Long-term effects of a forest amelioration experiment

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Abstract: We evaluated the soil chemistry, plant species composition, and forest growth rate on a site where a site amelioration project had been realized 30 years earlier. The initial goal of the project was the improvement of a site that had been degraded by litter raking. We wanted to know which amelioration method produced a sustainable result and how different treatments might be rated by today's standards. Treatments included fertilization, underplanting with N-fixing plants, and a combination of both. The amelioration was combined with stand conversion by means of natural regeneration and spruce underplanting. In all treatments, a spruce-dominated stand replaced the secondary pine stand. The biomass of the formerly recalcitrant forest floor (143 $Mg \cdot ha^{-1}$) was reduced by 30 to 50% in treated plots, thereby reducing the total soil pool of C, N, and exchangeable cations. The mineral soil of treated plots was enriched with N, Ca, and Mg. An increase in pH was restricted to the forest floor. The C pool of treated soils was much smaller than that of the control plots. However, the loss from the soil was at least partly offset by increased growth rates of the aboveground tree biomass. In treated plots, the stem volume was more than twice that of control plots (38.3 m^3). Soil chemical data and the composition of the ground vegetation suggest that even the control plots have changed compared with pre-treatment conditions. Comparison of different blocks of the experiment suggests that the exclusion of roe deer (*Capreolus capreolus*) by fencing was the most significant treatment required for successful stand conversion. Prior to fencing, deer browsing inhibited the establishment of a new stand.

Résumé : La chimie du sol, la composition en espèces végétales et le taux de croissance de la forêt ont été évalués dans un site qui avait subi des traitements d'amélioration de la station 30 ans auparavant. Initialement, le projet avait pour but d'améliorer une station dégradée à cause du râtelage de la litière. On voulait savoir quelle méthode avait produit un résultat durable et si les divers traitements étaient toujours utiles selon les normes en vigueur aujourd'hui. Les traitements suivants avaient été appliqués : fertilisation, plantation en sous-étage avec des plantes fixatrices d'azote et une combinaison de ces deux traitements. Les travaux d'amélioration avaient été combinés à une conversion du peuplement au moyen de la régénération naturelle et de la plantation d'épicéas en sous-étage. Tous les traitements ont abouti au remplacement des peuplements secondaires préexistants de pin par une forêt dominée par l'épicéa. La biomasse de la couche organique récalcitrante qui était en place (143 $Mg \cdot ha^{-1}$) a été réduite de 30 à 50% dans les parcelles traitées entraînant une réduction des réserves totales de carbone, d'azote et de cations échangeables. Le sol minéral s'est enrichi d'azote, de calcium et de magnésium dans les parcelles traitées. L'augmentation du pH était limitée à la couche organique. La réserve de carbone des sols traités était beaucoup plus faible que celle des parcelles témoins. Cependant, les pertes dans le sol étaient compensées au moins en partie par un plus fort taux de croissance de la biomasse épigée dans les parcelles traitées. Dans les parcelles traitées, le volume du tronc avait plus que doublé comparativement aux parcelles témoins (38,3 m^3). Les données sur la chimie du sol et la composition du couvert végétal indiquent que les parcelles témoins ont également changé comparativement aux conditions présentes avant les traitements. La comparaison des différents blocs de l'essai montre que le traitement le plus important pour réussir la conversion des peuplements est l'exclusion des chevreuils (*Capreolus capreolus*) au moyen de clôtures. Avant l'utilisation de clôtures, le broutage par les chevreuils empêchait l'établissement de nouveaux peuplements.

[Traduit par la Rédaction]

Introduction

For centuries the management of forests in the Alps was strongly interwoven with agriculture, and forestry played only a supporting role to meet the needs of agriculture. In medieval times, mineral nitrogen (N) fertilizer was not yet available, and it was difficult to meet the food demands of the rapidly growing human population. Apparently, the land was used to its carrying capacity; malnutrition and famine were frequent. The organic matter of the forest floor and the leaf litter were a desperately needed source of protein. Forest floor material was raked, and leaves from lower branches were pollarded in a defined rotation to provide bedding and fodder for livestock. Forests were also used as pastures for livestock, and gaps in the forest were often used as fields, comparable to today's agroforestry systems. Grazing cattle produced the much needed organic fertilizer that was used in agricultural fields to compensate for nutrient losses from crop removal. From 4 to 6 ha of forest were necessary to meet the biomass demand of an average farmer (Johann 1968). Peasants in the Alps were entitled to litter raking and to maintain forest pastures. These formal rights, called "servitutes", applied not only to their own land but also to forests owned by the local community or noblemen. Litter was raked on almost

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every accessible forest.

