for European forests for use in air pollution and climate change science. *Iforest-Biogeosciences and Forestry* 4, 162-166.

CLRTAP *UN ECE Conventionon long-range transboundary air pollution*. [online] Available from: http://live.unce.org./env/lrtap/welcome.html.

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement* 20(1), 37-46.

Coulson, R.N. & Stephen, F.M. (2008). Impacts of insects in forest landscapes: Implications for forest health management. In: Paine, T.D. (Ed.) *Invasive Forest Insects, Introduced Forest Trees, and Altered Ecosystems*. pp. 101-125 Springer. ISBN 978-1-4020-9290-9.

Coulston, J.W., Koch, F.H., Smith, W.D. & Sapio, F.J. (2008). Invasive forest pest surveillance: survey development and reliability. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 38(9), 2422-2433.

Czokajlo, D., Wink, R.A., Warren, J.C. & Teale, S.A. (1997). Growth reduction of Scots pine, Pinus sylvestris, caused by the larger pine shoot beetle, Tomicus piniperda (Coleoptera, Scolytidae), in New York State. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 27(9), 1394-1397.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J. & Wotton, B.M. (2001). Climate change and forest disturbances. *Bioscience* 51(9), 723-734.

Davis, L.S., Johnson, K.N., Bettinger, P.S. & Howard, T.E. (2001). *Forest management*. 4th. ed. New York: McGraw-Hill Science / Engineering / Math.

Diaz, S., Fargione, J., Chapin, F.S. & Tilman, D. (2006). Biodiversity loss threatens human well-being. *Plos Biology* 4(8), 1300-1305.

Dobbertin, M. (2005). Tree growth as indicator of tree vitality and of tree reaction to environmental stress: a review. *European Journal of Forest Research* 124(4), 319-333.

Drobyshev, I., Anderson, S. & Sonesson, K. (2007). Crown condition dynamics of oak in southern Sweden 1988-1999. *Environmental Monitoring and Assessment* 134(1-3), 199-210.

Eckmüllner, O. & Sterba, H. (2000). Crown condition, needle mass, and sapwood area relationships of Norway spruce (Picea abies). *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 30(10), 1646-1654.

Edenius, L., Bergman, M., Ericsson, G. & Danell, K. (2002). The role of moose as a disturbance factor in managed boreal forests. *Silva Fennica* 36(1), 57-67.

Edmonds, R.L., Agee, J.K. & Gara, R.I. (2000). *Forest Health and Protection*: McGraw-Hill Higher Education. ISBN 0-07-021338-0.

Eichhorn, J., Icke, R., Isenberg, A., Paar, U. & Schonfelder, E. (2005). Temporal development of crown condition of beech and oak as a response variable for integrated evaluations. *European Journal of Forest Research* 124(4), 335-347.

Eichhorn, J., Roskams, P., Ferretti, M., Mues, V., Szepesi, A. & Durrant, D. (2010). Visual assessment of crown condition and damaging agents, Manual part IV. In: *Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effect of air pollution on forests, UNECE ICP Forests.* p. 29. Hamburg: Programme cordinating centre of ICP Forests. ISBN 978-3-926301-03-1.

Eklundh, L., Johansson, T. & Solberg, S. (2009). Mapping insect defoliation in Scots pine with MODIS time-series data. *Remote Sensing of Environment* 113(7), 1566-1573.

EPPO (2005). Lymantria Mathura. *EPPO bullentin* 35(3), 464-467.

Ericsson, A., Nordén, L.G., Näsholm, T. & Walheim, M. (1993). Mineral nutrient imbalances and arginine concentrations in needles of Picea abies (L) Karst from 2 areas with different levels of airborne deposition. *Trees-Structure and Function* 8(2), 67-74.

EU *European Commission. Green paper, on forest protection and information in EU: preparing forest for climate change*. [online] Available from: http://ec.europa.eu/environment/forest/pdf/green_paper.pdf.

FAO (2009). *Global review of forest pests and diseases*. FAO Forestry paper 156: Food and Agricultural Organization of the United Nation. ISBN 978-92-5-106208-1.

Fenger, J. (2009). Air pollution in the last 50 years - From local to global. *Atmospheric Environment* 43(1), 13-22.

Ferretti, M. (1997). Forest health assessment and monitoring - Issues for consideration. *Environmental Monitoring and Assessment* 48(1), 45-72.

Ferretti, M. (2010). Harmonizing forest inventories and forest condition monitoring - the rise or the fall of harmonized forest condition monitoring in Europe? *Iforest-Biogeosciences and Forestry* 3, 1-4.

Ferretti, M., König, N. & Granke, O. (2010). Quality Assurance within the ICP Forests monitoring programme. Manual part III. In: *Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests*. UNECE ICP Forests Programme Co-ordinating Centre, Hamburg. ISBN 978-3-926301-03-1.

