Principles of Ecological Restoration of Boreal Forested Ecosystems: Finland as an Example

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1 Introduction

The degree of past and present human influence varies considerably in different parts of the circumboreal forest zone. Almost natural boreal forest dynamics still prevail over considerable areas in many regions of northern Canada and Russia. On the other hand, in regions like the southern parts of Scandinavian countries, forest ecosystems have been fundamentally altered by past utilization and are now almost totally regulated by management. In these ecosystems, natural disturbances only play a minor role in forest structure and dynamics. For example, in southern Finland this is the case not only in managed forests, but also in many protected areas that have a long history of extensive utilization (Working group… 2000). This constitutes a problem for conservation, since in addition to the small area of protected forest, the value of reserves as a habitat for naturally occurring species has also been reduced because of habitat degradation. In this situation ecosystem restoration can be used to accelerate the formation of structural and habitat features resembling those of natural forests in order to enhance the conservation function of both protected and managed forests. It is evident that in areas that have been strongly affected by past and present forest utilization, including southern Finland, extensive restoration of both managed and protected forest ecosystems is needed if we want to bring these ecosystems closer to their natural level of biological diversity (Working group… 2000).

In 1999, the Ministry of Environment commissioned a working group to evaluate the current state of forest protection in southern Finland. The commission report (Working group… 2000) lists a number of measures that should be taken to improve the protection situation. The recommendations include: 1) additional conservation of poorly represented forest types, such as herb-rich forests and spruce mires, 2) restoration of forests both within protected areas and managed forests surrounding them, 3) formation of larger conservation networks around the existing core

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areas, 4) enhancing biodiversity-oriented silvicultural methods in managed forests.

Forest management methods have been considerably modified in Finland during the 1990s. The forestry legislation was reformed in 1997. The new forestry law sets ecological and social sustainability, preservation of biodiversity and sustainable yield of forests as equally important goals. Consequently, governmental, industrial and private forestry organizations all reformed their management guidelines during the past decade (e.g. Luonnonsuojelualueiden hoidon … 1994, Monimuotoisuus UPM-Kymmenen … 1998, Korhonen and Savonmäki 1997). New management practices that are already widely applied include setting aside habitats of special importance for forest biodiversity (so-called key biotopes), retention of living and dead trees in harvesting, and favoring prescribed burning and deciduous admixture. All these measures add structural features of natural forests into managed forests, hence the measures can be regarded as restoration in the widest sense. However, at present we have only a limited understanding on the ecological efficiency of these restoration activities in managed forests.

In Finland, most of the restoration studies have focused on drained peatlands (Heikkilä and Lindholm 1995, 1997; Vasander et al. 1998). Restoration of mires usually includes filling the ditches in order to restore hydrology, and removing trees if the original mire type was open. Restoration of managed forests on mineral soils has received much less attention. Possible methods include prescribed burning of stands, which both increases the amount of dead wood and initiates a natural succession, forming dead wood artificially by girdling or felling, and imitating gap dynamics by creating small openings in even-aged stands (Tukia 2000, Tukia et al. 2000).

There is a need to develop restoration methods that are ecologically and economically efficient, as well as socially acceptable. The purpose of this paper is to outline general principles and approaches for restoration of boreal forest and peatland ecosystems. Detailed practical methods of restoration of specific forest and peatland types are not presented. The paper is largely based on experiences in Finland.

2 General Aims and Principles of Restoration

Restoration of forests aims at rehabilitating structures and attributes that are typical of natural forest ecosystems. Restoration actions are typically discrete events in time, but they aim at initiating long-term developmental processes, like tree and dead tree successions, or paludification. Restoration of forest ecosystems can be focused on species, structures or dynamics. However, as all these aspects of forest ecosystems are closely interrelated, it is not feasible to focus only on one aspect, e.g. species, without considering other aspects of the ecosystem at the same time. The fact that forested ecosystems are complex and dynamic systems characterized by multi-scale heterogeneity (Pickett et al. 1997) highlights the need for a holistic ecosystem-level approach to restoration (Pickett and Parker 1994, Christensen et al. 1996).

Understanding the structure and function of natural forested ecosystems forms the necessary basis for all forest restoration activities (Landres et al. 1999, Bergeron et al. 2002, Kuuluvainen 2002). Knowledge of the composition, structure and function of natural forests – both the average values and range of variation – is needed to set goals for restoration and to evaluate the success of particular restoration actions. However, defining the natural forest is not a simple task (Kuuluvainen 2002). Especially in ecosystems that are frequently disturbed such as the boreal forest, we often lack knowledge about the range of natural variability of the forest structure in the area to be restored. Even if we have this knowledge, a natural forest may be so variable over time that it does not provide any static targets for restoration (White and Walker 1997, Landres et al. 1999). To overcome this problem, the goals of restoration can and should vary to cover the natural range of variability, which in turn can be defined using existing information from multiple sources (Landres et al. 1999, Kuuluvainen 2002). Potential sources of information include: 1) local analyses of biological archives by e.g. palaeoecological methods (Tolonen 1983, Pitkänen 1999), 2) retrospective analyses of forest structure based on historical materials (Lähde et al.

1991, Östlund et al. 1997, Axelsson and Östlund 2000), 3) research done in ecologically similar but more natural forests (Kuuluvainen et al. 1998, Kuuluvainen 2002), and 4) modeling (Pennanen 2002, Pennanen and Kuuluvainen 2002). Generally, restoration must focus on main ecosystem- and landscape-level goals. In most cases the correct direction of restoration actions is already known (Kuuluvainen 2002).