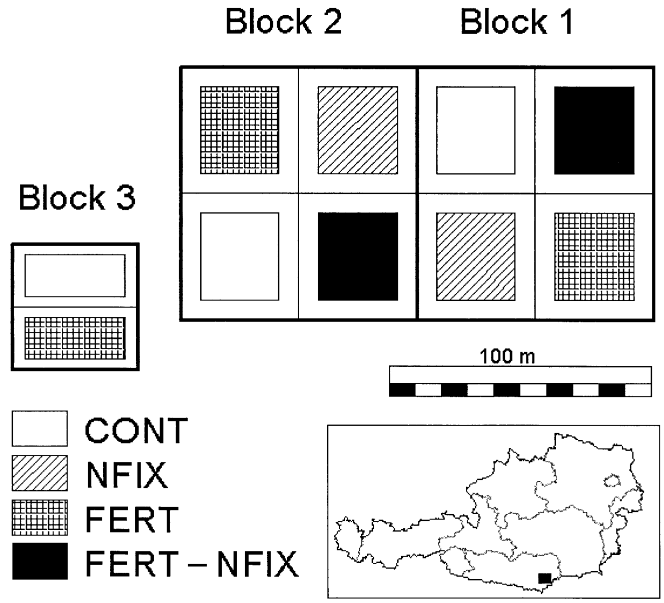
Documents from the 19th century in monasteries of the Austrian province of Carinthia describe how land was donated "ad emeliorandum", which meant that forest land was to be transformed to agricultural land. The original forest was an oak forest, as shown by the semantic roots of the area's name "Dobrowa". "Dob" is a slavic word for *Quercus robur* L. (English oak), and "dobje" means oak forest, later germanized to "Dobrowa". Oak forests were usually used as pastures, where pigs lived on acorns. The forest stand structure became increasingly open, and the conversion to agricultural land was easy. The nutrient export out of the remaining forests was substantial, and forests gradually changed from deciduous and mixed-deciduous forests to secondary pine forests. Scots pine (*Pinus sylvestris* L.), as an early successional tree, is well adapted to nutrient-poor soils and regenerated well in the widely spaced forest stands. Records from the 16th century already mentioned the occurrence of pine forests, suggesting that the site degradation was already advanced at this stage.

There are only a few quantitative estimates for the nutrient transfer from forests to agricultural land. For a particular region in the Alps, the annual N export was approximately 25 kg N·ha^{-1}, together with a loss of acid neutralizing capacity (soil acidification) of 2 kmol base cations·ha^{-1} (Glatzel 1999). Forest growth rates declined by up to 50%, but this loss was considered inevitable, and certainly justified, given the need to increase the yield of agricultural crops. The endpoint of site degradation in the Alps and their foothills were open pine forests with a dense understory of dwarf shrubs, even though the natural forest community would have been a deciduous forest or a mixture of conifers and broadleaf trees. In other parts of Europe, e.g., Northern Germany and Great Britain, reforestation efforts were often unsuccessful or economically unfeasible, and large heathlands developed. Only by the end of the 19th century, when several forestry faculties were established in Europe, did foresters investigate the adverse impacts of litter raking on forest productivity and set up field experiments where different options for ameliorative treatments of forests were tested.

In the mid-1900s, the production of small pine poles offered good business opportunities, but the actual growth rate lagged behind what might be expected under the given climatic and geological conditions. In the 1960s, an ambitious amelioration program was pursued to improve sites. Mature pine stands were fertilized and underplanted with Norway spruce (*Picea abies* (L.) Karst.) and thereafter gradually replaced. Government subsidies covered fertilizer costs. The primary goal was to maximize wood yield. Spruce stands were established if possible, whereas species of the potential natural forest community were often ignored. In the experiment described here, Norway spruce was favored because it copes well with frosty spring temperatures. Soil fertility was considered too low for commercially valuable deciduous tree species. Undisturbed forest stands that would have been suitable to propose hypotheses explaining the distribution of the potential natural vegetation were not available in the vicinity. Hence, no convincing indication for the establishment of a mixed-deciduous stand was given.

Here we present the results of a case study, in which the underplanting of spruce in a mature secondary pine forest was supported by (1) fertilizer applications, (2) planting and seeding of N-fixing black alder (*Alnus glutinosa* (L.) Gaertn.) and lupine (*Lupinus polyphyllus* Lindl.), and (3) a combination of both strategies. These methods have proven successful in earlier experiments (Fiedler et al. 1973). In this paper we focus on soil chemical properties, herbaceous vegetation status, tree biomass, and nutrient content in needles, almost 30 years after treatments.

Fig. 1. Location of experimental plots at the Dobrowa site. The plot size was 1000 m^2 and plots were separated by a 15 m wide buffer strip.



Methods

Study site and objectives

The study site is located in the province of Carinthia, Austria (46°07′N, 14°39′E). The climate is characterized by frequent temperature inversions: the average temperature in January is −4.6°C, the average of all months is 6.2°C. Precipitation averages about 1000 mm·year^{-1} (Kilian et al. 1994). The terrain is flat, the altitude is 460 m. The parent material consists of coarse gravelly moraine material, which is weathered to a depth of more than 50 cm. Soils are Dystric Cambisols with a rather biologically inactive mor humus. Below 20 cm soil depth, roots are sparse and profile morphology shows little differentiation. In 1967, blocks 1 and 2 of the experiment were placed in a 60-year-old pine stand with a low site index. Stem density was 800 individuals/ha. Dominant trees were 17 m tall and had a mean diameter at breast height (DBH) of 16 cm. An adjacent 45-year-old pine stand was included in the experiment as block 3. This stand had a stem density of 1700 individuals/ha; the dominant trees were 12.5 m tall with DBHs of less than 12 cm. The arrangement of plots is shown in Fig. 1. The ground cover vegetation at all plots was dominated by *Calluna vulgaris* (L.) Hull and *Vaccinium myrtillus* L.