FHM *USDA Forest Service, National Forest Health Monitoring* [online] Available from: http://fhm.fs.fed.us/aboutus/index.shtml.

FIA *USDA Forest Service, Forest Inventory and Analysis National Program*. [online] Available from: http://www.fia.fs.fed.us/.

Fischer, R., Lorenz, M., Granke, O., Mues, V., Iost, S., van Dobben, H., Reinds, G.J. & de Vries, W. (2010a). *Forest Condition in Europe. 2010 Technical report of ICP Forests. Work report of the Institute for World Forestry 2010/1* ICP Forests, Hamburg.

Fischer, R., Lorenz, M., Köhl, M., Mues, V., Granke, O., Iost, S., van Dobben, H., Reinds, G.J. & de Vries, W. (2010b). *The condition of forest in Europe (2010). Executive Report*. ICP Forests and European Commission, Hamburg and Brussels.

Fleiss, J.L., Cohen, J. & Everitt, B.S. (1969). Large sample standard errors of Kappa and weighted Kappa. *Psychological Bulletin* 72(5), 323-327.

Fridman, J. & Walheim, M. (2000). Amount, structure, and dynamics of dead wood on managed forestland in Sweden. *Forest Ecology and Management* 131(1-3), 23-36.

FutMon *FutMon, Life+ EU*. [online] Available from: http://www.futmon.org/.

Ganey, J.L. & Vojta, S.C. (2011). Tree mortality in drought-stressed mixed-conifer and ponderosa pine forests, Arizona, USA. *Forest Ecology and Management* 261(1), 162-168.

Gillis, M.D., Omule, A.Y. & Brierley, T. (2005). Monitoring Canada's forests: The National Forest Inventory. *Forestry Chronicle* 81(2), 214-221.

Gordon, I.E. (1996). *Theories of Visual Perception*. Second. ed. Chichester: John Wiley & Sons Ltd. ISBN 0-471-96825-0.

Gregoire, T.G. & Valentine, H.T. (2008). *Sampling strategies for natural resources and the environment*. Boca Raton: Chapman & Hall/CRC.

Gärdenfors, U. (Ed.) (2010). *The redlist of Swedish species*. Artdatabanken, SLU. Uppsala. ISBN 9789188506351.

Hansson, P. (1996). *Gremmeniella abietina in Northern Sweden - Silvicultural aspects of disease development in introduced Pinus Contorta and in Pinus sylvestris.* Diss. Umeå:Swedish University of Agricultural Sciences.

Hansson, P., Persson, M. & Ekvall, H. An estimation of economical loss due to the *Gremmeniella abietina* outbreak in Sweden 2001 - 2003. In: Stanosz, G.R., *et al.* (Eds.) *Proceedings of Foliage, Shoot and Stem Diseases. Proceedings of the Meeting of Working Party 7.02.02. of the International Union of Forestry Research Organizations, Corvallis, Oregon, USA, June 13-19 2004.*, Corvallis, Oregon, USA2005. pp. 67-69.

Hargrove, W.W., Spruce, J.P., Gasser, G.E. & Hoffman, F.M. (2009). Toward a national early warning system for forest disturbances using remotely sensed canopy phenology. *Photogrammetric Engineering and Remote Sensing* 75(10), 1150-1156.

Hartebrodt, C. (2004). The impact of storm damage on small-scale forest enterprises in the south-west of Germany. *Small-Scale Forest Economics, Management and Policy* 3(2), 203-202.

Hartig, R. (1889). *Lehrbuch der Baumkrankheiten* Berlin: Springer. (In German).

Hinrichsen, D. (1987). The Forest Decline Enigma. *Bioscience* 37(8), 542-546.

Horsley, S.B., Long, R.P., Bailey, S.W., Hallett, R.A. & Hall, T.J. (2000). Factors associated with the decline disease of sugar maple on the Allegheny Plateau. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 30(9), 1365-1378.

Hunt, R.S., Geils, B.W. & Hummer, K.E. (2010). White pines, Ribes, and blister rust: integration and action. *Forest Pathology* 40(3-4), 402-417.

ICPForests (2010). *Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests*. UNECE, ICP Forests, Hamburg. ISBN 978-3-926301-03-1.

ICPForests *International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests)*. [online] Available from: http:/www.icp-forests.org/.

Innes, J.L. (1988). Forest health surveys - problems in assessing observer objectivity. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 18(5), 560-565.

Innes, J.L. (1993). *Forest health. Its assessments and status*. Wallingford: C.A.B. International. ISBN 0-85198-793-1.

Innes, J.L., Landmann, G. & Mettendorf, B. (1993). Consistency of observations of forest tree defoliation in 3 European countries. *Environmental Monitoring and Assessment* 25(1), 29-40.

Jeger, M.J. & Pautasso, M. (2008). Plant disease and global change - the importance of long-term data sets. *New Phytologist* 177(1), 8-11.