Imitating the natural forest in every respect is often not possible or even desirable. For instance, areas to be restored are usually too small to allow the imitation of the fire size distribution found in natural forest (Niklasson and Granström 2000). Therefore, the reintroduction of fire as a part of an ecosystem restoration project should be carried out according to a long-term, landscape-level plan to eventually create a post-fire habitat mosaic resembling that found in naturally fire-dynamic landscapes.

Successful restoration of forested landscapes requires long-term planning and actions. However, as a consequence of the long periods of time involved, the occurrence of unexpected events become an inevitable companion of restoration. This is partly due to our ignorance of ecosystem functioning, which restricts the possibilities to make precise predictions about the outcomes of restoration activities. The other reason is more fundamental and is related to the unpredictability of the environment and the nonlinear relationships between processes that regulate ecosystem change (Christensen et al. 1996). Therefore, all restoration planning should acknowledge that surprises can occur and try to buffer the ecosystem to be restored against surprises, such as abrupt environmental changes. One way to do this is to restore larger ecosystem complexes instead of small areas.

Restoration ecology is a science that is closely connected to practice, but practice should also be closely connected to science. Practical restoration projects should be closely linked with monitoring and research whenever possible (Young 2000). Monitoring enables us to adjust what we do in order to better achieve our goals (so called adaptive management, cf. Walters 1986, Walters and Holling 1990). Incorporation of research into management generates synergy benefits, e.g. by making it possible to set up experiments on scales that are relevant, both ecologically and managerially. It also helps to ensure the formation of a basis of knowledge of the long-term effects of restoration, which in turn can be used in planning future restoration efforts.

3 The Role of Restoration in Nature Conservation

Protecting pristine ecosystems is always the first option in nature conservation, but when this is not possible, restoration can be used to complement conservation efforts. In nature conservation, restoration can be used: 1) within protected areas to shift forest structure closer to natural state in order to enhance habitat quantity and quality for focal species, 2) in the vicinity of protected areas to enlarge and complement small and fragmented areas to form larger and better connected units that can maintain natural-like landscape-level successional and disturbance dynamics, 3) to create buffer zones between managed and protected areas and to improve the connectivity between protected areas (Fig. 1).

Restoration of protected areas closer to their natural state may considerably increase the capacity of these areas to support populations of many species that would otherwise decline or disappear in the long run. The reason for this, e.g. in southern Finland, is that only a small portion of the protected forests are at present close to their natural state (Jaakkola 1997, 1999). The protected areas are often too small and fragmented to allow natural forest dynamics and population processes of particularly disturbance-adapted species to take place. In such cases, restoration can be used to enlarge and combine smaller areas to form larger functional landscape units that can better meet the goals of ecosystem and species protection.

From the species conservation point of view, restoration of managed forests located close to existing source areas of the species is usually most efficient (Tilman et al. 1997, Huxell and Hastings 1999, Hanski 2000). It is most likely that habitats will be colonized by their typical species if the patches are close to existing sources of potential colonists. Thus, restoration can be used in managed forests to complement the protection

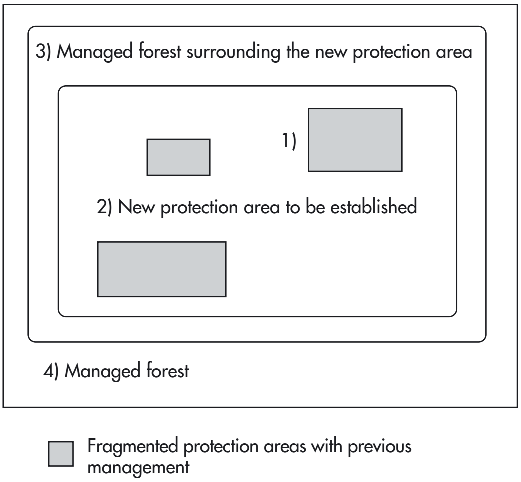

Fig. 1. A simplified illustration of the uses of restoration in conservation of forested ecosystems. 1) Protected forests are often far from their natural state because of previous management. Restoration can be used to improve the naturalness of forest structures to enhance habitat quantity and quality for focal species. 2) The present protection areas are often small and isolated. Restoration can be used to enlarge and complement small and fragmented protected areas to create larger and better connected units. 3) Restoration can be used in managed forests surrounding protected areas to create buffer zones between managed and protected forests in the vicinity of protected areas and to enhance the conservation function of protected areas. 4) General restoration principles can be applied in the production forest as a whole to improve the habitat quality of the forest matrix.

function of reserves (Fig. 1). Restoration of existing protection areas and close by managed forests may be both ecologically and economically a more sensible strategy than setting aside new, previously managed forests. Restoration can be regarded as the most important means of maintaining and complementing networks of protected forests in areas where the forest landscape has been strongly altered by human impacts, such as in southern Scandinavia.

In southern and central Finland, restoration projects have been initiated in several protection areas during the 1990's. However, lacking a strategic large-scale and long-term restoration plan, the restoration actions have often been separate, locally planned, short-term measures. In addition, due to limited resources the monitoring of ecosystem responses has usually been insufficient or completely lacking.