Treatments and development of stands

The fertilization treatment (FERT) included the application of 550 kg N, 30 kg P, 160 kg K, 1250 kg Ca, and 40 kg Mg per hectare, from 460 kg Thomas slag, 690 kg patent kali (sulpomag), 1150 kg limestone, and 2500 kg nitramoncal per hectare. Thomas slag is a byproduct of steel production containing limestone and impurities, which release nutrients. Patent kali consists of readily soluble K_2SO_4 and $MgSO_4$. Nitramoncal is a mixture of NH_4NO_3 and finely ground limestone. This combination of fertilizers had been useful in earlier experiments (Baule and Fricker 1967). The limestone, Thomas slag, and patent kali were applied in April 1967. In May 1967 and April 1969, 1250 kg of nitramoncal were applied. In N-fixing (NFIX) plots, 2500 black alders/ha were underplanted and 2.9 $kg \cdot ha^{-1}$ of lupine seeds were sown in April 1967. The underplanting of N-fixing plants has a long tradition in the restoration of forests degraded by litter removal (Fiedler et al. 1973). It was expected that plant growth and microbial activity at the site were primarily N limited and hypothesized that alder and lupine might fix significant amounts of N, improve tree nutrition, and increase the growth rate. The third treatment (FERT–NFIX) was a combination of both fertilizer applications and N-fixing plants. The stand density at the control plots (CONT) was similar to that of the other plots in the respective blocks, but no ameliorative treatment was done.

Stand treatment also started in 1967. The pine stands of blocks 1 and 2 were moderately thinned to approximately 760 individuals/ha, and the natural disturbances during stand development were monitored. Snow breakage affected mostly block 3 and led to an uneven distribution of pines until 1978. In 1976, the number of pines in blocks 1 and 2 was reduced to 250 individuals/ha to accomplish the conversion of the mature pine stand to the regenerating mixed stand. The alder was cut in 1976, 1981, and 1986 and resprouted from the stumps. Among the pines, alders had reached a height of approximately 2 m. The density of the pine stands was reduced to 40 individuals/ha in 1986 in blocks 1 and 2. The remaining pines served as holdover trees. The stems of thinned pines were removed, but the branches and needles of pine and the entire alder biomass were left in the stand. Natural regeneration of spruce, beech, and oak was monitored from the beginning of the experiment. Severe browsing by roe deer (*Capreolus capreolus*) hampered the development of the young trees until a fence was erected around blocks 1 and 2 in 1976. In the following year, spruce was underplanted in the gaps of all plots in blocks 1 and 2. The trees were planted along a 2×2 m grid and developed vigorously. In subsequent years, weeds (*Rubus* spp. and *Pteridium aquilinum* (L.) Kuhn) were removed (Johann 1989). Block 3 was never fenced, and no underplanting was done.

Soil analysis

Soil samples were collected in summer 1993. Four soil profiles were sampled from each plot. Sampling units were the forest floor material and depths 0–5, 5–10, and 10–20 cm. Pedogenetic soil horizons were ignored in this sampling protocol. We analyzed pH (0.01 M $CaCl_2$), exchangeable cations (unbuffered 0.1 M $BaCl_2$ extract), acid extractable cations and P (HNO_3–$HClO_4$ digest), and total contents of C and N (autoanalyzer). The methods and the laboratory equipment are described in Karrer and Englisch (1998). Soil bulk density was estimated from the C content according to Kay (1998).

Biomass assessment

Height and diameter (DBH) of all trees were routinely measured every 5 years. Needle samples were collected from five dominant trees in each plot of blocks 1 and 2 in 1995. The samples were split into the following classes: current-year, 2-year-old, and older needles. Chemical analysis included total concentration of N, P, K, Ca, and Mg. Total aboveground stem volume was estimated from height, and DBH was estimated with an allometric function (Pollanschütz 1974).

Vegetation survey

The vegetation was surveyed at every plot in 1993 and 1994 according to the relevé method of Braun-Blanquet (1964). Species abundance was assessed using the ordinal scale of Westhoff and van der Maarel (1978). Our analysis includes vegetation data from five stands in the vicinity of the experimental stand. These data were collected between 1969 and 1971 and serve as a reference for the pre-treatment situation at our site.

Statistical data evaluation

Treatment effects were analyzed by means of analysis of variance (ANOVA) and multiple comparisons of means. The experimental design for soil chemistry was unbalanced because treatments NFIX and FERT–NFIX were not performed in block 3. A comparison between treatments was done by a general linear model (PROC GLM) and the Waller–Duncan test (α = 5%). For needle data, ANOVA and the Student–Newman–Keuls (SNK) test for comparison of means were used (SAS Institute Inc. 1992). A detrended correspondence analysis was carried out for the vegetation data with the program CANOCO version 3.12 (ter Braak 1991). The original species abundance data were transformed into the nine-steps scale of van der Maarel (1979).

Results

The amelioration had a strong effect on the forest floor material and on the chemical soil properties. Primarily in the control plots, the organic layer was a thick mor, which was distinctly separated from the mineral soil. Five years after the start of the experiment, the mass of the humus layer in the FERT and FERT–NFIX plots had been greatly reduced, but it remained unchanged in the NFIX and CONT plots. In 1993, the mass of the humus layer was significantly higher in the control plots than in the treated plots: CONT, 143 ± 50 $Mg \cdot ha^{-1}$ (mean $\pm$ SE); FERT, 54 ± 5 $Mg \cdot ha^{-1}$; NFIX, 64 ± 11 $Mg \cdot ha^{-1}$; FERT–NFIX, 97 ± 19 $Mg \cdot ha^{-1}$. Differences among FERT, NFIX, and FERT–NFIX were not statistically significant. Only the CONT plots showed an abrupt boundary between the forest floor and the mineral soil.