Jepsen, J.U., Hagen, S.B., Ims, R.A. & Yoccoz, N.G. (2008). Climate change and outbreaks of the geometrids Operophtera brumata and Epirrita autumnata in subarctic birch forest: evidence of a recent outbreak range expansion. *Journal of Animal Ecology* 77(2), 257-264.

Johansson, S.B.K., Vasaitis, R., Ihrmark, K., Barklund, P. & Stenlid, J. (2010). Detection of Chalara fraxinea from tissue of Fraxinus excelsior using species-specific ITS primers. *Forest Pathology* 40(2), 111-115.

Johnson, J. & Jacob, M. (2010). Monitoring the effects of air pollution on forest condition in Europe: is crown defoliation an adequate indicator? *Iforest-Biogeosciences and Forestry* 3, 86-88.

Jonsson, M. (2008). Live-storage of Picea abies for two summers after storm felling in Sweden. *Silva Fennica* 42(3), 413-421.

Jönsson, A.M., Appelberg, G., Harding, S. & Barring, L. (2009). Spatio-temporal impact of climate change on the activity and voltinism of the spruce bark beetle, Ips typographus. *Global Change Biology* 15(2), 486-499.

Kaitera, J. (2000). Analysis of Cronartium flaccidum lesion development on pole-stage Scots pines. *Silva Fennica* 34(1), 21-27.

Kandler, O. & Innes, J.L. (1995). Air-pollution and forest decline in Central-Europe. *Environmental Pollution* 90(2), 171-180.

Karlman, M. (2001). Risks associated with the introduction of Pinus contorta in northern Sweden with respect to pathogens. *Forest Ecology and Management* 141(1-2), 97-105.

Karlman, M., Hansson, P. & Witzell, J. (1994). Scleroderris canker on lodgepole pine introduced in Northern Sweden. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 24(9), 1948-1959.

Kolb, T.E., Wagner, M.R. & Covington, W.W. (1994). Concepts of forest health - Utilitarian and ecosystem perspectives. *Journal of Forestry* 92(7), 10-15.

Kupfer, J.A., Myers, A.T., McLane, S.E. & Melton, G.N. (2008). Patterns of forest damage in a southern Mississippi landscape caused by Hurricane Katrina. *Ecosystems* 11(1), 45-60.

Köhl, M. (1991). Forest damage inventories - Possible causes for the variation of needle-leaf loss assessment between observers and consequences for check assessments. *Allgemeine Forst Und Jagdzeitung* 162(11-12), 210-221.

Laflamme, G. & Lachance, D. (1987). Large infection center of Scleroderris canker (European race) in Quebec Province. *Plant Disease* 71(11), 1041-1043.

Larsen, J.B. (1995). Ecological stability of forests and sustainable silviculture. *Forest Ecology and Management* 73(1-3), 85-96.

Lawrence, M., McRoberts, R.E., Tompoo, E., Gschwanter, T. & Gabler, K. (2010). Comparisons of national forest inventories. In: Tompoo, E., *et al.* (Eds.) *National forest inventories: pathways for common reporting*. pp. 19-33. New York: Springer. ISBN 978-90-481-3232-4.

Lesinski, J. (1989). Morphological vigour indicators in Norway spruce. In: Tichý (Ed.) *Proceedings of the IUFRO Workshop Ecological on Monitoring in Forestry*. pp. 38-46. Ústí n. L., Czechoslovakia.

Lesinski, J. & Landmann, G. (1985). Crown and branch malformation in confers related to forest decline. In: Cape, J.N., *et al.* (Eds.) *Scientific basis of forest decline symptomatology, Air Pollution Research Report 15*. pp. 95-105. Brussels: Commision of European Communities.

Liedeker, H., Schütt, P. & Klein, R.M. (1988). Symptoms of forest decline (Waldsterben) on Norway and red spruce - a morphological comparison in Vermont. *European Journal of Forest Pathology* 18(1), 13-25.

Likens, G.E., Driscoll, C.T. & Buso, D.C. (1996). Long-term effects of acid rain: Response and recovery of a forest ecosystem. *Science* 272(5259), 244-246.

Lindelöw, Å. (2011). Insektsskador i Svenska skogar under 2010 - en återblick. *Växtskyddsnotiser* 66, 1-3. (In Swedish).

Lindelöw, Å. & Schroeder, M. (2001). Spruce bark beetle, *Ips typographus* (L.), in Sweden: Monitoring and risk assessment. *Journal of Forest Science (Prague)* 47(Special Issue 2), 40-42.

Lindelöw, Å. & Schroeder, M. (2008). The storm "Gudrun" and the spruce bark beetle in Sweden. In: Steyrer, G., *et al.* (Eds.) *Second meeting of Forest Protection and Forest Phytosanitary Specialists, Vienna, Austria, 27-28 November 2007.* Forstschutz aktuell nr 44, Bundesforschungs- und Ausbildungszentrum für wald, Naturgefahren und Landschaft (BFW), Vienna, Austria.

