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Silviculture in Polluted Areas

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Introduction

The influence of industrial pollution on forest health has long been recognized as a serious applied and scientific problem. Although numerous field experiments have been established to determine practical measures for both the alleviation of pollution impacts on stand vitality and the rehabilitation of damaged forests, a general strategy has not emerged, and 'silviculture in polluted areas' is still in the incipient stages of development. Maintenance of forests in polluted areas requires more intensive management than in unpolluted areas, involving 'soft' techniques and highly skilled manual labor.

The prescriptions that form the basis of silviculture in polluted areas should be preventive, aimed at improving the ecological stability of stands in such a way that they will better resist pollution impacts. In many cases the vitality and productivity of forests affected by chronic acidification and heavy-metal contamination can be maintained by chemical amelioration. However, to be successful, the revitalization strategy should first aim at identification of nutritional disturbances and then apply diagnostic fertilization to alleviate these disturbances, balancing the anticipated beneficial and adverse effects. Suggested silvicultural measures include the creation of substitute stands, maintenance of stand integrity, a decrease in rotation time, avoidance of monocultures, and replacement of clear-cuts by selective logging and gap-oriented regeneration. The practical application of silvicultural measures, with successful amelioration of pollution impacts, is still limited to a very few areas of boreal and temperate forests.

Polluted Forests: Past, Present, and Future

Pollution, Polluters, and Pollutants

Historically, sulfur dioxide was the first pollutant to cause local but severe forest deterioration. This is the best-studied pollutant, under both experimental and natural conditions. In high concentrations it causes acute foliar damage, which weakens and then kills the trees; in low concentrations it contributes to regional acidification. Conifers are generally more sensitive to SO_2 than broadleaved species.

Fluorine emissions to the atmosphere started to increase in the late 1930s, reaching peak values in the late 1960s. These emissions were primarily associated with aluminum production, and they caused severe but local forest damage. However, fluorine emissions strongly decreased between 1970 and 1980 due to effective measures taken to minimize the release of fluoride from aluminum smelters to the atmosphere.

Heavy metals are very common pollutants but in general do not spread far from smelters. Only some of the largest polluters have caused detectable contamination of soils and vegetation at distances exceeding 50 km from the emission source. Heavy metals emitted by Monchegorsk and Norilsk can be detected (in atmospheric aerosols) and identified (e.g., attributed to the specific polluter) at distances up to 2000 km from the polluter. However, these long-transported metals have never been said to cause any biotic effects, especially in forests. Although most heavy metals are extremely toxic, they have rarely been reported as a cause of forest death. However, heavy metals adversely affect seedling establishment, thus hampering the natural revegetation of contaminated areas long after any decline in atmospheric pollution levels.

Increased deposition of nitrogen started to play an important role in European forests several decades ago. Although this pollutant does not create the dramatic landscapes of some other pollutants, its effects are insidious and long-lasting. In some countries, such as the Netherlands, annual deposition of nitrogen in the late 1980s reached $200\,\mathrm{Kg\,N\,ha^{-1}}$, making eutrophication more important than the impact of 'traditional' pollutants. Increases in N deposition are also a big issue in some parts of North America, such as the San Bernardino Mountains of California.

Finally, ozone was recently identified as a possible contributor to forest damage in Europe and North America. Although unequivocal evidence for O_3-induced foliar injury on woody species under field conditions has only been found in a few places, mostly in regions with a warm and sunny climate (the Mediterranean, south California), and in alpine areas, including Sierra Nevada and the Appalachian mountain chains, ozone obviously weakens the trees leaving them vulnerable to other assaults and stresses. Overall, the quantitative risk assessment of O_3 impact on mature trees and forests is uncertain at the

European scale. Research suggests that risks exist, but these need to be validated for stand conditions.

Extent and Severity of Impacts

Local scale Extensive forest mortality around large sources of pollution has sometimes transformed forests to barren 'industrial deserts', and – despite the relatively small areas affected – has attracted considerable public and scientific attention in recent decades. The most striking examples of severe local pollution have long been associated with the Canadian smelters (Trail, Sudbury, Wawa). However, after implementation of strong emission controls in most industrial countries during the 1970s, the largest individual polluters are now located in Western Europe and Russia, with the Norilsk smelter in Northern Siberia being the largest globally: forest damage had been observed at distances over 150 km from this smelter. The largest point sources of fluorine-containing emissions are also situated in Siberia (Bratsk, Shelekhov, Irkutsk). The most extensive scientific information concerning both severe pollution impact on forest ecosystems and experimental remediation measures has been collected around the Monchegorsk smelter (Kola Peninsula, northwest Russia).

