

Chapter 12

Forest Damage



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Abstract

- Heterobasidion root and butt rot pose a greater risk in continuous cover forestry (CCF) than in rotation forestry (RF) in conifer-dominated forests, regardless of whether selective, gap or shelterwood cutting is used.

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- Damage from wind, snow, spruce bark beetle, and large pine weevil are likely to be less severe in CCF than in RF. However, the conversion of RF to CCF may briefly expose stands to windthrow.
- Browsing by large herbivores on saplings may limit regeneration of tree species other than spruce in continuous cover forestry and reduce tree species diversity, but alternative silvicultural practices may also increase forage availability in the field and shrub layer. Browsing damage outcomes for saplings in CCF are difficult to predict.
- For many types of damage in CCF, substantial knowledge gaps complicate the assessment of damage risk.

Keywords Abiotic damage · Heterobasidion root rot · Forest disease · European spruce bark beetle · Cervid damage

Forest damage can be roughly divided into abiotic and biotic damage. Abiotic damage refers to harmful effects that arise from non-living, environmental factors. Abiotic stressors that can lead to tree mortality and habitat destruction include wind, snow, frost, flood, and drought. Biotic damage that weakens or kills trees, and in some cases triggers large-scale forest die-offs, can be caused by insects, fungi, oomycetes and mammals. Multiple stressors can coincide and interact to some degree at tree, forest, or landscape scales.

Tree species, populations of trees or even individual trees vary in their genetic resistance to specific abiotic and biotic stressors, depending on past selection pressures (Mageroy et al. 2023). Tree resistance can also change with age: older trees may be able to fight off a specific attacker through certain combinations of constitutive and induced defence, whereas young seedlings may lack crucial defence mechanisms and succumb, or the stressor in question may only concern trees of a specific age or size. Biotic damage arises through complex interactions between the tree, the biotic damaging agent, and the environment. Conditions that predispose trees and favour the propagation and spread of biotic damaging agents are normally the precursor to biotic outbreaks.

At the individual-tree level, resistance to abiotic or biotic stressors can be defined as the ability of a tree to limit damage or to prevent the damage or attack altogether. At the stand or landscape level, forest resilience refers to the ability to absorb perturbations and maintain desired forest functioning, structure, and composition. As forest resilience to specific abiotic and biotic stressors depends on the tree-species composition and age structure, forest operations strongly influence resilience in managed forests. While CCF is not a novel concept, there is generally very little documented information about tree resistance and forest resilience toward abiotic and biotic stressors in CCF conditions. The current understanding of factors that lead to abiotic and biotic outbreaks is almost exclusively based on studies in even-aged conifer monocultures subjected to rotation forestry (RF), the backbone of forestry in the northern hemisphere.

In this chapter we summarise the current knowledge and make some predictions about how structural features of CCF forests and associated forest operations (outlined in other chapters of this book), can either strengthen or weaken forest resilience to specific abiotic or biotic stressors.

12.1 Windthrow, Snow and Drought

Wind and snow are, by area affected, the most significant abiotic causes of forest damage in Fennoscandia (Díaz-Yáñez et al. 2016; Korhonen et al. 2021). In addition, drought is increasingly damaging pine and spruce. Like all abiotic damage sources, wind, snow and drought are strongly associated with exceptional weather conditions, forest and landscape structure, and the physical properties of trees. There are regional differences in the prevalence of these damage types.

The importance of wind damage increases as wind speed reaches storm levels. Snow damage occurs when the snow load suddenly becomes exceptionally large. Forest structure, particularly basal area and stem density, affects both types of damage significantly (Peltola 2006; Suvanto et al. 2021; 2019). Wind blows faster through less dense forests. Recently thinned forests, where trees have not had time to adapt to the new spatial pattern and the altered living conditions, are particularly susceptible. Also snow damage is usually most severe in recently thinned stands, especially if thinning has been delayed. There may also be indirect interactions between biotic and abiotic damage agents. For example, pre-commercial thinning is sometimes employed to mitigate browsing damage, but may lead to snow damage (e.g., Päätaalo et al. 1999; Wallentin and Nilsson 2014).