Lindenmayer, D.B., Franklin, J.F. & Fischer, J. (2006). General management principles and a checklist of strategies to guide forest biodiversity conservation. *Biological Conservation* 131(3), 433-445.

Lindgren, M. & Pouttu, A. (2010). *Minutes from International cross-calibration course on crown condition (Nordic Countries).* Finnish Forest Research Institute, Vantaa Research unit. Vantaa.

Lindgren, M., Salemaa, M. & Tammanen, P. (2000). Forest condition in relation to environmental factors. In: Mälkönen, E. (Ed.) *Forest condition in a changing environment-The Finnish case Forestry Sciences (Vol 65)*. pp. 142-155. Dordrecht: Kluwer Academic.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolstrom, M., Lexer, M.J. & Marchetti, M. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management* 259(4), 698-709.

Lindroth, S. (1984). *Skogsskador extra observationer vid Riksskogstaxeringen år 1984*. SLU, Institutionen för skogstaxering. (In Swedish).

Lorenz, M. (1995). International co-operative programme on assessment and monitoring of air pollution effects on forests - ICP forests. *Water Air and Soil Pollution* 85(3), 1221-1226.

Lorenz, M. (2010). Objectives, strategy and implementation of ICP Forests. Manual Part I. In: *Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests* UNECE, ICP Forests, Hamburg. ISBN 978-3-926301-03-1.

Lorenz, M. & Mues, V. (2007). Forest health status in Europe. *Thescientificworldjournal* 7, 22-27.

Lovett, G.M., Burns, D.A., Driscoll, C.T., Jenkins, J.C., Mitchell, M.J., Rustad, L., Shanley, J.B., Likens, G.E. & Haeuber, R. (2007). Who needs environmental monitoring? *Frontiers in Ecology and the Environment* 5(5), 253-260.

Lovett, G.M., Canham, C.D., Arthur, M.A., Weathers, K.C. & Fitzhugh, R.D. (2006). Forest ecosystem responses to exotic pests and pathogens in eastern North America. *Bioscience* 56(5), 395-405.

Lu, Z., Streets, D.G., Zhang, Q., Wang, S., Carmichael, G.R., Cheng, Y.F., Wei, C., Chin, M., Diehl, T. & Tan, Q. (2010). Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000. *Atmospheric Chemistry and Physics* 10(13), 6311-6331.

Lundin, L., Aastrup, M., Bringmark, L., Grandin, U., Hultberg, H., Pihl-Karlsson, G., Lewin-Pihlblad, L., Löfgren, S., Teutschbein, C. & Thunholm, B. (2008). Report on national ICP IM activities in Sweden. In: Kleemola, S., *et al.* (Eds.) *The Finnish Environment 28/2008*. pp. 109-115. Finnish Environment Institute, Helsinki.

Långström, B., Lindelöw, Å., Schroeder, M., Björklund, N. & Öhrn, P. (2010). The spruce bark beetle outbreak in Sweden following the january-storms in 2005 and 2007Available from: http://pub.epsilon.slu.se/5076/1/langstrom_b_etal_100823.pdf.

Manion, P.D. (1991). *Tree Disease Concepts*. 2nd. ed. New Jersey: Prentice Hall Career & Technology. ISBN 0-13-929423-6.

Matzner, E. & Murach, D. (1995). Soil changes induced by air pollutant deposition and their implication for forests in Central Europe. *Water Air and Soil Pollution* 85(1), 63-76.

MCPFE *Forest Europe*. [online] Available from: http://www.foresteurope.org/.

McRoberts, R.E., Hansen, M.H. & Smith, W.B. (2010). National forest inventories reports: United States of America. In: Tomppo, E., *et al.* (Eds.) *National forest inventories: pathways for common reporting*. pp. 569-580. New York: Springer. ISBN 978-90-481-3232-4.

McRoberts, R.E., Tomppo, E., Schadauer, K., Vidal, C., Stahl, G., Chirici, G., Lanz, A., Cienciala, E., Winter, S. & Smith, W.B. (2009). Harmonizing National Forest Inventories. *Journal of Forestry* 107(4), 179-187.

Michaelian, M., Hogg, E.H., Hall, R.J. & Arsenault, E. (2011). Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. *Global Change Biology* 17(6), 2084-2094.

Moffat, A.J. (2002). The state of British forests at the beginning of the 21st century. *International Forestry Review* 4(3), 171-183.

Moffat, A.J., Davies, S. & Finer, L. (2008). Reporting the results of forest monitoring-an evaluation of the European forest monitoring programme. *Forestry* 81(1), 75-90.