4 Spatial and Temporal Scales of Forest Restoration

Consideration of relevant spatial and temporal scales is a critically important aspect of restoration. Therefore, a hierarchical multi-scale approach is most useful in restoration. The most relevant hierarchical scales are those of 1) species populations and habitats, and 2) communities and landscapes (Montalvo et al. 1997, Ehrenfeld and Toth 1997, Bell et al. 1997). Following this hierarchy, restoration can be divided into short-term and long-term actions.

Often the most urgent, short-term goal for restoration is to improve the quality of the habitats of threatened species. Potential methods include, e.g. stand treatments to enhance the complexity of forest structure and to increase the amount of dead wood, or restoration of the original groundwater level by damming of ditches in drained peatlands. However, the long-term goal must be holistic: to restore entire ecosystems and their complexes to resemble natural ones in terms of species diversity, structure and dynamics. Thus, the long-term goal of restoration should not be restricted to conserving specific species or groups of species, but to restore whole functional ecosystems on larger spatial scales.

In the boreal zone, incorporation of landscape-scale restoration planning should be emphasized, because several fundamental processes of the boreal forest ecosystem occur on large spatial scales. Such processes include disturbances like forest fires and population dynamics of many species (such as many herbivores and predators). One example is the reintroduction of fire as a disturbance factor. In boreal forests this is important, because in the absence of fire forest structural variability decreases, tree species composition and composition of ecological communities change and some species may even become locally extinct. It has been estimated that in Fennoscandian boreal forests at least 60 species are dependent on fire (Engelmark and Hytteborn 1999).

In conclusion, the aim of landscape-level restoration activities should be to create and maintain a mosaic of successional stages and habitat types that maintains viable populations of species that would naturally occur in the area. This means that all local-level short-term actions must be evaluated in the framework of long-term landscape-level restoration goals.

5 A Hierarchical Multi-Scale Approach to Landscape Restoration

Restoration methods in a broad sense can be derived from general restoration principles (see above) and from comparisons and analyses of differences between the natural variability and current state of forest structures in a given area (Fig. 2, Tables 1 and 2). In natural forest ecosystems a versatile set of disturbances, operating in a hierarchical manner on different temporal and spatial scales, determines the dynamics of ecosystem structure and function (Attiwill 1994, Kuuluvainen 2002). This means that restoration of the features of primeval forested landscapes requires imitating the multi-scale disturbance dynamics typical of natural forests (Kuuluvainen 2002). To facilitate this it is useful to adopt a hierarchical approach to restoration planning and implementation and to take different levels of ecological organization into account, from broad landscape patterns to microsite variability on the forest floor. Restoration should use a set of methods that create multiple scale structures similar to those found in natural forests.

In Fennoscandian conditions landscape-level restoration often includes restoration of a mosaic of mineral soils and peatlands and different kinds of water bodies (Fig. 3, Sjöberg and Ericson 1997). This means that an understanding of natural forested ecosystems forms the necessary basis for all forest restoration. As ecotones of different ecosystem types are often particularly important for biodiversity, they should be given special emphasis in restoration. The logic behind the use of some of the most common restoration methods both on mineral soils and peatlands is discussed below (Tables 1 and 2).

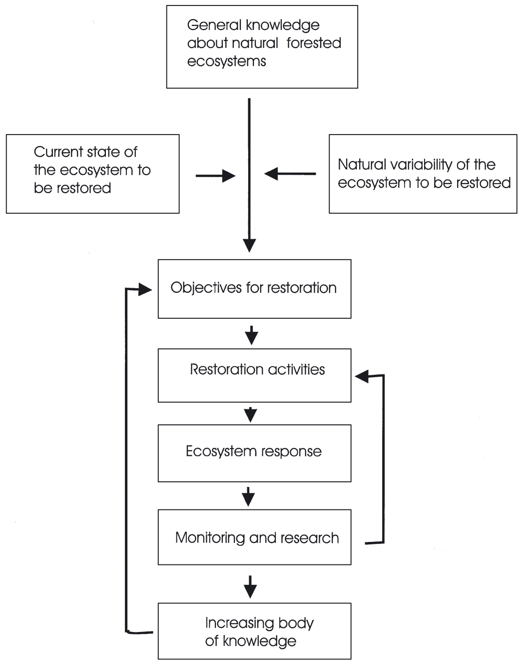

Fig. 2. Diagram illustrating the framework and basic components of restoration and how monitoring and research should be integrated as essential components of the restoration process.

5.1 Controlled Use of Fire

Use of fire is a necessary component of boreal forest restoration, because fires have always been an essential part of the ecology of natural boreal forests (Zackrisson 1977, Pitkänen 1999). By using fire in a controlled manner it is possible to diversify stand structures, to increase dead wood and to create open and warm habitats and later, young successional stages dominated by deciduous trees (Table 2). On the landscape level it is important to ensure long-term fire continuity to provide habitat for fire-dependent species. In a forest fire some trees die immediately, some within a few years and some survive the fire. The

Table 1. Stand- and landscape-level structures and processes characteristic of natural boreal forests that have diminished because of forest utilization and management and that restoration attempts to rehabilitate. Structural features describe the state of forest ecosystems at a given point in time, while processes refer to the dynamics of disturbance and successional processes in time. It is important to note that, although listed here separately, structures and processes are two sides of the same coin, since structures are created and maintained by these disturbance and successional processes