Regional scale Large areas of forest require rehabilitation as a result of the impacts of acidic deposition and other forms of pollution. The problem is particularly apparent in central Europe, with the most striking example being the 'Black Triangle,' an area along the German–Czech–Polish border. This region has been heavily affected by industrial pollution over the past 50 years, with severe consequences for the forests, landscapes, environment, and public health. Model calculations demonstrate that by 2050 severe regional problems will also occur in Southeast Asia, South Africa, Central America, and along the Atlantic coast of South America. However, almost no relevant research had been conducted in these regions, which may pose a serious problem for sustainable silviculture in the near future, when local foresters are faced with the need to mitigate pollution impacts.

Global scale In 1985, 8% of the forested areas of the world received annually $>1\,kg\ H^{+}\,ha^{-1}$ as sulfur, and it is estimated that 17% of the forested areas of the world will receive this pollution load by 2050 (**Figure 1**). Similarly, 24% of the global forest was exposed to O_3 concentrations exceeding 60 ppb in 1990, and this proportion is expected to increase to 50% of global forest by 2100. These model calculations, however, should be treated with caution, as they are based on a number of assumptions and simplifications; however, it seems more likely that more and more extensive areas will require specific management that accounts for pollution impacts. Moreover, current predictions of forest responses to global climate change do not consider important physiological changes induced by air pollutants that may amplify climatic stress.

Forestry Facing Pollution: History, Theory, and Practice

Silviculture in Polluted Areas: An Operational Field

The impact of pollutants in concentrations exceeding critical levels (or permissible loads) results in the deterioration of forest ecosystems, and they move from their original state towards industrial barrens (secondary open landscapes with $<10\%$ vegetation cover and extensive soil erosion) with the rate proportional to both the severity and the longevity of the pollution impacts.

In two-dimensional space, with canopy closure along the horizontal axis and pollution load along the vertical axis (**Figure 2**), industrial barrens occupy the upper left-hand corner (low canopy closure, intolerable pollution load) as opposed to undisturbed forests in the lower right-hand corner (high canopy closure, low pollution load). Clear-cuts occupy the space along the left vertical axis (low to zero canopy closure, low to intolerable pollution load).

The costly measures aimed at changing the landscape appearance in areas affected by very high levels of pollution are called 'regreening'; these changes do not lead to forest formation. Forest restoration can be attempted only following a decrease in pollution loads; it results in the formation of semistable forests on previously deforested contaminated (acidified) landscapes. Restored forests, as well as existing forests subjected to pollution, need to be managed differently from unpolluted forests. This practice, accounting for environmental changes caused by pollution, can be called 'silviculture in polluted areas.' The lower part of **Figure 2** represents traditional silviculture, or 'silviculture in unpolluted areas.'

As forest regeneration is very sensitive to pollution, and dense forests better sustain pollution impacts than sparse forests, silvicultural practices involving clear-cutting should be adjusted at lower pollution loads than practices based on selective logging and gap-oriented regeneration.

Silviculture in Polluted Areas: Myth or Reality?

The practical measures applied in some of polluted forests are still too intuitive to be called 'silviculture';