Windthrow, in particular, increases in mosaic-like landscapes, where clearcutting creates sharp forest edges where the wind can blow strongly (Zeng et al. 2010, 2007). In terms of the physical properties of trees, stem diameter and height, their ratio, and root depth are the most significant factors affecting both wind and snow damage (Peltola 2006). Thicker trees, and trees with higher height-diameter ratios, increase the risk, while a deeper root system anchors the tree and reduces windthrow risk.

Abiotic damage has received little attention in the continuous cover forestry context. The risk of wind damage in CCF is likely to be smaller than in RF stands (Hahn et al. 2021; Hanewinkel et al. 2014; Nevalainen 2017; Pukkala et al. 2016), with the exceptions of shelterwood cutting (Hånell and Ottosson-Löfvenius 1994) and the conversion phase (Potterf et al. 2022). This is due, among other things, to differences in silvicultural methods, which affect the mean diameter and basal area of the growing stock (Pukkala et al. 2016). A diverse forest structure reduces wind speed inside the forest, reducing the risk of wind damage (Dobbertin 2002; Hanewinkel et al. 2014; Pukkala et al. 2016).

CCF-managed forests could be expected to recover more quickly from drought than even-aged stands, as they generally have a lower density of mature trees (Hlásny et al. 2014). Young naturally regenerated seedlings on a site managed using

CCF would be at lower drought risk due to the shade and shelter provided by the overstorey.

The importance of landscape structure has not been studied, but it is likely to impact damage risks significantly. If all forest management were to shift directly to CCF, the results of stand-level studies could be generalised. However, it is likely that diversification of forest management will lead to a mosaic of management practices. In this case, for example, clearcuts may still abut selectively cut stands, increasing wind damage risk to the latter. On the other hand, mature stands benefit from CCF in neighbouring stands.

12.2 Root Rot

12.2.1 *The Biology of Root Rot Fungi*

There are two *Heterobasidion* species in the Nordic countries. *Heterobasidion parviporum* causes root and butt rot in spruce and larch. *Heterobasidion annosum* has a wider host range. It causes root rot in pine but can also kill birch and juniper trees, and cause root and butt rot in spruce similar to *H. parviporum*. Despite its narrower host range, *H. parviporum* can also kill pine seedlings, compromising tree species diversification via natural regeneration in CCF (Korhonen 1978).

12.2.2 *Root Rot in Rotation Forestry*

Heterobasidion species spread to new sites by spores. In unmanaged forests, this usually occurs via bare-wood surfaces unprotected by bark. However, in managed forests, mechanised operations have opened a new and more efficient route for the spread of *Heterobasidion* root rot. Logging creates unprotected stump surfaces which are at risk of infection during the sporulation season. As a result, the prevalence of root rot in Nordic forests has significantly increased compared to what it would have been without human influence. Root rot has also become one of the most economically significant tree diseases in forestry, causing direct economic losses (reduced growth, lost timber value due to rot, mortality), and making trees more vulnerable to other damage agents, particularly wind (Fig. 12.1).

Heterobasidion root rot fungi arrive at a new site when their windborne basidiospores land on freshly cut tree stumps. Following spore germination, mycelia penetrate the stump and its root system, and can continue into other trees of the current and next generation through root contacts. These events result in disease hotspots up to tens of metres in diameter that may persist for hundreds of years. In individual stumps, these root rot fungi can survive for more than 50 years (Greig and Pratt 1976; Piri 1996). In Finland, prevention of root rot infection is mandatory in



Fig. 12.1 Root rot caused by *Heterobasidion* fungi weakens the root system, making trees more susceptible to windthrow. Photo: Jarkko Hantula

cuttings during snow-free periods (Piri et al. 2019). In Sweden, stump treatment is also practised in snow-free thinning operations, but not yet in final harvests. In Norway, stump treatment is currently voluntary and rarely used (Hietala et al. 2016).

There are both chemical (urea) and biological (RotStop®, *Phlebiopsis gigantea*) stump-treatment methods. Basinox is a new treatment that can be applied in Sweden. It is based on one strain of an unidentified *Pseudomonas* bacterium. All these agents provide good but incomplete protection against spore-mediated infection when conducted properly. However, these methods do not eradicate established root rot fungus. Existing mycelia in root systems continue to spread despite stump treatment.