The strongest effect on soil chemistry was achieved by the FERT–NFIX treatment. Only the FERT treatment significantly increased the pH of the forest floor, but no treatment had an effect on the pH of the mineral soil. The C content of the soil, the cation exchange capacity (not shown), and total contents of P and K, and exchangeable K and Al did not differ significantly among treatments. Nitrogen content in the 0–5 cm layer varied significantly among the treatments, with NFIX and FERT–NFIX > CONT, and FERT in an intermediate position. The C/N ratio in the forest floor and in the 0–5 cm layer was

Table 1. Chemical characteristics of the forest floor (O horizon) and the mineral soil.

Layer	CONT	NFIX	FERT	FERT–NFIX
pH ($CaCl_2$)				
O horizon	3.76 (0.38)*b*	3.96 (0.50)*ab*	4.35 (0.45)*a*	4.22 (0.37)*ab*
0–5 cm	3.66 (0.14)*a*	3.67 (0.09)*a*	3.84 (0.30)*a*	3.78 (0.12)*a*
5–10 cm	4.03 (0.08)*a*	3.98 (0.08)*a*	3.97 (0.31)*a*	4.01 (0.07)*a*
10–20 cm	4.14 (0.04)*ab*	4.11 (0.07)*b*	4.19 (0.07)*a*	4.08 (0.08)*b*
C ($mg \cdot g^{-1}$)				
O horizon	419 (54)*a*	360 (55.7)*a*	402 (44.5)*a*	347 (60.1)*a*
0–5 cm	56.5 (22.3)*a*	48.3 (9.1)*a*	44.8 (8.7)*a*	47.8 (6.4)*a*
5–10 cm	18.9 (5.3)*a*	19.9 (3.8)*a*	19.4 (3.8)*a*	22.3 (5.1)*a*
10–20 cm	9.8 (2.6)*a*	9.3 (2.1)*a*	9.6 (2.5)*a*	12.0 (2.2)*a*
N ($mg \cdot g^{-1}$)				
O horizon	12.9 (1.71)*a*	14.6 (2.06)*a*	13.8 (2.54)*a*	13.8 (1.99)*a*
0–5 cm	1.40 (0.58)*b*	1.86 (0.45)*ab*	1.54 (0.33)*ab*	1.96 (0.36)*a*
5–10 cm	0.55 (0.22)*b*	0.70 (0.15)*ab*	0.53 (0.19)*b*	0.76 (0.13)*a*
10–20 cm	0.23 (0.13)*a*	0.28 (0.15)*a*	0.20 (0.16)*a*	0.35 (0.19)*a*
C/N				
O horizon	32.8 (4.5)*a*	25.0 (5.0)*b*	30.0 (5.9)*b*	25.2 (2.9)*b*
0–5 cm	41.0 (7.0)*a*	26.5 (4.5)*b*	29.9 (7.7)*b*	24.7 (3.0)*b*
5–10 cm	38.0 (13.3)*a*	29.0 (6.2)*a*	49.0 (51.1)*a*	29.4 (6.3)*a*
10–20 cm	55.3 (30.0)*a*	44.4 (30.8)*a*	68.6 (37.1)*a*	40.6 (17.1)*a*
Exchangeable K ($mmol_c \cdot kg^{-1}$)				
0–5 cm	1.57 (0.70)*a*	1.20 (0.75)*a*	1.49 (0.51)*a*	1.33 (0.31)*a*
5–10 cm	0.64 (0.24)*a*	0.56 (0.35)*a*	0.73 (0.24)*a*	0.66 (0.30)*a*
10–20 cm	0.41 (0.08)*a*	0.28 (0.19)*b*	0.41 (0.22)*a*	0.53 (0.25)*a*
Exchangeable Ca ($mmol_c \cdot kg^{-1}$)				
0–5 cm	11.12 (8.75)*c*	13.54 (3.40)*b*	24.17 (7.56)*a*	21.98 (3.82)*a*
5–10 cm	1.83 (1.42)*c*	2.48 (1.05)*b*	7.14 (3.71)*a*	5.08 (1.01)*a*
10–20 cm	0.79 (0.46)*b*	0.53 (0.33)*b*	3.20 (2.07)*a*	1.80 (0.84)*a*
Exchangeable Mg ($mmol_c \cdot kg^{-1}$)				
0–5 cm	3.39 (1.94)*b*	4.60 (0.97)*a*	5.51 (1.84)*a*	4.88 (1.02)*a*
5–10 cm	0.88 (0.48)*c*	1.21 (0.24)*b*	1.83 (0.58)*a*	1.45 (0.48)*ab*
10–20 cm	0.46 (0.19)*b*	0.45 (0.13)*b*	1.01 (0.35)*a*	0.73 (0.22)*ab*
Exchangeable Al ($mmol_c \cdot kg^{-1}$)				
0–5 cm	50.1 (6.1)*a*	50.0 (7.2)*a*	36.7 (8.7)*a*	42.8 (6.9)*a*
5–10 cm	26.9 (6.1)*a*	30.0 (3.7)*a*	27.7 (5.5)*a*	30.1 (3.7)*a*
10–20 cm	19.2 (1.4)*a*	19.9 (3.6)*a*	18.5 (1.9)*a*	22.2 (3.9)*a*
Base saturation (%)				
0–5 cm	21.9 (2.5)*b*	25.1 (3.1)*b*	42.0 (5.1)*a*	35.8 (2.7)*a*
5–10 cm	10.1 (0.8)*b*	11.4 (1.6)*b*	24.1 (3.6)*a*	17.8 (1.3)*a*
10–20 cm	7.0 (0.6)*b*	5.2 (1.5)*b*	18.1 (2.6)*a*	10.1 (1.3)*ab*
Acid extractable P ($mg \cdot g^{-1}$)				
O horizon	1.11 (0.21)*a*	1.20 (0.16)*a*	1.22 (0.20)*a*	1.13 (0.22)*a*
0–5 cm	0.40 (0.06)*a*	0.36 (0.15)*a*	0.41 (0.06)*a*	0.40 (0.06)*a*
5–10 cm	0.39 (0.05)*a*	0.37 (0.03)*a*	0.39 (0.05)*a*	0.36 (0.04)*a*
10–20 cm	0.40 (0.04)*a*	0.39 (0.03)*a*	0.37 (0.04)*a*	0.35 (0.04)*a*
Acid extractable K ($mg \cdot g^{-1}$)				
O horizon	1.38 (0.30)*a*	1.35 (0.22)*a*	1.48 (0.26)*a*	1.35 (0.15)*a*
0–5 cm	0.78 (0.23)*a*	0.71 (0.22)*a*	0.86 (0.32)*a*	0.74 (0.27)*a*
5–10 cm	0.75 (0.24)*a*	0.78 (0.23)*a*	0.96 (0.30)*a*	0.79 (0.29)*a*
10–20 cm	1.00 (0.24)*a*	0.83 (0.10)*a*	0.86 (0.16)*a*	0.75 (0.24)*a*