Moriondo, M., Good, P., Durao, R., Bindi, M., Giannakopoulos, C. & Corte-Real, J. (2006). Potential impact of climate change on fire risk in the Mediterranean area. *Climate Research* 31(1), 85-95.

Mota, M.M., Braasch, H., Bravo, M.A., Penas, A.C., Burgermeister, W., Metge, K. & Sousa, E. (1999). First report of Bursaphelenchus xylophilus in Portugal and in Europe. *Nematology* 1, 727-734.

Mues, V. (2006). *Results from the international cross-comparison courses 2005.* Programme co-ordinating centre of ICP Forests, Federal Research Centre for Forestry and Forest Products, Hamburg.

Nevalainen, S. (1999). Gremmeniella abietina in Finnish Pinus sylvestris stands in 1986-1992: a study based on the National Forest Inventory. *Scandinavian Journal of Forest Research* 14(2), 111-120.

Nevalainen, S., Lindgren, M., Pouttu, A., Heinonen, J., Hongisto, M. & Neuvonen, S. (2010). Extensive tree health monitoring networks are useful in revealing the impacts of widespread biotic damage in boreal forests. *Environmental Monitoring and Assessment* 168(1-4), 159-171.

NFI *Swedish National Forest Inventory*. [online] Available from: http://www.slu.se/en/collaborative-centres-and-projects/swedish-national-forest-inventory/.

Nihlgård, B. (1985). The ammonium hypothesis - an additional explanation to the forest dieback in Europe. *Ambio* 14(1), 2-8.

Nordlander, G. & Hellqvist, C. (2008). *Övervakning av snytbaggeskador i Södra Sverige 2008*. SLU, Department of Ecology, Uppsala.(In Swedish).

Oksanen, E., Manninen, S., Vapaavuori, E. & Holopainen, T. (2009). Near-ambient ozone concentrations reduce the vigor of Betula and Populus species in Finland. *Ambio* 38(8), 413-417.

Oliva, J., Thor, M. & Stenlid, J. (2010). Long-term effects of mechanized stump treatment against Heterobasidion annosum root rot in Picea abies. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 40(6), 1020-1033.

Ontario *Forest health condition in Ontario*. [online] Available from: http://www.mnr.gov.on.ca/en/Business/Forests/2ColumnSubPage/STEL02166919.html.

Ostry, M.E. & Laflamme, G. (2009). Fungi and diseases - natural components of healthy forests. *Botany-Botanique* 87(1), 22-25.

Overpeck, J. & Udall, B. (2010). Dry times ahead. *Science* 328(5986), 1642-1643.

Percy, K.E. & Ferretti, M. (2004). Air pollution and forest health: toward new monitoring concepts. *Environmental Pollution* 130(1), 113-126.

Power, J.M. (1988). Decision support systems for the forest insect and disease survey and for pest management. *The Forestry Chronicle* 64(2), 132-135.

Pröbstl, U., Virth, V., Elands, B. & Bell, S. (Eds.) (2010). *Management of recreation and nature based tourism in European Forests*. Berlin Heidelberg: Springer-Verlag.

Ranneby, B., Cruse, T., Hägglund, B., Jonasson, H. & Swärd, J. (1987). *Designing a new national forest survey for Sweden*. Uppsala: Fakulteten för skogsvetenskap, Sveriges lantbruksuniversitet. (Studia forestalia Suecica 177 ISBN 91-576-2982-X.

Rebetez, M., Mayer, H., Dupont, O., Schindler, D., Gartner, K., Kropp, J.P. & Menzel, A. (2006). Heat and drought 2003 in Europe: a climate synthesis. *Annals of Forest Science* 63(6), 569-577.

Requardt, A., Schuck, A. & Kohl, M. (2009). Means of combating forest dieback - EU support for maintaining forest health and vitality. *Iforest-Biogeosciences and Forestry* 2, 38-42.

Rigina, O., Baklanov, A., Hagner, O. & Olsson, H. (1999). Monitoring of forest damage in the Kola Peninsula, Northern Russia due to smelting industry. *Science of the Total Environment* 229(3), 147-163.

Ringvall, A., Petersson, H., Stahl, G. & Lamas, T. (2005). Surveyor consistency in presence/absence sampling for monitoring vegetation in a boreal forest. *Forest Ecology and Management* 212(1-3), 109-117.

Roloff, A. (1990). Morphological changes in the crowns of European beech (Fagus sylvatica L.) and other deciduous tree species. In: Ulrich, B. (Ed.) *International Congress on Forest Decline Research: State of Knowledge and Perspectives, Friedrichshafen am Bodensee, Germany, 2-6 October 1989. Lectures Volume 1*. pp. 81-107. Karlsruhe (Germany). ISBN 3-923704-05-4.

Santos, M.J. & Whitham, T.G. (2010). Predictors of Ips confusus outbreaks during a record drought in Southwestern USA: Implications for monitoring and management. *Environmental Management* 45(2), 239-249.