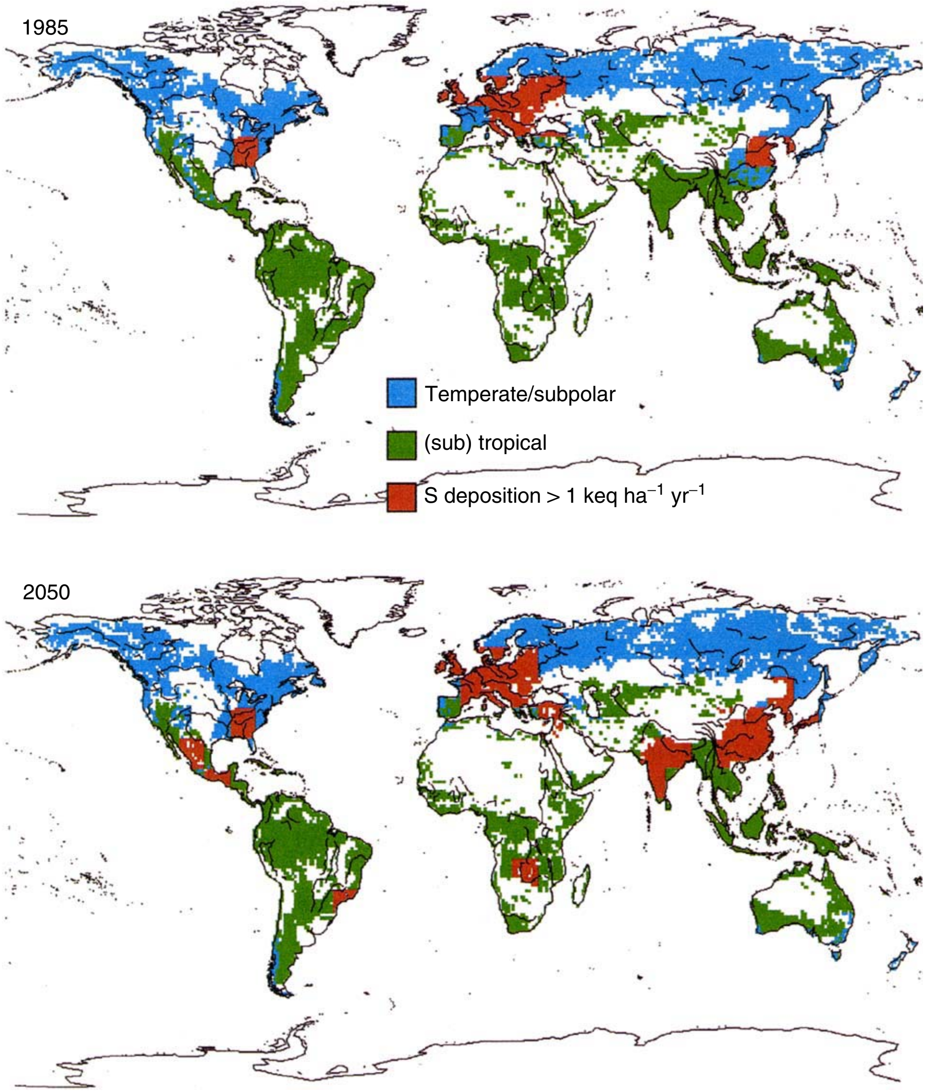

Figure 1 The global distribution of forest cover where total sulfur deposition exceeds 1 keq ha^{-1} year^{-1}, for 1985 and 2050. Reproduced with permission from Fowler D, Cape JN, Coyle M, *et al.* (1999) The global exposure of forests to air pollutants. *Water Air Soil Pollution* 116: 5–32.

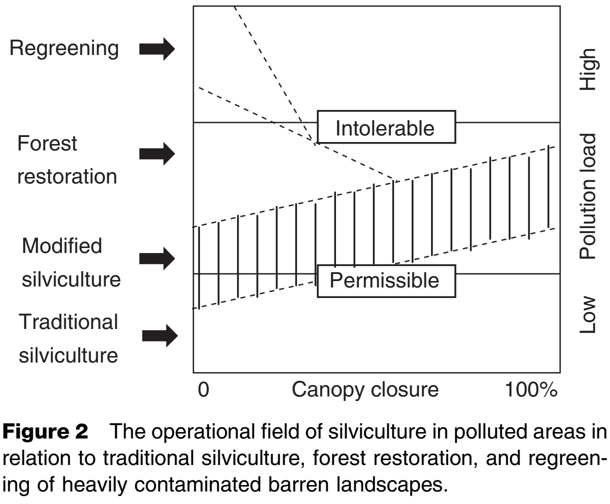

Figure 2 The operational field of silviculture in polluted areas in relation to traditional silviculture, forest restoration, and regreening of heavily contaminated barren landscapes.

optimistically, the silviculture in polluted areas, which can be seen as a specific branch of silviculture, is now *in statu nascendi*. It will need to develop for several decades at least to become 'the science of managing a polluted forest,' and even more time is necessary before 'the art of managing a polluted forest' is evident. This delay is partly related to the long time, measured in decades, that is necessary to evaluate the consequences of modified forestry practices and hence recommend (or not recommend) these practices for wide-scale application.