Table 1. *Concluded.*

Layer	CONT	NFIX	FERT	FERT–NFIX
Acid extractable Ca (mg·g^{-1})				
O horizon	5.16 (1.66)*b*	5.74 (2.30)*ab*	8.98 (4.02)*ab*	6.94 (2.45)*a*
0–5 cm	0.52 (0.17)*a*	0.58 (0.27)*a*	0.89 (0.19)*a*	0.78 (0.13)*a*
5–10 cm	0.38 (0.13)*a*	0.46 (0.20)*a*	0.61 (0.16)*a*	0.59 (0.17)*a*
10–20 cm	0.45 (0.11)*a*	0.40 (0.23)*a*	0.53 (0.10)*a*	0.45 (0.21)*a*
Acid extractable Mg (mg·g^{-1})				
O horizon	1.79 (0.63)*b*	2.38 (0.79)*ab*	2.23 (0.50)*ab*	2.46 (0.45)*a*
0–5 cm	3.83 (0.48)*a*	3.75 (0.42)*a*	3.96 (0.64)*a*	3.84 (0.51)*a*
5–10 cm	4.46 (0.53)*a*	4.38 (0.31)*a*	4.46 (0.52)*a*	4.44 (0.52)*a*
10–20 cm	4.85 (0.45)*a*	4.58 (0.25)*a*	4.39 (0.48)*a*	4.53 (0.66)*a*

Note: Values are means with standard errors of means in parentheses, n = 8. Different letters indicate statistically significant differences among groups (Waller–Duncan test, α = 5%).

Table 2. Mean nutrient concentration of needles (n = 5; mg·g^{-1}) 30 years after the first experimental treatment in the site.

	Needle age	CONT	FERT	NFIX	FERT–NFIX
N	1	9.3*a*	13.6*b*	13.8*b*	11.8*b*
	2	9.0	11.0	11.8	10.6
	>2	7.8*a*	9.5*b*	9.6*b*	9.6*b*
P	1	1.14	1.48	1.56	1.29
	2	0.89*a*	1.11*b*	1.14*c*	1.05*c*
	>2	0.80*a*	0.86*b*	0.94*b*	0.85*b*
K	1	2.9	4.4	4.7	3.5
	2	2.1	3.4	3.6	2.4
	>2	1.9	2.8	3.0	2.0
Ca	1	3.9*a*	9.4*c*	6.4*b*	6.0*b*
	2	6.5*a*	13.1*c*	11.4*b*	10.5*b*
	>2	8.5*a*	16.5*c*	18.1*c*	13.9*b*
Mg	1	1.0*a*	1.3*b*	1.1*a*	1.2*b*
	2	1.1*a*	1.3*b*	1.1*a*	1.2*b*
	>2	0.9*a*	1.1*b*	0.9*a*	1.1*b*

Note: Different letters indicate statistically significant differences (ANOVA, SNK test).

significantly higher in CONT, whereas there was no difference among the treatments. Differences in exchangeable Ca and base saturation among the treatments were are follows: FERT and FERT–NFIX > NFIX > CONT. Total Ca and Mg in the forest floor were significantly higher in the FERT–NFIX treatment. Exchangeable Mg showed a depth trend. In the 0–5 cm layer, exchangable Mg was significantly lower in the control plots than in the treatment plots, and in the 10–20 cm layer, there was no difference between the CONT and the NFIX treatment, FERT was significantly higher, and the FERT–NFIX treatment assumed an intermediate position (Table 1).