Schlyter, P. & Anderson, S. (1997). *IR-95 - Flygbildsbaserad inventering av skogsskador i sydvästra Sverige* Skogstyrelsen Rapport 1997:3. (In Swedish).

Schlyter, P., Stjernquist, I., Barring, L., Jonsson, A.M. & Nilsson, C. (2006). Assessment of the impacts of climate change and weather extremes on boreal forests in northern Europe, focusing on Norway spruce. *Climate Research* 31(1), 75-84.

Schreurs, M.A. (2011). Transboundary cooperation to adress acid rain: Europe, North America and East Asia compared In: Dinar, S. (Ed.) *Beyond resource wars scarcity environmental degredation and international cooperation*. Massachusetts institute of Technology JZ1324:B49.

Schulze, E.D. (1989). Air-pollution and forest decline in a spruce (Picea abies) forest. *Science* 244(4906), 776-783.

Schütt, P. & Cowling, E.B. (1985). Waldsterben, a general decline of forests in Central-Europe - Symptoms, development and possible causes. *Plant Disease* 69(7), 548-558.

Seidling, W. & Mues, V. (2005). Statistical and geostatistical modelling of preliminarily adjusted defoliation on an European scale. *Environmental Monitoring and Assessment* 101(1-3), 223-247.

Shaw, J.D. (2008). Benefits of a strategic national forest inventory to science and society: the USDA Forest Service Forest Inventory and Analysis program. *Iforest-Biogeosciences and Forestry* 1, 81-85.

Shin, J.H. & Chun, J.H. (2011). Forest monitoring in times of climate change from the Asian view. *Forest Science and Technology* 7(2), 47-52.

Skilling, D.D. (1981). Scleroderris canker - the situation in 1980. *Journal of Forestry* 79(2), 95-97.

Skogsstyrelsen (2010). *Swedish Statistical Yearbook of Forestry*. Swedish Forest Agency, Jönköping Sweden.

Skovsgaard, J.P., Thomsen, I.M. & Barklund, P. (2009). *Skötsel av bestånd med askskottsjuka. Fakta skog Nr 13*. SLU. ISSN 1400-7789. (In Swedish).

Sliggers, J. & Kakebeeke, W. (2004). *Cleaning the air: 25 years of the Convention on Long-range Transboundary Air Pollution*. ECE/EB.AIR/84, UN/ECE, Geneva, Switzerland.

SLU *SkogsSkada*. [online] Available from: http://www-skogsskada.slu.se/SkSkPub/MiPub/Sida/SkSk/SkogsSkada.jsp.

Solberg, S. (1999a). Crown condition and growth relationships within stands of Picea abies. *Scandinavian Journal of Forest Research* 14(4), 320-327.

Solberg, S. (1999b). *Forest health monitoring: Evaluation of methods, trends and causes based on a Norwegian nationwide set of monitoring plots.* Diss. Ås:Agricultural University of Norway.

Solberg, S. (2004). Summer drought: a driver for crown condition and mortality of Norway spruce in Norway. *Forest Pathology* 34(2), 93-104.

Solberg, S., Andreassen, K., Clarke, N., Torseth, K., Tveito, O.E., Strand, G.H. & Tomter, S. (2004). The possible influence of nitrogen and acid deposition on forest growth in Norway. *Forest Ecology and Management* 192(2-3), 241-249.

Solberg, S., Dobbertin, M., Reinds, G.J., Lange, H., Andreassen, K., Fernandez, P.G., Hildingsson, A. & de Vries, W. (2009). Analyses of the impact of changes in atmospheric deposition and climate on forest growth in European monitoring plots: A stand growth approach. *Forest Ecology and Management* 258(8), 1735-1750.

Solberg, S., Kvindesland, S., Aamlid, D. & Venn, K. (2002). Crown condition and needle chemistry of Norway spruce in relation to critical loads of acidity in south-east Norway. *Water Air and Soil Pollution* 140(1-4), 157-171.

Solberg, S. & Strand, L. (1999). Crown density assessments, control surveys and reproducibility. *Environmental Monitoring and Assessment* 56(1), 75-86.

Sonesson, K. (1999). Oak decline in southern Sweden. *Scandinavian Journal of Forest Research* 14(4), 368-375.

Stoerig, P. (1996). Varieties of vision: From blind responses to conscious recognition. *Trends in Neurosciences* 19(9), 401-406.

Stoyan, D. & Penttinen, A. (2000). Recent applications of point process methods in forestry statistics. *Statistical Science* 15(1), 61-78.

Strand, G.H. (1996). Detection of observer bias in ongoing forest health monitoring programmes. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 26(9), 1692-1696.