Cultivating a *Heterobasidion*-resistant tree species for one rotation effectively eliminates the disease from a site. For a site infected with *H. parviporum*, both Scots pine and all deciduous trees are suitable alternatives, but not larch or lodgepole pine. The situation is worse in sites with *H. annosum*, as this species infects all conifers, causing similar root rot as *H. parviporum* in spruce. *Heterobasidion annosum* also infects birch but does not spread from a harvested pure birch stand to subsequently planted conifers due to the quick decay of hardwood stumps.

12.2.3 Root Rot in Continuous Cover Forestry

In CCF, selective cutting and gap cutting during snow-free periods can facilitate spore infection by *Heterobasidion*, either through stump surfaces or root damage caused by logging machinery. The total stump surface area exposed by logging in CCF, whether selective cutting, gap cutting or shelterwood preparation, tends to be

similar or slightly smaller over time than that in RF. For this reason, the risk of stump-surface infection by spores is generally only slightly lower in CCF. On the other hand, the risk of stem and root damage by forest machinery to the remaining trees is significantly greater in CCF than in RF. This probably largely evens out the difference in root rot risk between CCF and RF (Dwyer et al. 2004). Therefore, further information is needed on possible differences in the spore-mediated spread of *Heterobasidion* species between continuous cover and even-aged forests.

Forest regeneration in CCF relies on existing undergrowth in selective cuttings, increasing its *Heterobasidion* risk compared to RF. Understorey vegetation favours the effective vegetative spread of root rot in to growing trees, as well as the persistence of *Heterobasidion* infection in infected root systems (Piri 1996; Piri and Valkonen 2013; Fig. 12.2). In CCF, dense sapling stands form where the soil has been exposed during logging or conditions are otherwise favourable for undergrowth. The next generation of trees in RF can become infected via root contacts with stumps of infected prior-generation trees. In CCF, the several-years-long co-presence of susceptible overstorey and understorey trees facilitates the root-to-root spread of infection between tree generations. In addition, understorey trees can be quite old, allowing their root systems much more time to become infected with root rot compared to trees in even-aged forestry.

In gap cuts or strip clearcuts, the difference in risk of root rot compared to even-aged forestry is smaller when broadleaf trees are left to grow in the openings as mixed stands (Piri et al. 1990) or even if new spruce seedlings are planted. However,



Fig. 12.2 The dense understorey in continuous cover forestry provides ideal conditions for the vegetative spread of root rot through the formation of a network of interconnected roots. Photo: Erkki Oksanen / Luke

using only undergrowth saplings for regeneration bears the same risk as selection cutting. The consequences of variation in management are also affected by which species of *Heterobasidion* is present. *Heterobasidion annosum* may also attack birch and can potentially spread both to and from birch and spruce or pine.

Controlling root rot that has already entered a site is practically impossible in a selection-cut managed forest because changing the tree species is not possible. However, control can be tried at small root rot centres including only a few trees by creating small openings around them and removing all surrounding trees susceptible to root rot, and regenerating with resistant tree species. Also, future attenuation of existing disease by new control measures like *Heterobasidion*-debilitating viruses (Vainio et al. 2018; Piri et al. 2023) could change the situation.

Controlling widespread *Heterobasidion* root rot, on the other hand, requires a clearcut and subsequent switch to a resistant tree species. It is never advisable to establish continuous cover stands on a site already infected with *Heterobasidion* if only susceptible tree species can efficiently reproduce. Examples of this situation include spruce on nutrient-rich mesic soil or pine on a dry nutrient-poor site. Even on a healthy site, it is safest to conduct forest management activities only during the winter, when spore dispersal is negligible. However, a warming climate or growing popularity of CCF poses logistical challenges for timber harvesting, making it impossible to avoid summer logging. In such a case, the quality of forest management becomes more important, especially regarding stump treatment and quick action to contain emerging root rot centres.