Structural features to be restored

At stand level
- Old trees, especially deciduous trees (above all *Populus tremula* and *Salix caprea*)
- Broken, leaning, damaged and cavity trees
- Trees with abundant epiphytic lichen flora
- Various kinds of fallen dead wood, especially large logs
- Standing dead trees (snags)
- Burned living and dead trees
- Mounds and pits caused by uprooting
- Mixtures of coniferous and deciduous tree species
- Trees of varying ages and sizes
- Structurally and compositionally diverse understory canopies
- Diverse microhabitat mosaics in relation to water table in peatland forests

At landscape level
- Natural variability of size distribution of habitat patches
- Natural variability of post-fire and other successional stages
- Natural-like landscape connectivity
- Natural-like ecotones

Processes to be restored

At stand level
- Gap disturbances on the scale of single trees or groups of trees
- Fine-scale soil disturbances
- Post-fire successions
- Successions following other disturbances besides fire
- Natural tree stand succession and self-thinning
- Multiple pathways of wood decay successions
- Natural successions of peatland forests

At landscape level
- Natural variability of fire regime
- Natural variability of distribution and spatial pattern of young deciduous successional stages
- Natural variability of distribution and spatial pattern of old successional stages
- Natural variability of distribution and spatial pattern of fire-free areas (fire refugias)
- Natural variability of dynamics and spatial distribution of dead wood
- Natural-like hydrology of peatland forests

selective effect of fire disturbance increases the structural variability of the post-fire stand and creates beneficial conditions for tree regeneration (Vanha-Majamaa et al. 1996). The effects of fire on the soil organic layer also enhance tree regeneration and activation of the soil seed bank. Large amounts of dead wood in open conditions, and competition-free substrates created by fire are important habitats for a large number of decomposer fungi and sproxylic insects (Penttilä and Kotiranta 1996, Wikars 1997).

Table 2. Methods and goals of restoration of boreal forest ecosystems

Method	Goal
Controlled use of fire	Creation of more complex stand structures Creation of open warm habitats Creation of (charred) dead wood Creation of young deciduous successional stages
Creation of small gaps	Creation of stand-structural features typical of late-successional natural forests Increase the amount of deciduous trees Creation of different kinds of dead wood and decay successions
Damaging of trees	Creation of more complex stand structures Creation of different kinds of dead wood and decay successions Creation of soil disturbances
Reforestation of roads	Enhancement of landscape connectivity Restoration of natural hydrology
Damming or filling in ditches	Raising the water table Restoration of peatlands Creation of dead wood in forested peatlands
Flooding	Imitation of natural flooding dynamics Restoration of alluvial forests Creation of dead wood
Species reintroduction	Rehabilitation of natural species composition

5.2 Creating Small Gaps and Dead Trees

Damaging and felling of individual trees and small groups of trees to create small gaps imitate fine-scale disturbances found in natural forests and create subsequent habitats (Table 2). Fine-scale disturbances are important since they create structural heterogeneity on multiple scales, from the pit and mound microtopography formed by uprooted trees to the deaths of small understory trees, canopy trees or groups of trees. All these phenomena contribute to local tree regeneration and successional sequence (Kuuluvainen 1994, Ulanova 2000).

Damaging and felling of individual trees aims at accelerating the formation of forest structures, such as dead wood and canopy gaps, that would naturally require a long successional development to appear. Single tree falls can be emulated by cutting trees, or by using an excavator to pull or push the trees down to create the pit-mound microtopography typical of wind-thrown trees. Mechanical harvesters can be used to cut trees at the height of several meters to imitate stem breakage in natural forests. The cambial zone of living stems can be damaged to create slowly dying trees, which are common in natural forests and form an important habitat for many species. It is preferable to use a variety of methods to damage trees in order to create multiple pathways of tree death and wood decay succession (Table 2).

In natural forests small gaps are created when single trees or groups of trees die. The size of such gaps can vary between 0.001–0.1 ha. Creation of a gap-phase structure, which in natural boreal forests is perhaps most typical of old-growth *Picea*-dominated forests, may be relevant as part of a restoration project, because natural gap dynamics usually emerge in late successional stages (Kuuluvainen et al. 1998). By creating small gaps it is possible to diversify forest structure and tree species composition and to produce more dead wood while still maintaining the moist and shady microclimate typical of old growth forests. When making gaps it is important to ensure the formation of fine-scale soil distur-

Fig. 3. A typical habitat mosaic of forests and mires in the middle boreal forest zone, here in the Seitseminen National Park, southern Finland. Landscape-level restoration requires simultaneous consideration of adjacent interacting forest and mire ecosystems. Here the drained mires have been restored by filling in the ditches. As the mires were originally open and only sparsely forested, most of the trees have been cut and removed from the site. Forests around the mires remain affected by previous management actions. The mires and forests of the Seitseminen National Park are being restored on the basis of local and regional, short and long-term goals and timetables. Photo by Oy HeliFoto Ab, © Metsähallitus.

bances, because pits and mounds are important for both species diversity (Jonsson and Esseen 1990) and tree regeneration (Kuuluvainen and Juntunen 1998).

5.3 Restoration of Forested Peatlands

Restoration of drained, forested peatlands requires restoration of both mire- and forest-related features and processes (Fig. 3, Table 2). Drainage of peatlands has been very extensive, especially in southern Finland, where 78% of spruce mires and 72% of pine mires and treeless mires have been drained (Virkkala et al. 2000). The need for restoration is especially high in spruce mires in hemi and southern boreal zones, where less than 1% of them have been protected and almost half of these protected spruce mires have been drained (Virkkala et al. 2000).