Sullivan, T.P. & Sullivan, D.S. (2008). Vole-feeding damage and forest plantation protection: Large-scale application of diversionary food to reduce damage to newly planted trees. *Crop Protection* 27(3-5), 775-784.

Sverdrup, H., Warfvinge, P. & Nihlgard, B. (1994). Assessment of soil acidification effects on forest growth in Sweden. *Water Air and Soil Pollution* 78(1-2), 1-36.

Söderberg, U. (1993). Increment analyses. In: Thomsen, M.G. (Ed.) *Proceedings from the Meeting in the SNS-ad hoc group on Monitoring of Forest Damage, 26. - 28.4 1993, Ås, Norway*. Ås: Norsk institutt for skogforskning, og institutt for skogfag, Norges landbrukshögskole; Aktuelt fra skogforsk). ISBN 82-7169-618-1.

Teale, S.A. & Castello, J.D. (2011). The past as a key to the future: a new perspective on forest health. In: Castello, J.D., *et al.* (Eds.) *Forest health An integrated perspective*. pp. 3-16 Cambridge University Press. ISBN 978-0-521-76669-2.

Thompson, S.K. (1992). *Sampling*. New York: John Wiley & Sons. ISBN 0-471-54045-5.

Thorell, K.E. & Ostlin, E.O. (1931). The national forest survey of Sweden. *Journal of Forestry* 29(4), 585-591.

Tkacz, B., Moody, B., Castillo, J.V. & Fenn, M.E. (2008). Forest health conditions in North America. *Environmental Pollution* 155(3), 409-425.

Toet, H., Fridman, J. & Holm, S. (2007). *Precisionen i Riksskogstaxeringens skattningar 1998-2002. Arbetsrapport 167*. Sveriges Lantbruksuniversitet, Institutionen för Skoglig resurshushållning. Umeå. ISSN 1401-1204. (In Swedish).

Tompoo, E., Gschwantner, T., Lawrence, M. & McRoberts, R.E. (Eds.) (2010). *National Forest Inventories - pathways for common reporting*. Springer Science+Business media B.V. ISBN 978-90-481-3232-4.

Ulrich, B. (1986). The role of soil acidification in forest decline - Long-term consequences and silvicultural possibilities. *Forstwissenschaftliches Centralblatt* 105(5), 421-435.

USDA *National Forest health Monitoring, USDA Forest Service*. [online] Available from: http://www.fhm.fs.fed.us/.

Wahlström, K.T. (1992). *Infection biology of Armillaria species: In vitro pectinolytic activity, infection strategy field distribution and host responses.* Diss. Uppsala:Swedish University of Agricultural Sciences.

Valentini, R., Matteucci, G., Dolman, A.J., Schulze, E.D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grunwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, U., Berbigier, P., Loustau, D., Guomundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S. & Jarvis, P.G. (2000). Respiration as the main determinant of carbon balance in European forests. *Nature* 404(6780), 861-865.

Valinger, E. & Fridman, J. (2011). Factors affecting the probability of windthrow at stand level as a result of Gudrun winter storm in southern Sweden. *Forest Ecology and Management* 262(3), 398-403.

Welsh, C., Lewis, K. & Woods, A. (2009). The outbreak history of Dothistroma needle blight: an emerging forest disease in northwestern British Columbia, Canada. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 39(12), 2505-2519.

Westfall, J. & Ebata, T. (2009). *2008 Summary of forest health conditions in British Columbia. Pest Management Report Number 15*. British Columbia Ministry of Forests and Range, Victoria, BC.

Westman, L. & Lesinski, J. (1986). *Kronutglesning och andra förändringar i grankronan* Naturvårdsverket. Rapport 3262. ISSN 0282-7298. (In Swedish).

WGE *UN ECE Working group on effects of the Convention on long-range transboundary air pollution*. [online] Available from: http://live.unce.org/env/lrtap/WorkingGroups/wge/welcome.html.

Witzell, J., Barklund, P., Bergquist, J., Berglund, M., Bernhold, A., Blennow, K., Hansson, L., Hansson, P., Lindelöw, Å., Långström, B., Nordlander, G., Petersson, M., Rönnberg, J., Stenlid, J., Valinger, E., Wallertz, K., Witzell, J. & Åhman, I. (2009). *Skador på skog*. Söderköping: Skogsstyrelsen. (In Swedish).

Voller, J. & Harrison, S. (Eds.) (1998). *Conservation biology principles for forested landscapes*. Vancouver: UBC Press.

Woodall, C.W., Amacher, M.C., Bechtold, W.A., Coulston, J.W., Jovan, S., Perry, C.H., Randolph, K.C., Schulz, B.K., Smith, G.C., Tkacz, B. & Will-Wolf, S. (2011). Status and future of the forest health indicators program of the USA. *Environmental Monitoring and Assessment* 177(1-4), 419-436.