12.3 Other Significant Forest Diseases

Compared to *Heterobasidion* root rot, knowledge about other forest diseases in continuous cover forestry is limited. General knowledge can still inform understanding of factors that favour the spread of the specific causative agents and predispose the trees to infection. Before treating these predictions as credible scientific information, it is essential to subject them to rigorous testing in controlled experiments.

12.3.1 *Scleroderris* Canker

Shoot mortality due to the fungus *Gremmeniella abietina* causing scleroderris canker on pine trees varies annually from insignificant to extremely severe epidemics in boreal forests. The last serious outbreaks occurred in Finland in the 1980s and in Sweden at the turn of the 2000s. The risk of shoot mortality is mainly influenced by the location of the forest stand and the weather of preceding summers (Witzell and Karlman 2000; Thomsen 2009). In addition, the quality of forest management, such as timely thinning, and the provenance of the trees significantly affect damage risk.

Pine provenances from much further south than the growth site are particularly susceptible (Uotila 1985). Continuous cover forestry is usually based on natural regeneration, so it carries a low risk in terms of tree origin. In the Nordic countries, even-aged forests based on seeding or planting are typically regenerated with site-suitable seed origins, so scleroderris canker risk should not differ between continuous cover or even-aged forests. However, the risk of shoot mortality increases in even-aged forests if they are regenerated with too-southern seed origins, for example for climate change adaptation purposes.

The risk of shoot mortality by *G. abietina*, like many other shoot and needle diseases, increases in moist microclimates and under the shade of other trees (Read 1968; Niemelä et al. 1992). In continuous cover forests, air humidity does not differ significantly from that of even-aged seedling stands or young forests. However, shading by overstorey trees may slightly increase shoot-mortality risk for suppressed pine seedlings owing to a microclimate that may favour the pathogen and predispose the tree. Careful forest management can override these factors, as seedling stands grown on dry soils with continuous cover do not differ significantly from even-aged forest cultivation stands. Therefore, thinning and selection cuts in continuous cover stands must be carefully timed, just as in even-aged stands, to ensure that the microclimate does not become favourable for scleroderris canker.

Nevalainen (2017) compared CCF and RF, mentioning the risk of *G. abietina* infection originating from nurseries. This undoubtedly occurs despite the health requirements of seedlings, but the actual damage caused by *G. abietina* depends crucially on the prevailing conditions at the site, as noted above. Therefore, the contribution of nursery infections to *G. abietina* damage is marginal, and in this respect, there should be no significant difference in scleroderris canker risk between continuous cover and even-aged forest management.

The information in this section comes from data on even-aged forests and logical reasoning derived from it, not on experimental research on different forest structures, which is therefore clearly needed.

12.3.2 Scots Pine Blister Rust

Scots pine blister rust (also called pine stem rust, cronartium rust or resin top disease) is caused by *Cronartium pini*. This fungus has two forms (Hantula et al. 2002; Samils et al. 2021). The heteroecious form has a complete life cycle that includes the sexual sporulation stage on a herbaceous intermediate host, usually white swallow-wort (*Vincetoxicum hirundinaria*) or small cow-wheat (*Melampyrum sylvaticum*, Kaitera et al. 2005). The autoecious variant with an incomplete life cycle spreads directly from pine to pine. The heteroecious and autoecious forms are clearly differentiated and usually occur in separate populations locally, but with no clear separation at a larger geographic scale in Finland and Sweden (Samils et al. 2021).

The worst pine stem rust damage in Finland and Sweden has been linked to the heteroecious form; the presence of intermediate host plants on a site is a risk factor. Thus, it is not advisable to establish pine forests on overly nutrient-rich soils (Kaitera et al. 2005; Samils and Stenlid 2022). If the forest management method increases or decreases the occurrence of intermediate host plants, it may also impact the susceptibility of trees to cronartium rust. Small cow-wheat has become increasingly rare in Lapland due to forest densification (Jalkanen 2014), but so far there is no research-based evidence on whether the increased light in continuous cover forests could make this intermediate host more common.

Knowledge about the genetic basis of resistance to Scots pine blister rust is poor, but experience from North America indicates that there is genetic resistance against the closely related white pine blister rust (Sniezko and Liu 2022). Therefore, it is not advisable to use blister-affected trees as seed trees, either in RF or in CCF because of the likely susceptibility of their offspring.