The key element in restoring forested mires is water. In pristine mires, natural variations in water flow, e.g. due to exceptionally wet weather conditions, can cause disturbances. Water may also change its route, causing waterlogging and subsequent tree deaths in some areas, and enhance tree growth and seedling establishment in other areas where the water level drops down. Drainage always changes the natural flow of waters, and drainage in one part of a mire ecosystem may also change the hydrology in the undrained parts.

The principal aim of mire restoration is always to restore the original flow paths of waters by damming or filling in the ditches. The uneven subsidence of peat surface after drainage may complicate the restoration of the natural water flow. As peat subsidence is usually most pronounced near ditches, water may continue to flow along or stay in the ditches, instead of spreading across the mire as in a natural state. Extending the dams, in the form of low banks, several meters away from the ditches may solve this problem. The aim of such banks is to spread the water flow more evenly across the mire.

On a larger scale, peat surface subsidence is greatest where the peat layer is thick, originally wet, and nutrient level is high, especially near main drainage channels due to their deepness (e.g. Minkkinen and Laine 1998 and references therein). Therefore, exactly original water conditions are hard to achieve, and the result is more a mosaic of areas that are drier and wetter than in the original, natural state.

While the restoration of the natural water flow and high water table are essential for mire ecosystem functions (e.g. peat accumulation), the restoration of the structure and dynamics of the tree stand is also needed in originally forest-covered drained peatlands. Typical characteristics of pristine spruce mires include long continuity (mean interval between fires over 400 years), trees of all sizes and ages and large amounts of dead wood present, and continuous regeneration (gap-phase dynamics) (Hörnberg et al. 1998, Siitonen and Saaristo 2000). Peatland forests maintain their uneven-sized and -aged structure for quite a long time after drainage (Hökkä and Laine 1988, Uuttera et al. 1996), but thinning operations level off the unevenness of the tree stand structure (Uuttera et al. 1997, Päivänen 1999).

Technically the methods for restoring the structure and the dynamics of peatland forests are the same as those used in restoring mineral soil forests. In naturally sparsely forested mires, such as *Pinus* mires, partial harvesting is often plausible for both ecological and economical reasons. Restoring the natural uneven structure of tree stands in *Picea* mires requires continuous regeneration. Elevated microhabitats, such as logs, are crucial for the regeneration of spruce (Hörnberg et al. 1997). Due to previous management, logs are not necessarily available in drained peatland forests. Very often some trees die due to the raised water table after damming of the ditches. If this is not to be expected, logs should be created by felling trees. Restoring the hardwood component of the stand is usually not a problem since at least birch as a pioneer tree species readily recolonizes restored mire habitats with enough light. In some cases birch may become a problem when it forms dense thickets that prevent regeneration of other tree species and recolonization of original mire plant species.

6 Environmental Effects of Restoration

Restoration actions may temporarily provide suitable substrates for some pest species. There are several species of insect and fungi that colonize freshly dead trees. Some scolytid beetles, especially, may increase their population sizes under favorable conditions. Adult beetles may attack temporarily weakened trees in the surroundings and cause economic damage. These species typically favor open and warm habitats. To avoid socio-economic problems, large amounts of dead trees and burned forest sites should not be created simultaneously too close to private forest sites (Fagerblom and Heliövaara 2000). These aspects should be taken to account when choosing areas for the restoration.

The hydrological effects of restoration in mineral soils have not been monitored. However, the areas involved are usually rather small. Experiences from natural disturbances (Schindler et al. 1980) have showed that even after large-scale windthrow or fire, the water quality in downstream brooks has remained acceptable, and only moderate increases in nutrient concentrations occurred. Runoff can increase considerably due to reduced evapotranspiration. Schindler et al. (1980) concluded that there appears to be little reason for fearing that increased nutrient losses after a fire or windthrow will have adverse effects on downstream waters.

The effects of restoration on drained mires have been monitored in the Seitseminen National Park, southwestern Finland (Sallantaus 1999). The three monitored catchments were mostly dominated by oligotrophic or even ombrotrophic pine mires, some of which were nearly open before drainage, but areas with hardwood and spruce mires were also included. The treatments varied from almost complete tree removal to only moderate thinning.

In all cases, concentrations of nutrients in downstream waters increased after restoration, as expected. However, the increase in phosphorus concentrations was unexpectedly high. In a monitored lake, total phosphorus increased five-fold within one year, when all the drained mires in its catchment were restored within a short period of time. Similar increases were observed also in the monitored brooks with a similar degree of restoration. However, in the second year after restoration, the concentrations were already rapidly decreasing.

The increases in concentrations of phosphorus and other nutrients after restoration were rather large, but not exceptional when compared e.g. with the impacts of forestry practices in peat soils. Previous fertilizations of the drained mires may have exacerbated the leaching of phosphorus in the case of Seitseminen National Park. Similar or even higher increases have been observed following clear-cuttings on peatlands, both in drained (Nieminen 1999) and undrained (Ahtiainen 1992) mires.

Other changes in water quality also take place after restoration of drained mires (Sallantaus 1999). For example, leaching of dissolved organic carbon increases for some time after restoration when increased amounts of water reach the changed, decomposed surface peat of the drained area. Ammonium concentrations may also increase slightly.