The International Union of Forest Research Organizations (IUFRO) Working Group on silviculture in polluted areas was established in 1951, and existed in the IUFRO structure until 1996. Activities of this group were mainly experimental, but they steadily declined in the mid-1990s due to a loss of scientific interest and (presumably) an absence of social or industrial demands for results. Not surprisingly, publications in this field are scarce and mainly restricted to reports on small-scale and usually short-term experiments. No general overview has ever been attempted, and silvicultural textbooks usually ignore the existence of polluted areas.

On a few occasions, specific silvicultural practices have not only been developed but also applied in polluted areas. These practices have resulted from the extensive and long-term efforts of scientists, and are largely based on site-specific information. Adjustment of these practices for other polluted areas would require extensive research; direct application of existing methods could easily result in adverse consequences.

What Can Be Done with a Polluted Forest?

The decision on what to do with a polluted forest naturally depends on the primary objectives of a stand at a given site. Any decisions will obviously differ between commercial forests and ecologically important forests that have a role in, for example, watershed regulation, erosion control, or nature protection.

When commercial forests started to die due to pollution impact, the first reaction of foresters was often to cut down the damaged stands in order to prevent further losses of timber. This practice was widely applied in central Europe until at least the mid-1970s, when it became obvious that the cost of harvested timber was minor in relation to the costs of rehabilitation measures required after clear-cutting. Despite this knowledge, some local regulations (such as in Russia) still require the immediate felling of pollution-damaged forest in order to make use of the timber, regardless of what happens after the clearcutting. This emphasis on short-term economic values of the forest can be highly detrimental to longer-term values, as illustrated by the difficulties in reforesting areas such as the Ore Mountains of the Czech Republic.

The polluted forest never dies completely, and even the dead trees maintain some climatic and biotic stability for the contaminated habitats, in particular preventing soil erosion. The old clear-cuts under severe pollution impact can be rapidly transformed into industrial barrens, while some vegetation in the adjacent uncut areas remains alive (**Figure 3**). Therefore stand integrity should be maintained as long as possible, allowing some time for the development of pollution control technologies and the application of rehabilitation strategies.

It might sometimes be possible to plan different forms of timber production for different levels of pollution, but in practice this has been done only exceptionally. If a pollution impact had not been expected when a forest was established, or no preventive measures had been taken despite an obvious danger of pollution impact, the forestry practices are best modified when the process of forest degradation is at its initial stages. Whenever possible, the modified management strategy should allow an optimal balance between timber production and long-term sustainability of forest ecosystems. In some countries, modification of silvicultural practice in polluted areas is obligatory, but in most cases the

Figure 3 The former Scots pine forest 1.5 km north of the nickel–copper smelter at Nikel, Russia. Pictures are taken from the same position: uncut area (left) and former clear-cutting (right). Photographs by M. Kozlov.

recommendations developed by scientists are implemented only rarely, either because of the high cost of the suggested measures or through ignorance or negligence. In many areas, there is a recognition that severely polluted forests should not be used for timber production, especially in the ecosystems that have been badly damaged. Instead, the emphasis is on regaining ecosystem stability and integrity, and preventing any further deterioration of the forest. This is the approach often adopted in North America, with the reforestation of slopes around the Trail smelter in British Columbia, Canada, being an example.

Suggested Silvicultural Measures

Maintenance of Existing Forests

General strategy As the visible symptoms of forest damage appear long after ecosystem stability has become affected, and after a long period of invisible or latent damage, emergency measures are needed to help declining stands. Regular restorative measures, forming the basis of silviculture in polluted areas, should be preventive, aimed at an improvement of the ecological stability of stands in such a way that they will better resist future pollution impacts. The maintenance of forests in polluted areas requires more intensive management than in unpolluted areas, involving 'soft' techniques and highly skilled manual labor.

The health of forests depends not only on pollutant toxicity or soil nutritional quality but also on a number of other environmental factors, including climate, water supply, stand density and composition, weeds, pests, and pathogens. Therefore, the direct mitigation of pollution effects is only one of several options; any technically possible and economically feasible measure to improve forest growth could be used to maintain and improve the stability of forests suffering from pollution.