Wulder, M.A., Dymond, C.C., White, J.C., Leckie, D.G. & Carroll, A.L. (2006). Surveying mountain pine beetle damage of forests: A review of remote sensing opportunities. *Forest Ecology and Management* 221(1-3), 27-41.

Wulff, S. (1994). Senaste nytt om skadad skog. In: *Skador på skog och virke. Skogsfakta konferens nr 18*. SLU. (In Swedish).

Wulff, S. (1996). The Special Forest Damage Inventory by the Swedish National Forest Inventory. In: Söderberg, U., *et al.* (Eds.) *Monitoring Forest Damage in the Nordic Countries. Selected proceedings from meeting of the SNS-ad hoc Group on monitoring of forest damage, 9-10 May 1995*. pp. 37-45. Umeå: SLU, Department of Forest Resource Management and Geomatics, Report 4.

Wulff, S. (2002). The accuracy of forest damage assessments - Experiences from Sweden. *Environmental Monitoring and Assessment* 74(3), 295-309.

Wulff, S. (2004). Nonsampling errors in Ocular Assessments. In: Wiersma, B.G. (Ed.) *Environmental Monitoring*. pp. 337-346. Boca Raton: CRC Press. ISBN 1-56670-641-6.

Wulff, S. (2006). *Instruktion för fältarbetet vid den nationella skogsskadeövervakningen ICP-Forests Level I år 2006*. SLU, Inst för skoglig resurshushållning och geomatik, Umeå. (In Swedish).

Wulff, S. (2007). Consistency of Forest Damage Assessment. In: Eichhorn, J. (Ed.) *Symposium: Forest in a Changing Environment - Results of 20 years ICP Forest Monitoring Göttingen, 25.-28.10.2006*. pp. 270-275. Schriften aus der Forstlichen Fakultät der Universität Göttingen und der Nordwestdeutchen Forstlichen Versuchsanstalt. Band 142.: J.D. Sauerländer´s verlag Frankfurt am Main.

Wulff, S. & Hansson, P. (2011). Askskottsjukan i Götaland. Nationell riktad skadeinventering 2009 och 2010. Umeå: SLU, Inst f skoglig resurshushållning. p. 7. (In Swedish).

Wulff, S., Hansson, P. & Witzell, J. (2006). The applicability of national forest inventories for estimating forest damage outbreaks - Experiences from a Gremmeniella outbreak in Sweden. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 36(10), 2605-2613.

Wulff, S., Lindelöw, Å., Lundin, L., Hansson, P., Axelsson, A.-L., Barklund, P., Wijk, S. & Ståhl, G. (2011). Adapting forest health assessments to changing perspectives on threats - a case example from Sweden. *Environmental Monitoring and Assessment*. DOI 10.1007/s10661-011-2130-7

Acknowledgements

For more than 20 years I have been working on the topic of this thesis. In 1997 I enrolled as a doctoral candidate and since then I have been working part-time on my studies. The studies have been carried out at times between ordinary duties, involving managing fieldwork and reporting results from monitoring forest damage in Sweden. However, now is the time to finalize my studies.

Many people have contributed to my work towards this thesis, which may never have started without an encouraging push from Professor Bo Ranneby. I also want to thank my supervisors, Ass. Professor Ulf Söderberg and Professor Göran Ståhl, for always believing in me and all their valuable support during my doctoral studies. Göran, without your self-sacrificing support this thesis would not have reached the finishing line. I also want to thank Mats Walheim for always being a good discussion partner throughout the years, Per Hansson for good co-operation, and Mats, Per, Anna Hedström Ringvall, and Åke Lindelöw for valuable comments on previous versions of this thesis. Thank you also all past and present co-workers, Cornelia Roberge, Anna H R, Sören Holm and all my colleagues at the office for providing a good spirit of comradeship and a stimulating work environment. I also want to thank Anne-Maj Jonsson, Carina Westerlund, Ylva Jonsson, Linda Ågren, Bo-Gunnar Olsson for keeping me on the right track with the administration, Anders Pålsson and Michael Holmlund helping me with the field equipment, Bo Eriksson, Joakim Eriksson and Mats W. for keeping me on the right track in the field exercises, and Per Nilsson, Jonas Dahlgren, Jonas Fridman, Neil Cory, Göran Kempe, and Bertil Westerlund for help with NFI-data. Furthermore I want to express my gratitude to all the fieldworkers, in the NFI, the NFDI, and other projects who throughout the years have actively participated in the fieldwork and in all conceivable sorts of field tests. Thanks also Stefan Anderson and Sture Wijk at the National Board of Forestry for fruitful discussions on assessment methods and for providing good company during many field exercises and meetings.

Finally, my deepest gratitude goes to my family. To my life companion and beloved Anne-Maj, who has given me all the energy and strength needed to finish this thesis, I give a big bear hug for all your patience. A big hug also goes to my sons, Jonas and Christoffer, for being an unending source of joy.