The major adverse hydrological impact of the restoration of drained mires is the increased leaching of phosphorus (Sallantaus 1999), although only minor increases have also been reported (Vasander et al. 1998). It is still unclear how common this problem is and whether it can be reduced or avoided. It is, however, a matter that must be taken into account when planning and carrying out the restoration work in drained mires.

The risks of pest outbreaks and negative impacts in water systems may strongly affect public attitudes towards restoration. Even in cases where there is no actual risk of harmful environmental impacts, the situation should be carefully presented to the public.

7 Research and Development Needs

There is a need for both basic research to set general restoration strategies and goals and for developing monitoring and research to document the responses of ecosystems to restoration activities. Monitoring and research should be essential components of long-term restoration projects (see Fig. 2). At the moment, there is a lack of research results dealing with different aspects of restoration in boreal forested ecosystems. Restoration projects should be organized so as to enable experimental testing of methods. This would allow the continuous accumulation of knowledge that can be used to direct the restoration efforts more efficiently in the future. From the point of view of ecological restoration, five important areas of research emerge.

1) *Structure, dynamics and species composition of natural forest-peatland mosaic landscapes.* Knowledge of the natural variability of the structure and dynamics of natural forests forms the necessary reference and background for all restoration activities. At present, our limited understanding of the natural variability of the structure and dynamics of natural forest landscapes makes it difficult to set restoration goals and assess restoration results. Above all, we lack a full understanding of interactions between different disturbance agents and the long-term cumulative effects of disturbance dynamics in natural forest ecosystems. Ultimately, we should be able to define landscape-specific targets for restoration, since each forested landscape is likely to be a special case. However, in many cases the direction of restoration actions is evident (Kuuluvainen 2002), and during long-term restoration projects the restoration methods and goals can be modified based on monitoring and new research results (adaptive management).
2) *Controlled use of fire in restoration.* A better understanding of the behavior and consequences of fire in different types of forest is needed to develop controlled burning techniques. This is necessary in order to successfully apply fire as

a large-scale restoration tool in boreal forests. In research, modeling of fire behavior should go hand in hand with empirical experimentation.

3) *Creating dead wood*. The large-scale reduction of dead wood caused by intensive forest management is one of the principle threats to forest fauna and flora in Fennoscandian boreal forests (Siitonen 2001). The average amounts of dead wood are often low even within reserves e.g. in southern Finland because of previous management activities in these areas. Therefore, both ecologically and economically efficient methods must be found that increase the amount of dead trees in places where the existing supply is scarce. This requires experimentation combined with research and monitoring on practically relevant scales and a multidisciplinary approach that addresses ecological, economic and social issues.
4) *Restoration methods of forested peatlands*. Restoration of forested peatlands includes the restoration of both forest and peatland components, which is sometimes problematic (see Fig. 3). Accordingly, research is needed to develop efficient methods for these ecosystems.
5) *Monitoring methods for restoration*. Cost-efficient methods of monitoring restoration success should be developed, because ecosystems do not always respond to restoration as expected. In addition, the fact that environmental changes are occurring emphasizes the importance of monitoring in restoration projects.

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References

Ahtiainen, M. 1992. The effects of forest clear cutting and scarification on water quality of small brooks. Hydrobiologia 243/244: 465–473.

Attiwill, P.M. 1994. The disturbance dynamics of forest ecosystems: the ecological basis for conservative management. Forest Ecology and Management 63: 247–300.

Axelsson, A.-L. & Östlund, L. 2000. Retrospective gap analysis in a Swedish boreal forest landscape using historical data. Forest Ecology and Management 5229: 1–14.

Bell, S.S., Fonseca, M.S. & Motten, L.B. 1997. Linking restoration and landscape ecology. Restoration Ecology 5: 318–323.

Bergeron, Y., Leduc, A., Harvey, B.D. & Gauthier, S. 2002. Natural fire regime: a guide for sustainable management of the Canadian boreal forest. Silva Fennica 36(1): 81–95. (This issue).

Christensen, N.L., Bartuska, A.M., Brown, J.H., Carpenter, S., D’Antonio, C., Francis, R., Franklin, J.F., MacMahon, J.A., Noss, R.J., Parsons, D.J., Peterson, C.H., Turner, M.G. & Woodmansee, R.G. 1996. The report of The Ecological Society of America Committee on the scientific basis for ecosystem management. Ecological Applications 6: 665–691.

Ehrenfeld, J.G. & Toth, L.A. 1997. Restoration ecology and the ecosystem perspective. Restoration Ecology 5: 307–317.

Engelmark, O. & Hytteborn, H. 1999. Coniferous forests. Acta Phytogeographica Suecica 84: 55–74.

Fagerblom, A. & Heliövaara, K. 2000. The law for the prevention of insect and fungi damage to forests in Finland. University of Helsinki, Dept. Applied Zoology, Reports 28. 59 p. (In Finnish with English summary).

Hanski, I. 2000. Extinction debt and species credit in boreal forests: modelling the consequences of different patterns of forest restoration. Annales Zoologici Fennici 37: 271–280.

Heikkilä, H. & Lindholm, T. 1995. The basis of mire restoration in Finland. In: Wheeler, S.C., Shaw, S.C., Fojt, W.J. & Robertson, R.A. (eds.). Restoration of temperate wetlands. John Wiley & Sons. p. 549–556.