This article describes restorative measures that are likely to prevent or at least slow down forest deterioration in polluted areas. For commercial forests it is also important to promote the vigor of stands as well as to attempt to produce larger trees in a shorter time, as the stands may need to be cut prematurely. Shortening the rotation time is recommended so that trees are cut before they start to die from pollution, and also to minimize soil acidification, which increases with stand age; the latter is especially important for stands of Norway spruce (*Picea abies*). In the most polluted temperate forests, rotation times may be reduced by 20–40 years, and in moderately polluted forests by 10–20 years; forests subjected to low pollution load can be cut at the same interval as unpolluted forests. Large-scale curative measure should only be applied if they are likely to mitigate the expected adverse consequences of pollution impact for at least 20 years.

Stand integrity management The maintenance of continuous canopy (closure $>80\%$) is especially important in polluted boreal forests, because it not only maintains a favorable microclimate near the ground but also provides some shelter for individual trees. Intentional or accidental increases in crown exposure of healthy trees often results in severe crown damage. In nitrogen-polluted forests, any disturbance of stand structure may have even more dramatic consequences, because it leads to nitrate mobilization, implying high risks of water contamination. Disturbances caused by silvicultural management should therefore be minimized, and a gap-oriented natural regeneration is preferable to clear-cuts.

Silvicultural systems based on the maintenance of diverse forests (both in terms of species composition and distribution of age classes) often need almost no adjustment when pollution increases. The continuous cover method prescribes the removal of individual trees and tree groups weakened or damaged by pollution, thereby maintaining integrity of the stand. This approach is ecologically sound, although in the long term it can result in the conversion of a predominantly coniferous forest to one dominated by broadleaved trees, simply due to the higher sensitivity of conifers to pollution.

If cutting is considered in polluted areas, the forest should not be felled until adequate regeneration is established. This is especially true of mountain areas, where the forests have important soil and climate protective roles. Large, uninterrupted clear-cuts should be avoided; instead, a two-pass system with initial cuts of 15–30 m wide strips has been recommended as facilitating the reconstruction of damaged forests. The remaining forest strips can be harvested in a second pass after 7–10 years, when young forest has established in the cleared strips.

Liming No other silvicultural method is so debatable as the liming of polluted forests. Its principle is based on the idea that soil acidification due to the uptake of weak acids not only results in modification of nutrient availability but may cause toxic damage of fine roots of trees. An alternative theory attributes some forms of forest decline primarily to the leaching of magnesium and calcium directly from needles, giving less importance to nutrient deficiency in soil.

The main objective of older liming trials and practices was to enhance the mobilization of nutritional elements in acidic forest soils and thus increase stand productivity. However, the majority of German liming trials indicate either insignificant or no growth increase. In both Finland and Sweden, liming of Norway spruce and Scots pine (*Pinus sylvestris*) stands actually resulted in slight growth reductions. As expectations of increased tree growth were not met, and important questions about the ecological side effects of liming arose, widespread liming was discontinued in the mid-1970s. However, with the appearance of symptoms of magnesium deficiency in many forests, liming was reconsidered as a means of stabilizing stands affected by acidic deposition. Over the past two decades, dolomite lime or easily soluble neutral salts such as magnesium sulfate have been applied to many forests in central and northern Europe, the United Kingdom and the USA.

Diagnostic liming trials conducted in Germany suggest that Mg-containing lime improves the Mg status of soils, although the effect is considerably slower compared with rapidly soluble Mg fertilizers. Some of the trials conducted in the Bohemian Mountains have demonstrated a positive effect of Mg-containing lime on the growth of Norway spruce. More recently, the application of granulated magnesium-rich limestone to Scots pine stands growing on soils heavily contaminated with Ni and Cu in southwest Finland enhanced both the aboveground volume increment and the fine root production. However, the stimulation of fine root growth in the uppermost soil layers may not always be beneficial to the stand as it increases the risk of damage by drought, frost, and windthrow.

Fertilization Fertilization has long been used in forestry both to improve forest health and to enhance the productivity of stands, including forests suffering from excesses of sulfur dioxide and fluorine. As many forest ecosystems developed under conditions in which nitrogen supply is the limiting factor for tree growth, N-containing mineral fertilizers were widely applied between 1950 and the 1970s, also to aid the recovery of degraded forests.