The chemical needle analysis showed that all treatments raised the N concentration of the needles compared with the control. Positive effects on P, K, Ca, and Mg were also evident (Table 2). It is remarkable that the plants in the NFIX treatment, which depend solely on K, Ca, and Mg from the mobilized soil nutrient pool, had nutrient contents similar to plants in the FERT and FERT–NFIX treatments, which received nutrients from fertilizers.

Table 3. Total amounts of C and N and exchangeable K, Ca, and Mg in the soil.

	CONT	FERT	NFIX	FERT–NFIX
Carbon (Mg·ha^{-1})				
Forest floor	55.7	20.4	23.0	36.0
Mineral soil				
0–5 cm	20.2	17.2	19.6	20.2
5–10 cm	11.5	11.0	12.3	13.2
10–20 cm	13.6	13.1	10.1	15.9
Total	101.4	61.7	65.0	85.3
Nitrogen (kg·ha^{-1})				
Forest floor	1890	779	918	1420
Mineral soil				
0–5 cm	520	660	754	826
5–10 cm	362	356	429	459
10–20 cm	435	420	340	466
Total	3207	2215	2441	3171
Potassium (kg·ha^{-1})				
Forest floor	205	78	82	132
Mineral soil				
0–5 cm	21	21	19	21
5–10 cm	14	15	15	15
10–20 cm	21	19	19	27
Total	261	133	135	195
Calcium (kg·ha^{-1})				
Forest floor	900	515	344	680
Mineral soil				
0–5 cm	60	177	111	187
5–10 cm	16	63	30	62
10–20 cm	12	58	14	47
Total	988	813	499	976
Magnesium (kg·ha^{-1})				
Forest floor	325	131	141	228
Mineral soil				
0–5 cm	15	31	23	25
5–10 cm	6	14	9	11
10–20 cm	6	18	7	12
Total	352	194	180	276

The mean height of spruce in 1996 was 4 m in CONT plots, 10.1 m in FERT plots, 8.6 m in NFIX plots, and 9 m in FERT–NFIX plots. The height of beech, which accounted for less than 10% of trees, also varied greatly (4.2 m in CONT, 6.9 m in FERT, 5 m in NFIX, and 6.5 m in FERT–NFIX). The mean diameter of the dominant 100 trees was 18 cm in CONT, 27 cm in FERT, 21 cm in NFIX, and 23 cm in FERT–NFIX. The stem volume per hectare was 38.3 m^3 in the CONT plots, 107.8 m^3 in the FERT plots, 81.3 m^3 in the NFIX plots, and 85.6 m^3 in the FERT–NFIX plots. The FERT treatment more than doubled the stem volume as compared with the control. A nutrient budget for the soils in blocks 1 and 2 is given in Table 3. Except for Ca, the control plots contained the largest nutrient pool mainly because of the sequestration of nutrients in the forest floor. In all other treatments, the nutrient pool in the soil (forest floor, 0–20 cm) was lower. At least a part of the nutrients is retained in the aboveground biomass as a consequence of enhanced growth rates.

All treatments affected the plant species composition. The formerly dominant dwarf shrubs are still present in the control sites but rare in treated plots. In the treated plots, ferns (e.g., *Dryopteris carthusiana* (Vill.) H.P. Fuchs, *Athyrium filix-femina* (L.) Roth), some Compositae (e.g., *Mycelis muralis* (L.) Dum., *Cirsium arvense* (L.) Scop.), and mosses are newly established. *Rubus fructicosus* and *Rubus idaeus* (L.) are also present in the FERT–NFIX plots. The vegetation samples are published in Jandl et al. (2000). The initially sown *Lupinus polyphyllus* invaded all plots. Beech and oak seedlings regenerated in all plots. Fencing to keep out roe deer was sufficient for the establishment of beech, but oak establishment required site amelioration and was most successful in the FERT–NFIX plots. The successional course of the experiment was assessed by a detrended correspondence analysis. The loadings of the first two factors are given as coordinates (Fig. 2). The treatments group together. Vegetation samples from 1969 and 1971 (J4–J8 in Fig. 2) represent pre-treatment conditions. The FERT–NFIX treatment is most different from this reference, FERT lies outside the cluster of the other treatments, and NFIX lies between CONT and FERT–NFIX. The two fenced control plots (blocks 1 and 2) are distinct from the pre-treatment conditions, which is indicative of a natural succession that is accompanied by a loss of species: *Potentilla erecta* (L.) Räuschel, *Chamaecytisus supinus* (L.) Link, and *Carex pilulifera* (L.). have disappeared from the control sites. A peculiar pattern is shown in the fertilized plot of block 3 (see curved arrow in Fig. 2). This plot had been fertilized, but in contrast with the FERT treatments in blocks 1 and 2, it did not receive further treatment, such as fencing, spruce underplanting, and weed removal; therefore, no young stand was established. This fertilized but not underplanted plot is similar to pre-treatment plots. We assume that fertilization without stand conversion had initially changed the herbaceous vegetation in a similar manner as the other fertilized plots. The abundance of *Calluna vulgaris* was at first reduced, but was able to recover, because of the absence of a young tree stand. The effect of the fertilization on the herbaceous vegetation was not sustainable.