— & Lindholm, T. 1997. Soiden ennallistamistutkimus vuosina 1987–1996 [Mire restoration studies from 1987 to 1996.]. Metsähallituksen luonnon-

suojelujulkaisuja, Sarja A 81: 1–75. (In Finnish).
Huxell, G.R. & Hastings, A. 1999. Habitat loss, fragmentation and restoration. Restoration Ecology 7: 309–315.
Hökkä, H. & Laine, J. 1988. Suopuustojen rakenteen kehitys ojituksen jälkeen. (Post-drainage development of structural characteristics in peatland forest stands.) Silva Fennica 22: 45–65.
Hörnberg, G., Ohlson, M. & Zackrisson, O. 1997. Influence of bryophytes and microrelief conditions on Picea abies seed regeneration patterns in boreal old-growth swamp forests. Canadian Journal of Forest Research 27: 1015–1023.
— , Zackrisson, O., Segeström, U., Svensson, B.W., Ohlson, M. & Bradshaw, R. 1998. Boreal swamp forests. Biodiversity "hotspots" in an impoverished forest landscape. BioScience 48: 795–802.
Jaakkola, S. 1997. Seitsemisen metsien ennallistamissuunnitelma. Käsikirjoitus [Restoration plan of the forests of Seitseminen. Manuscript]. Metsähallituksen luonnonsuojeluarkisto, Vantaa. (In Finnish).
— 1999. Nuuksion kansallispuiston ennallistamissuunnitelma [Restoration plan of Nuuksio national park]. Metsähallituksen luonnonsuojelujulkaisuja B 53. (In Finnish).
Jonsson, B.G. & Esseen, P.-A. 1990. Treefall disturbance maintains high bryophyte diversity in a boreal spruce forest. Journal of Ecology 78: 924–936.
Korhonen, K.-M. & Savonmäki, S. (ed.). 1997. Metsätalouden ympäristöopas [Environmental forestry guide]. Metsähallitus, Helsinki, 130 s. (In Finnish).
Kuuluvainen, T. 1994. Gap disturbance, ground microtopography, and the regeneration dynamics of boreal coniferous forests in Finland, a review. Annales Zoologici Fennici 31: 35–51.
— 2002. Natural variability of forests as a reference for restoring and managing biological diversity in boreal Fennoscandia. Silva Fennica 36(1): 97–125. (This issue).
— & Juntunen, P. 1998. Seedling establishment in relation to microhabitat variation in a windthrow gap in a boreal Pinus sylvestris forest. Journal of Vegetation Science 9: 551–562.
— , Syrjänen, K. & Kalliola, R. 1998. Structure of a pristine Picea abies forest in north-eastern Europe. Journal of Vegetation Science 9: 563–574.
Lähde, E., Laiho, O., Norokorpi, Y. & Saksa, T. 1991. The structure of advanced virgin forest in Finland. Scandinavian Journal of Forest Research 6: 527–537.
Landres, P.B., Morgan, P. & Swanson, F.J. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications 9: 1179–1188.
Luonnonsuojelualueiden hoidon periaatteet. Valtion omistamien luonnonsuojelualueiden tavoitteet, tehtävät ja hoidon yleislinjat [Principles of management of nature conservation areas. Objectives functions, and general quidelines for management of the state-owned conservation areas]. 1994. Metsähallituksen luonnonsuojelujulkaisuja, Sarja B 1: 1–55. (In Finnish).
Minkkinen, K. & Laine, J. 1998. Long-term effect of forest drainage on the peat carbon stores of pine mires in Finland. Canadian Journal of Forest Research 28: 1267–1275.
Monimuotoisuus UPM-Kymmenen metsissä. Tausta ja toimenpiteet [Biodiversity in the forests of UPM-Kymmene. Background and actions]. 1998. UPM-Kymmene Metsä, Valkeakoski. 64 p. (In Finnish).
Montalvo, A.M., Williams, S.L., Rice, K.J., Buchmann, S.L., Cory, C., Handel, S.N., Nabhan, G.P., Primack, R. & Robichaux, R.H. 1997. Restoration biology: a population biology perspective. Restoration Ecology 5: 277–290.
Nieminen, M. 1999. Päätehakkuun ja maanmuokkauksen vaikutus valumaveden laatuun vanhoilla ojitusalueilla [Effect of final harvesting and site preparation on runoff water quality in old ditched areas]. In: Metsätalouden ympäristökuormitus. Tutkimusohjelman väliraportti [Environmental loading. Mid-term report of a research programme]. Metsäntutkimuslaitoksen tiedonantoja 745. p. 109–113.
Niklasson, M. & Granström, A. 2000. Number and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. Ecology 81: 1484–1499.
Östlund, L. Zackrisson, O. & Axelsson, A.-L. 1997. The history and transformation of a Scandinavian boreal forest landscape since the 19th century. Canadian Journal of Forest Research 27: 1198–1206.
Päivänen, J. 1999. Tree stand structure on pristine peatlands and changes after forest drainage. International Peat Journal 9: 66–72.
Pennanen, J. 2002. Forest age distribution under mixed-severity fire regimes – a simulation-based analysis for middle boreal Fennoscandia. Silva Fennica

36(1): 213–231. (This issue).

— & Kuuluvainen, T. 2002. A spatial simulation approach to the natural forest landscape dynamics in boreal Fennoscandia. Forest Ecology and Management. (In press).

Penttilä, R. & Kotiranta, H. 1996. Short-term effects of prescriobed burning on wood-rotting fungi. Silva Fennica 30: 399–419.