A change has occurred in recent decades, as N inputs in polluted areas now exceed the demand of some forest ecosystems. As a result, elements such as Mg have become limiting factors for tree growth on acidic substrates. In such circumstances, application of rapidly soluble mineral NPK fertilizers in acidified stands, even those with a high soil Mg content, induced Mg deficiencies and led to nutritional imbalances in Norway spruce, as well as to NO_3^- contamination of seepage water. Conversely, an organic slow-release fertilizer amended with magnesite-derived fertilizers led to balanced nutrition and a fast recovery of tree health.

Following the widespread appearance of Mg deficiency in central Europe in the 1980s, a large number of diagnostic Mg fertilizer trials were established. These trials demonstrated that Mg deficiency in Norway spruce, silver fir (*Abies alba*), Scots pine, Douglas-fir (*Pseudotsuga menziesii*), and beech (*Fagus sylvatica*) could be corrected through the application of soluble Mg fertilizers. Although nearly any source of Mg is able to improve the nutrition of trees, in some cases an improvement in stand vitality and growth was only recorded following the application of dolomite lime or magnesite; for example, the fertilization of forests on acidified soils was particularly efficient when the supply of nutrients was combined with pH stabilization measures. Site- and stand-specific K and Mg fertilization led to the successful recovery of affected deciduous and coniferous stands of all ages (**Figure 4**) and resulted in a long-lasting improvement in soil nutritional status, aboveground biomass production and fine root vitality.

Figure 4 Scots pine in a heavily polluted site, 10 km south of Monchegorsk smelter, 3 years after application of dolomite and NPK fertilizer. Note the condition of control trees in the background. Photograph courtesy of N. Lukina.

Removal of excess nutrients In northern boreal forests, growing on infertile soils, increases in nitrogen deposition have increased forest growth. This effect may appear beneficial for commercial forests in a short-term perspective, but it can be damaging for ecologically important forests, mainly due to changes in species composition and general loss of biodiversity. Moreover, from a long-term perspective the increased N availability may lead to the economically undesirable replacement of coniferous stands by broadleaved forests.

Reduction of the accumulated nutrients can be achieved by removal of the litter and humus layer, usually by mechanical sod-cutting; the experimental removal of litter in oak forests was once carried out by a powerful litter-blower. Grass mowing with subsequent removal, intensive grazing, and prescribed burning have also been suggested, although such techniques have rarely been applied, even at the experimental scale. Mechanical removal of litter and humus should be combined with intensive thinning, which reduces the litter production and increases the decomposition rate by changing the microclimate near the forest floor. As a palliative, measures enhancing the medium-term storage capacity of forest ecosystems for nitrogen should be applied before the nitrogen deposition levels are reduced, and nitrogen-releasing disturbances should be strongly avoided.

Protection against co-occurring stressors Forests damaged by pollution may be subjected to increased attacks of pests and pathogens, implying a need for careful monitoring and possibly for the application of protective measures at lower levels of infestations than recommended for unpolluted forests. Moreover, silvicultural measures, especially the application of N-containing fertilizers, may enhance forest damage by some herbivores.

Regeneration of Polluted Forests

General strategy The regeneration procedure that is adopted will obviously depend on the scale of disturbance and the site conditions, primarily microclimate, soil toxicity, and soil nutritional quality. If neighboring stands ameliorate the microclimate sufficiently, target forest stands with the original or an adjusted species composition can be established directly. On large clear-cuts, where the forest microclimate has been severely disrupted, substitute forest stands should first be established. This may be with a nurse crop of trees that will not necessarily be a component of the final forest, mainly due to change in species composition and general loss of biodiversity. For example, in the Ore Mountains, rowan (*Sorbus aucuparia*) has been used as a nurse crop for beech, enabling the beech seedlings to become established.

In the most severely affected areas, where soil toxicity inhibits the growth of seedlings, soil detoxification by liming should be undertaken, followed by the establishment of a herbaceous grass cover before trees and shrubs can be successfully established. Monospecific stands should be avoided, as these are unstable.

Site preparation Soil ploughing after clear-cutting is a common forestry practice, which has positive effects on the first phases of forest regeneration. In the Upper Silesian Industrial Region, full tillage of the sandy soil promoted better growth of nearly all tree species in their juvenile period than other methods of soil preparation (plowing or disk cultivation). Full tillage decreased soil acidity, reduced metal contents, enhanced microbiological activity, and decreased infections of young trees by root-rot fungi (*Heterobasidion annosum*). However, plowing also decreased mycorrhyzal infestation of Scots pine roots and the soil content of N, K, and Mg, requiring compensatory measures.