Taken together, the need for scientific information on pine stem rust and the role of management strategies in the damage patterns is urgent.

12.4 Insect Damage

12.4.1 *European Spruce Bark Beetle (Ips typographus)*

Insect damage in continuous cover forestry has so far been studied relatively little. However, the risk of damage can be assessed through the ecology of the pests and the forest structures produced by CCF. Based on this knowledge, the general perception among Finnish forestry professionals is that the risk of insect damage is lower in CCF than in RF (Nevalainen 2017). This difference may result from CCF having relatively lower effects of bottom-up forces (resource quality and quantity) than RF compared to top-down forces (natural enemy pressure, Klapwijk et al. 2016). We will examine below how well founded this view is, and present evidence for bark beetles, defoliators and regeneration pests (*sensu* Björkman et al. 2015).

The spruce bark beetle is the most economically damaging insect in the Nordic countries (e.g., Uotila 1994; Nuorteva et al. 2022). Other insects usually cause relatively economically insignificant growth decline, needle loss, and individual tree deaths. The economic losses caused by the spruce bark beetle vary annually but have been estimated to be EUR 5–21 million in recent years in Finland (Hantula et al. 2023). Because healthy trees may also be harvested to compensate for the cost of harvesting small-scale damage, this estimate—based on cutblock sizes rather than volumes or shares of damaged trees—is likely an overestimate. The real impact is difficult to assess due to limited inventory data. However, with climate change, damage events caused by insects are expected to become more common (Jönsson et al. 2007, 2009, 2011; Seidl et al. 2008, 2011, Öhrn et al. 2014; Økland et al. 2015; Ruosteenoja et al. 2016; Venäläinen et al. 2020; Hlásny et al. 2021). In Finland,

problems with the spruce bark beetle have so far remained relatively small and local (Viiri et al. 2019), although in the 2010s windthrow and drought appear to have increased secondary beetle damage (Nuorteva et al. 2022). In Sweden, spruce bark beetle damage has increased remarkably during the last decade. The total volume of spruce-bark-beetle-killed trees has been estimated at 32 Mm³ between 2018–2022 (Wulff and Roberge 2021), while in the 1990s the estimate was 1.5 Mm³ (Kärvemo and Schroeder 2010).

Large-scale bark beetle outbreaks are usually induced by windstorms (Ravn 1985; Furuta 1989; Krehan et al. 2010), but can also be caused by exceptionally warm summers and drought (Matthews et al. 2018). Normally the spruce bark beetle produces one generation per summer (Annala 1969) in northern Europe, but in some summers of the 2010s it has been able to produce two generations due to warm and dry weather (e.g., Pouttu and Annala 2011; Neuvonen et al. 2015; Neuvonen and Viiri 2017; Nuorteva et al. 2022). Mitigation of climate change would help limit forest damage, but forest structure can greatly determine how susceptible forests are to windthrows and bark beetles. From a forest management perspective, multi-species forests have been suggested to be less susceptible than monocultures for both the spruce bark beetle and storm damage (Seidl et al. 2011; Dobor et al. 2020; Müller et al. 2022). In extreme drought conditions, however, these generalisations may not hold (de Groot et al. 2023).

The spruce bark beetle prefers relatively large and already-weakened spruce trees (at least 15 cm in diameter at breast height) for various reasons (Netherer and Hammerbacher 2022; Nuorteva et al. 2022) (Fig 12.3). Such weakened trees can be found, for example, on the tops of hills, on sunny southwestern slopes, on the edges of clearcuts, in mature spruce stands, and on sites that are too dry for spruce (Wermelinger 2004). Advanced age and fungal infections can also weaken spruce trees. If there are significant numbers of nearby trees (e.g., tens of cubic metres) that have recently been killed by the spruce bark beetle, live trees are at risk because they may share the conditions favourable for the bark beetle. On the other hand, recurring hot and dry summers can expose large spruce trees to extensive damage at any site (Wermelinger 2004).