Pickett, S.T.A. & Parker, V.T. 1994. Avoiding the old pitfalls: opportunities in a new discipline. Restoration Ecology 2: 75–79.

— , Ostfeld, R.S., Shachak, M. & Likens, G.E. 1997. The ecological basis of conservation: heterogeneity, ecosystems, and biodiversity. Chapham & Hall, New York. 466 p.

Pitkänen, A. 1999. Palaeoecological study of the history of forest fires in eastern Finland. University of Joensuu, Publications in Sciences 58.

Sallantaus, T. 1999. Seitsemisen soiden hydrologinen seuranta. Raportti 30.9.1999. 20 p. + 26 app. Osaraportti hankkeesta: Keidassoiden, aapasoiden ja korpien ennallistaminen Natura 2000 -kohteilla. Life-projekti B4-3200/96/542. (In Finnish).

Schindler, D.W., Newbury, R.W., Beaty, K.G., Prokopowich, J., Ruszczynski, T. & Dalton, J.A. 1980. Effects of a windstorm and forest fire on chemical losses from forested watersheds and on the quality of receiving streams. Canadian Journal of Fishery and Aquatic Science 37: 328–334.

Siitonen, J. 2001. Forest management, coarse woody debris and saproxylic organisms: Fennoscandian boreal forests as an example. Ecological Bulletins 49: 11–41.

— & Saaristo, L. 2000. Habitat requirements and conservation of Pytho kolwensis, a beetle species of old-growth boreal forest. Biological Conservation 94: 211–220.

Sjöberg, K. & Ericson, L. 1997. Mosaic boreal landscapes with open and forested wetlands. Ecological Bulletins 46: 48–60.

Tilman, D., Lehman, C.L. & Kareiva, P. 1997. Population dynamics in spatial habitats. In: Tilman, D. & Kareiva, P. (eds.). Spatial ecology. The role of space in population dynamics and interspecific interactions. Monographs in Population Biology 30: 3–20.

Tolonen, K. 1983. The post-glacial fire record. In: Wein, R.W. & MacLean, D.A. (eds.). The role of fire in northern circumbolar ecosystems. John Wiley & Sons. p. 21–44.

Tukia, H. 2000. Metsien ennallistamisen ekologiaa [Ecological aspects of forest restoration]. Metsähallituksen luonnonsuojelujulkaisuja, Sarja A: 1–65. (In Finnish).

— , Hokkanen, M., Jaakkola, S., Kallonen, S., Kurikka, T., Leivo, A., Lindholm, T., Suikki, A. & Virolainen, E. 2000. Metsien ennallistaminen suojelualueilla – lähtötilanne 1995 [Restoration of forests in protected areas – starting situation in 1995]. Metsähallituksen luonnonsuojelujulkaisuja, Sarja A 118: 1–148. (In Finnish).

Ulanova, N.G. 2000. The effects of windthrow on forests at different spatial scales: a review. Forest Ecology and Management 135: 155–167.

Uuttera, J., Maltamo, M. & Hotanen, J-P. 1996. Stand structure of undrained and drained peatland forests in central Finland. Suo 47: 125–135.

— , Maltamo, M. & Hotanen, J-P. 1997. The structure of forest stands in virgin and managed peatlands: a comparison between Finnish and Russian Karelia. Forest Ecology and Management 96: 125–138.

Vanha-Majamaa, I., Tuittila, E.-S., Tonteri, T. & Suominen, R. 1996. Seedling establishment after prescribed burning of a clear cut and partially cut mesic boreal forest in southern Finland. Silva Fennica 30: 31–45.

Vasander, H., Tuittila, E-S., Komulainen, V-M., Laine, J. & Sallantaus, T. 1998. Restoration of peatlands drained for forestry in Finland. Proc. Int. Symp. "Peatland Restoration and Reclamation – Techniques and Regulatory Considerations", Duluth, Minnesota, USA, 14–18 July, 1998. International Peat Society, Jyväskylä. p. 88–93.

Virkkala, R., Korhonen, K.T., Haapanen, R. & Aapala, K. 2000. Metsien ja soiden suojelutilanne metsä- ja suokasvillisuusvyöhykkeittäin valtakunnan metsien 8. inventoinnin perusteella. (Protected forests and mires in forest and mire vegetation zones in Finland based on the 8th National Forest Inventory.) Suomen ympäristö 395: 1–49. (In Finnish with English summary).

Walters, C.J. 1986. Adaptive management of renewable resources. McGraw-Hill, New York.

— & Holling, C.S. 1990. Large-scale management experiments and learning by doing. Ecology 71: 2060–68.

White, P.S. & Walker, J.L. 1997. Approximating nature's variation: selecting and using reference information in restoration ecology: Restoration Ecology 5: 338–349.

Wikars, L. 1997. Effects of forest fire and the ecology of fire-adapted insects. Comprehensive summaries of Uppsala dissertations, Faculty of Science and Technology 272: 1–35.

Working group on the need for forest protection in southern Finland and Ostrobothnia. 2000. Forest protection in southern Finland and Ostrobothnia. The Finnish Environment 437. 284 p. (In Finnish with English summary).

Young, T. 2000. Restoration ecology and conservation biology. Biological Conservation 92: 73–83.

Zackrisson, O. 1977. Influence of forest fires on the North Swedish boreal forest. Oikos 29: 22–32.

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