Discussion

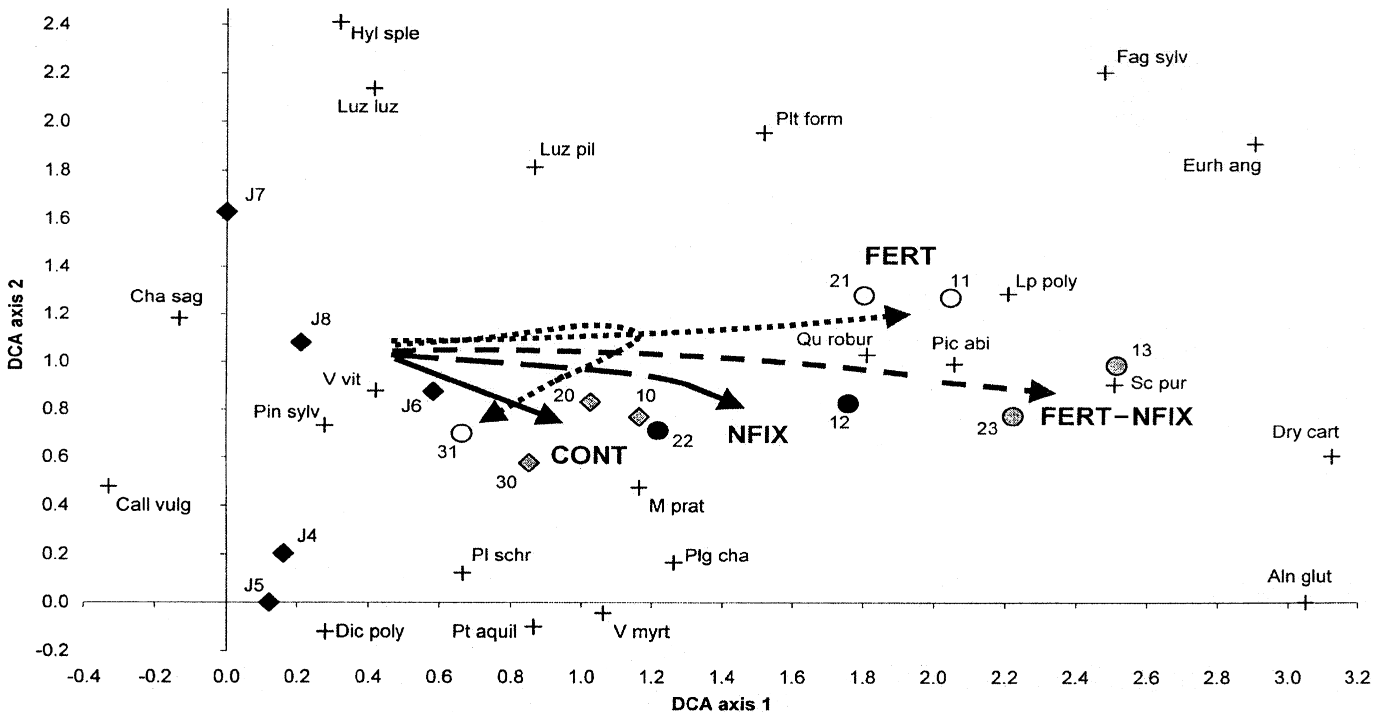
Forest soil amelioration experiments in Central Europe often have the goal of mobilizing nutrients from the slowly circulating pool in the forest floor. This was certainly achieved with all treatments. The decline in the mass of forest floor material and the improvement of the soil chemical status (Table 1) indicate that in all treatments the formerly recalcitrant nutrient pool in the forest floor has been mobilized. It is remarkable that the NFIX treatment had a strong effect on the nutrient distribution in the soil, even though the rate of N accretion was low. The depth effect of the FERT treatment is somewhat stronger although. Another major difference between these methods is obviously the response time. We conclude that FERT is the method of choice if soil fertility needs to be enhanced within only a few years. Often, however, more time is available to achieve the desired response. Rotation periods in Central European spruce forests often exceed 100 years. In such cases, soil amelioration can be achieved by N-fixing plants.

Stem growth accelerated with all treatments. The maximum response of the stem volume to the FERT treatment demonstrates that site factors such as climate and soil allow much higher growth rates, and that nutrient availability had limited the productivity. A similar, although weaker effect, can be achieved by N-fixing plants (NFIX). The combined NFIX–FERT treatment did not further increase stem volume. In concluding, FERT can be a valuable treatment, and the nutrient mobilization in the NFIX treatment is by no means superior to that of the FERT treatment. When interpreting the high stem volume at treated plots, one has to bear in mind that Table 3 depicts the status of a 30-year-old spruce stand as a snapshot and is thus not necessarily valid for the entire rotation period. Earlier N fertilizer experiments have shown that the addition of mineral N accelerates the growth rate only for several years. Even in our experiment, the growth response to the FERT treatment was highly variable with time. Five years after the start of the experiment FERT had been the most effective treatment. In contrast, the growth rate of Norway spruce was lower in the NFIX treatment than in the control, presumably because of competition between the N-fixing plants and the spruce seedlings (Pollanschütz 1973). The latest results now show that the FERT treatment is still superior with respect to tree growth, but that the NFIX treatment is only slightly lower and certainly is an equally valuable treatment, which could prove to be superior at the end of the rotation period.