12.4.2 Spruce Bark Beetle Impacts on Uneven- and Even-Aged Spruce Stands

Even-aged, structurally homogeneous monocultures are generally more susceptible to bark beetle outbreaks than mixed-species or uneven-aged stands, due to the host specialisation of the beetle species described above (Raffa et al. 2015). For the spruce bark beetle, a mature, pure spruce stand on a dry site would be particularly favourable, but even a mixed-aged spruce stand on dry sandy soils would not be immune to attack. However, continuous cover spruce stands differ from even-aged stands in several key respects. First, in continuous cover stands most trees are always too

small for the spruce bark beetle, and second, potential host trees—harvest-ready spruce trees—are considerably less frequent than in mature even-aged stands. Considering the whole rotation cycle, CCF never produces large dense clusters of mature trees, unlike clearcut-based RF. Third, the harvesting in continuous cover stands is focused on the largest and thus most potentially suitable tree species for the spruce bark beetle. According to the resource availability hypothesis (Endara and Coley 2011; Begon and Townsend 2021), low host-tree density limits the growth potential of the spruce bark beetle population; where there are fewer host trees, fewer new beetles will hatch. When beetle density is sufficiently low, the population is further limited by the Allee effect. According to this theory, mate selection and reproductive success are weaker in a sparse population than in a dense one (Stephens et al. 1999).

For these reasons, CCF seems to be better suited than RF for avoiding bark beetle damage in spruce stands. However, CCF may begin with a relatively even-aged forest, as is the case in a significant part of Nordic commercial forests. These forests may be treated by selective cutting, which aims to retain trees of as wide a size range as possible, or by gap cutting. If the retained trees are already quite large, root and stem damage to the residual stand caused by harvesting may increase the risk of bark beetles. Harvest residues release volatile compounds, attracting pioneer insects that seek suitable nearby trees. Strip roads open the canopy, increasing sun exposure, which stresses south-facing trees and exposes them to wind damage. Stressed trees release terpene alcohols and ketones that attract insects like the spruce bark beetle (Schiebe et al. 2019). The combined effect of creating strip roads and harvesting in uneven-aged forests may be similar to the impact of thinning in even-aged stands, but this topic warrants more study.

12.4.3 *Other Locally Economically Important Insects*

The risk of insects other than the spruce bark beetle under selective cutting has not been assessed, but a few experiments have assessed gap cutting from this perspective in the Nordic countries. Other bark beetle species potentially causing economic damage in spruce-dominated stands are the six-toothed bark beetle (*Pityogenes chalcographus*) and the small spruce bark beetle (*Polygraphus poligraphus*). The large pine weevil (*Hylobius abietis*) is also fairly common throughout the region, causing remarkable economic losses by killing conifer saplings (e.g., Björklund et al. 2003; Långström and Day 2004). A few other insect species cause growth loss or occasionally death of various tree species, notably sawflies (particularly the common pine sawfly *Diprion pini* and the European pine sawfly *Neopridion sertifer*) and the nun moth (*Lymantria monacha*, Hantula et al. 2023).

The six-toothed bark beetle and the small spruce bark beetle are common in spruce-dominated forests throughout the Nordic countries (Rassi et al. 2015; Artdatabanken 2023; Artsdatabanken 2023). The six-toothed bark beetle attacks and can kill smaller trees than the spruce bark beetle (Schebeck et al. 2022). Also



Fig. 12.3 Norway spruce trees killed by the spruce bark beetle (*Ips typographus*) in central Sweden. Photo: Anne-Maarit Hekkala

the small spruce bark beetle can kill weakened trees, particularly in warm and dry summers (Lekander 1959). Both species benefit from prolonged drought, higher-than-average summer temperatures, sun scorch at mature-forest edges (Schebeck et al. 2022), and from attacks to host trees by the spruce bark beetle (Hedgren 2004).