During the reforestation of clear-cuts exposed to acidic deposition, diagnostic fertilization and liming were applied in the same way as for the revitalization of damaged stands in Germany and the Czech Republic. Current recommendations are that liming be conducted at least twice, before the mechanical preparation of soils and after planting of seedlings. Fertilization should be restricted to planting holes or planting rows so as to minimize competition from weeds. Herbicide application may enhance seedling establishment in habitats covered by grasses (*Calamagrostis villosa* or *Agropyron repens*) but others recommend that herbicides be avoided during site preparation in polluted regions. Bulldozing of areas covered by *C. villosa*, the grass species that makes the replanting of forest trees extremely difficult or even impossible, promoted the establishment of pioneer trees and therefore accelerated the natural succession leading to the establishment of a full forest cover.

Selection of tree species In some cases, forest stands that are unable to fulfil their production, protection, or recreation functions as a result of recent or expected damage by pollution should be gradually converted. In particular, dense stands of Norway spruce trap more pollutants than broadleaved forests, and therefore a change to beech stands has a potential to reduce the impact of further deposition on forest soil to about half the value in spruce stands. Conversion may also be unintentional, resulting from subjective (partially economic) reasons, when trees requiring greater cultivation skills and continuous care, such as beech and silver fir (*Abies alba*), are replaced by less demanding tree species, primarily birches (*Betula pendula* Roth and *B. pubescens* Ehrh.) and mountain ash (*Sorbus aucuparia* L.), which simply occupy the clear-cuts when recultivation measures are insufficient or neglected. After 10–20 years, these substitute forests can be gradually converted by planting the seedlings of target species.

Substitute tree species should assure the environmental and, to a certain extent, also the production functions of forest ecosystems. The choice of tree species for the conversion depends primarily on the site conditions, but it is always advisable to allow the development of a forest with a tree composition typical for the region, and seed material should preferably represent a local ecotype.

Selection of resistant genotypes Conspecific plant individuals differ greatly in their sensitivities to both pollutant toxicity and the impact of co-occurring stressors. Some individuals of generally sensitive species, such as Scots pine and Norway spruce, can sustain extreme pollution loads for decades after their neighbors have been killed by pollution. Selection for pollution resistance has been demonstrated for trembling aspen (*Populus tremuloides*), birches, and willows, and several researchers have recommended the planting of the progenies of the resistant individuals in polluted areas. However, it seems that this recommendation had never been applied, nor have recommendations arising from several provenance experiments that demonstrated different pollution tolerances amongst geographical strains.

In view of the co-occurrence of numerous stressors in polluted areas, as well as the long production time of trees, it seems inadvisable to select genotypes on the basis of their resistance to a single stressor, even if this stressor is currently believed to be the most important. Sufficient genetic variation should therefore be maintained in the cultivated populations to allow for the distribution of risks.

Planting, tending, and thinning The reforestation measures to be adopted in clearcuts subjected to acidic deposition do not differ from those applied under normal forestry practices. Direct sowing is mostly used for birches (*Betula pendula* and *B. pubescens*) and *rowan*, provided that conditions permit. When using the seedlings, container-grown plants (normally with a bigger root-ball volume) are preferable to bare-root stock because they increase the chances of successful establishment. The best-growing seedlings and saplings should be selected with the assumption that their vigor will potentially assure relatively higher performance in contaminated habitats.

Stand density is linked to tree health via competition with neighbors, resistance to wind and snow, and the ability to regulate microclimate. It has long been suggested that young stands in areas affected by acidic deposition should be established with a low density, which would allow plants to develop large symmetrical crowns. However, recent recommendations have been to the effect that the number of seedlings planted in the polluted areas should be 15–20% higher than in unpolluted areas. This compensates for higher mortality and also offers more opportunities for selecting the trees with the best crown vitality during precommercial and commercial thinning.

Silvicultural measures in young stands growing in polluted areas should begin earlier and be more frequent but less intensive than in unpolluted areas. From the earliest stages of the stand, i.e., from the thicket stage onwards, care should be taken to ensure the optimal development of crowns but at the same time avoid disruption of the canopy. An additional problem is stand resistance to wind breakage, which is generally lowered by pollution; it can be increased by manipulation of the crown cover, specifically encouraging the growth of long crowns.