In a restoration experiment in Sweden, coniferous stands with small gaps (radius 20 m, 19% of the stand area) were examined for bark beetles. In the second post-harvest summer, the abundance and richness of primary bark beetles (notably those discussed above) had increased, but compared to reserves with a closed tree canopy, gap cutting did not affect the number of trees occupied by these beetles (Kärvement al. 2017). Three years later, however, the number of occupied trees was higher in gap-gut stands than in reserves or in burned stands (Hekkala et al. 2021). These findings, combined with the above discussion of spruce bark beetles in CCF and RF, suggest that clearings of varying sizes—from small gaps (as in CCF) to large clearcuts (as in RF)—benefit these beetles. One explanation could be that trees at gap edges abruptly become exposed to sun scorch, wind gusts and drought. This is potentially specific to this particular experiment, however, as it involved intentional killing of substantial amounts of trees to increase deadwood for biodiversity.

The large pine weevil feeds on the bark and phloem of trees, and is the most important pest of newly planted conifer saplings in Europe (Lalik et al. 2021). It is common in regeneration areas throughout Fennoscandia, with most damage occurring in the south, and benefits from warmer-than-average summers (Långström 1982; Rautio et al. 2014; Luoranen et al. 2023). In Nordic boreal forests, the consumption of seedlings and saplings peaks in the first growing season following logging but continues for 2–3 years (Långström 1982; Örlander and Nilsson 1999; Luoranen et al. 2017, 2022). Sapling consumption by the beetle in clearcuts increases from edges to centres and decreases under shelter trees (Nordlander et al. 2003a, 2003b). The large pine weevil uses conifer stumps up to 5 years old as a breeding substrate. In RF, seedlings are commonly planted 1 year after clearcutting, so regeneration may suffer if the pine weevil population is high. In CCF, however, seedlings of natural origin emerge more slowly in canopy openings (see Chap. 3), often after the peak of the pine weevil population. These findings suggest that CCF is less prone than RF to the damage caused by the large pine weevil.

Sawflies and the nun moth have not been examined in a CCF context. Their outbreaks are determined by similar factors to other forest insects: host trees of suitable species, age and density, abiotic factors or disturbances (drought, wind, fire), and biotic factors, such as predators, entomopathogens, viruses, bacteria and resource competitors (e.g., Biedermann et al. 2019). Generally, the host trees are less favourable for outbreaks of these species in CCF than in RF (see above).

The common and European pine sawflies lay their eggs on pine trees, and larvae feed on their needles. This slows tree growth, but if needles are extensively consumed in several consecutive summers, trees may die (Nevalainen et al. 2015). The growth decrease may be 4–40% or more in warm conditions (Perot et al. 2013; Blomqvist et al. 2022). As these sawflies occupy different-sized pine trees, CCF and RF may not differ much in terms of sawfly-outbreak likelihood, but this issue merits empirical research.

The nun moth is spreading northward in the Nordic countries and is common in the south. In Finland, for example, the species has expanded its distribution about 200 km northward in the past two decades (Fält-Nardmann et al. 2018). Thus far the nun moth has only caused occasional deaths of host trees in the Nordic countries (e.g., Melin et al. 2020), but in central Europe the species has for hundreds of years had peak years with vast areas of tree deaths (e.g., Nakládal and Brinkeová 2015). It feeds on many woody tree species, including the genera *Abies*, *Picea*, *Pinus*, *Betula*, *Prunus* and *Quercus*, as well as bilberry (*Vaccinium myrtillus*, Keena 2003). Features that predispose forested landscapes to nun moth outbreaks include strong dominance of one or a few tree species, and young forests (Hentschel et al. 2018). General preparedness for the nun moth by the Nordic forestry sector would benefit from empirical nun moth research into different logging methods, manipulations of tree-species composition, and CCF.

12.5 Damage by Deer

The effects of deer on forests have been extensively studied in connection with RF (Markgren 1974; Heikkilä 2000; Nikula et al. 2008), but there is very little research so far on deer damage in CCF (Nevalainen 2017; Komonen et al. 2020). Hence, the following evaluation of deer damage in CCF is based on studies done in even-aged forests. Comparing RF with CCF from the point of view of deer damage is difficult and not always meaningful. In RF, the biggest concern is usually damage to pine seedling stands, and in CCF, the areas that are usually naturally regenerated by spruce to have hardwoods or pine among the regeneration are of concern. There is an urgent need for data on how different forest management methods create forest structural features that predispose them to deer damage and how deer affect the regeneration potential of different tree species.

Nevalainen's (2017) expert survey combined with a literature-based analysis suggested that some even-aged forest management activities, such as tillage, can increase the risk of deer damage. This can happen by increasing the abundance of deciduous seedlings that impede the development of pine seedlings, increasing damage risk (Jalkanen et al. 2005; Nikula et al. 2008; Nevalainen et al. 2016). With increasing intensity of tree removal in spruce-dominated CCF stands, deciduous trees regenerated after felling experienced increasingly severe browsing pressure (Komonen et al. 2020). In this case, the problem is balancing a sufficiently high thinning intensity for regeneration and the increased risk of deer damage. There is a risk that if deer browsing prevents deciduous-tree regeneration, the biodiversity benefits sought from CCF will not be achieved.

At a larger scale, the impact of extensively practised continuous cover forestry on deer food resources and thus the risk of damage needs to be examined. This is particularly important when spruce, which is poorly suited to deer, is the main species regenerated in CCF, and pine regeneration areas are small scale. The current moose-damage situation depends on the balance between moose density and the area of pine-dominated seedling stands as pine is their preferred food resource (Nikula et al. 2021). Landscapes with more suitable food resources per moose is expected to have less moose damage. Similarly, if the area of pine-dominated seedling stands decreases, more damage is to be expected in the remaining pine stands.

Regeneration using Scots pine can be expected to increase with climate change, as pine is less sensitive than spruce to extreme heat and drought (Dyderski et al. 2018). This probably applies to both RF and CCF. For pine, the risk of deer damage in gap cuts applied in CCF can be assessed based on studies in different-sized clearcuts in even-aged forests. For example, smaller regeneration areas (below 0.5 ha) correlate with increased deer damage (Díaz-Yáñez et al. 2017). The explanation may be that small open areas create a favourable environment for moose, where seedling stands (providing food) and mature forests (providing shelter) are close to each other (Edenius et al. 2002). On the other hand, when moose are particularly abundant, no association between the risk of damage and the size of the clearcuts has been found (Andren and Angelstam 1993).

Furthermore, mixed stands are likely to gain wider use for improving ecosystem service delivery and increasing resilience of forests against environmental changes and damage agents (e.g., Jonsson et al. 2019). In both CCF and RF, this will increase important forage plant species in the field layer, such as dwarf shrubs (Atlegrim and Sjöberg 1996). Competition over dwarf shrubs from smaller deer increases the proportion of pine in the diet of moose (Spitzer et al. 2021) and results in more damage (Pfeffer et al. 2021). Thus, any silvicultural practice improving access to forage in the field layer is likely to decrease damage. The degree to which improved forage availability resulting from CCF compensates for decreased availability of browsable recruiting trees under even-aged forestry is difficult to predict (Roberge et al. 2016). These dynamics may also vary depending on local deer species composition and environmental conditions such as snow cover.

12.6 Conclusions and Future Perspectives

The risks of damage in continuous cover and even-aged forests differ significantly, but there is not much research comparing them. Therefore, reliably assessing many damage agents requires new research that focuses on their associated risks in CCF, as well as ways to manage them in both mineral soil and peatland forests.

As discussed above, root rot fungi are a particularly challenging problem for CCF. A site that is already affected by root rot should not be transferred to CCF under any circumstances. Additionally, it is possible that deer browsing on tree seedlings limits the regeneration of tree species other than spruce in CCF, but increasing forage availability in the field may reduce this effect. It is unclear whether the negative effects of browsing would be larger in CCF than in even-aged forestry. More research on landscape-level forage availability under different silvicultural practices is needed to understand how browsing may limit CCF.

Many damage-causing factors, such as *Cronartium pini* or *Gremmeniella abietina*, appear to be little impacted by the choice of CCF or RF; site quality and forest management are much more important. In addition, wind and snow damage, as well as the risk of damage caused by *Ips typographus*, are likely to be less significant in uneven-aged than in even-aged forests. It is important to understand that future forest landscapes will consist of a mosaic of different forest management practices and their stages, and therefore the risks of damage will vary considerably, depending on both stand- and landscape-level factors.

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