Forest Restoration

The full restoration of forests differs from the restoration of other types of vegetation, mostly in relation to the time required to complete the process, and there is no known example of a successfully completed restoration (*sensu stricto*) of the forest communities on lands contaminated by industrial pollution. The land reclamation program in Sudbury, Canada, the only practical example of a large-scale restoration of an area impacted by an extreme pollution conditions, has only been in operation for a relatively short period compared to the time required for successional processes to form forest ecosystems. However, this example (**Figure 5**) shows that it is possible to convert heavily contaminated barrens into forests over a period of about two decades, assuming that there is the social demand for such a conversion and sufficient financial support is granted.

Forest restoration in Sudbury started with liming and seeding of barren land, followed by planting tree seedlings, mostly of species that were dominant in the previous forest. The original motivation was to improve Sudbury's image as a treeless wasteland, but gradually the revegetation philosophy became increasingly based on landscape and ecosystem. New perspectives include assistance in the establishment

Figure 5 Revegetation of the Camberian Heights site in Sudbury, Canada. (a) 29 July 1981; (b) 20 May 1982, following liming and grass sowing; (c) 6 July 1988; (d) 28 April 2003. (a, b, c – reproduced with permission from Winterhalder K (1995) Natural recovery of vascular plant communities on the industrial barrens of the Sudbury area. In: Gunn J (ed.) *Environmental Restoration and Recovery of an Industrial Region*, pp. 93–102. New York: Springer-Verlag. d, photograph courtesy of K Winterhalder.)

of an appropriate understory in the re-established pine 'forests.'

When the Sudbury Environmental Enhancement program started in 1969, it was specifically stated that the intention was not to create a commercial forest. The main motive was aesthetic, which means that there was no plan to harvest these forests in the future, although they are not formally protected like a nature reserve.

Conclusion

As forests cover some 30% of the earth's land surface, account for some 70% of terrestrial net primary production, and are being bartered for carbon mitigation, it is critically important that we continue to develop the strategies aimed at sustainable forestry in the industrialized world. Forests were disturbed or destroyed by pollution for a quite long time, as an inevitable part of civilization. We inherit a large area from the past and the destruction continues to the present, in spite of efficient pollution control and advanced mitigation measures.

The key to the sustainable management of forests under pollution stress is the knowledge of the biological processes that are affected by pollution, as well as on basic forest ecology, and substantial progress in obtaining relevant knowledge was achieved during recent decades. However, the knowledge that a certain input may stress certain type of forests is of little use unless those forests can be identified reliably and treated accordingly. Identification of forest damage is progressing better than the mechanisms for making management decisions, most of which are currently based on empirical field trial results. More generally, silviculture in polluted areas, seen as a specific branch of silviculture, is still in the process of development. However, in spite of the limited theoretical framework, silviculture in polluted areas has already produced valuable practical results, showing that both forest restoration and sustainable forest management in polluted areas are possible – although costly – as they usually require highly skilled manual labor and intensive application of lime and fertilizers.

See also: **Afforestation**: Stand Establishment, Treatment and Promotion - European Experience. **Environment**: Environmental Impacts; Impacts of Air Pollution on Forest Ecosystems. **Genetics and Genetic Resources**: Genetic Aspects of Air Pollution and Climate Change. **Silviculture**: Forest Rehabilitation.

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SOCIAL AND COLLABORATIVE FORESTRY

Contents

Forest Functions

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Introduction

The term 'forest functions' is often used to describe a set of functional relations between forest and humans. Despite its descriptive and pragmatic advantages, the term offers some analytical shortcomings: these can be overcome, if the functional relations are separated into two classes: the effects of forests and the specific performance of forestry. This can offer a sound analytical base for forest policy and forest management.

Functions

A Descriptive and Pragmatic Concept

Trees and forests have always provided goods and services for individual or societal use. The term 'function' refers to the relation between forest and humans that is constituted by the process of offering and obtaining goods and services. Similar to the way in which the term is used in mathematics, forestry tries to encapsulate human–forest relationships by means of the term 'forest function.' It is not known when the term 'function' was used first in forestry but in 1953 Viktor Dieterich stated in his forest policy textbook a system of functional relations and described a so-called theory of forest functions (*Funktionentheorie*). Since the second half of the