From a silvicultural point of view, the most important decision during the course of the experiment was the fencing of the treated plots. Prior to fencing, the stand conversion of blocks 1 and 2 was mostly unsuccessful. Seedlings of spruce, beech, and oak were abundant but height growth was profoundly inhibited by roe deer browsing. The damage to the young spruce plantation was extensive, and when the landowner finally decided on the rather expensive fence, success occurred immediately (Johann 1989). The Dobrowa experiment demonstrates that under high deer density, amelioration experiments can hardly be economically successful and are an inefficient investment. The described amelioration methods must be supported by collateral measures to keep deer densities low. It is obvious from fenced monitoring plots that the natural regeneration and development of many tree species are greatly improved if roe deer density is low.

The success of the experiment is closely linked to the dynamics of the dwarf shrubs *Calluna vulgaris*, *Vaccinium vitis-idea*, and *Vaccinium myrtillus*. These shrubs were suppressed

Fig. 2. Ordination diagram of a detrended correspondence analysis (DCA) based on vegetation samples at the experimental plots (1993–1994) and reference samples (J4–J8, 1969–1971). Arrows indicate the temporal trend of different treatments. Circles and diamonds indicate the vegetation samples (numbers: first position, block; second position, treatment); crosses represent the centroids of 22 species with the highest weight: Aln glut, *Alnus glutinosa*; Fag sylv, *Fagus sylvatica*; Pic abi, *Picea abies*; Pin sylv, *Pinus sylvestris*; Qu robur, *Quercus robur*; Call vulg, *Calluna vulgaris*; Cha sag, *Chamaespartium sagittale*; Dry cart, *Dryopteris carthusiana*; Lp poly, *Lupinus polyphyllus*; Luz luz, *Luzula luzuloides*; Luz pil, *Luzula pilosa*; M prat, *Melampyrum pratense*; Plg cha, *Polygala chamaebuxus*; Pt aquil, *Pteridium aquilinum*; V myrt, *Vaccinium myrtillus*; V vit, *Vaccinium vitis-idaea*; Dic poly, *Dicranum polysetum*; Eurh ang, *Eurhynchium angustirete*; Hyl sple, *Hylocomium splendens*; Pl schr, *Pleurozium schreberi*; Plt form, *Polytrichum formosum*; Sc pur, *Scleropodium purum*.



by competition of N-fixing plants or by a direct effect of the fertilizer. As a result, young trees, ferns, and herbaceous plants with a higher nutrient demand could develop. Therefore, the spectrum of plants varies widely among treatments (Fig. 2).

The vegetation survey in the control plots corroborated the evidence that a natural succession, similar to that of many European forests, is presently occurring at the study site. (Fig. 2). Major reasons are thought to be the continuous increase in N availability and a change in forest management methods (Spiecker 1999). In this particular case, changes in regional N deposition rates may or may not have been crucial. The cessation of litter raking after the Second World War is certainly enough of a land-use change to explain the observed change of the herbaceous vegetation. The natural dynamics are progressing slowly, however. The amount of inactive nutrients in the forest floor is still high in the control plots, and the nutrient content in the mineral soil remains low. The N supply in the control plots is still insufficient (Table 2). Even if a natural tendency towards aggradation of forests takes place, the treatments greatly accelerated the processes. Apparently the pre-treatment conditions in the Dobrowa are very unfavorable, as dwarf shrubs still cope well with current site conditions and so far have delayed the succession.

Upon stand amelioration, the mobilization of recalcitrant forest floor material may be the primary target. If successful, this process is evident from a narrow C/N ratio. Mobilizing the forest floor counteracts the tendency of low-fertility sites to sequester C in the forest soil (Huntington 1995; Kauppi et al. 1992). Soil chemical data (Table 1) suggest that forest amelioration mineralizes a considerable amount of C. The entire idea of the snowball effect of amelioration fertilization is indeed based on the principle that the nutrient addition stimulates the microbiological activity by turning recalcitrant soil organic matter into a more attractive substrate (Oliver and Larsen 1990). Consequently, the mineralization of organic compounds releases the nutrients that are utilized by trees. During this process, C is respired and ultimately released into the atmosphere as CO_2. Simultaneously, C is fixed in the tree biomass. Table 1 suggests that the C pool in the soil is decreased by 20 to 40%. Increased growth rates of the stand bind a considerable amount of C in the biomass and may compensate for the C losses in the soil. It remains to be shown which of soil or biomass C is the longer lasting sink for C (Harmon et al. 1990; Nadelhoffer et al. 1999; Schulze et al. 2000).

The fate of N is under scrutiny from an environmental point of view. Its response to the treatments is quite different from that of C. The N retention capacity of the mineral soil is small, and N losses are inevitable. In plots that received mineral fertilizer (FERT and FERT–NFIX), the soil contains up to 30% less N than in the control plots. The tree biomass cannot possibly have retained this quantity, so that a net loss from the system must have occurred. Previous findings have shown that 500 kg N·ha^{-1} is simply an overdose and may even have caused reductions in the growth rates (Pollanschütz 1973). A comparison of the treatments shows that the N pool at the control plots is highest, but that the N concentration in the needles is low (Table 2). The net accretion by alder and lupine is only 3 kg N·ha^{-1}·year^{-1}. With respect to potential N eutrophication of forest ecosystems all over Europe, different points of view can be taken. From an environmental perspective a N-tight system is desired. Consequently, it could be preferred to leave forest ecosystems unameliorated and rely on the fact that N is stored as recalcitrant humus. From the perspective of timber production, it is clear that site amelioration increases N availability and can greatly improve the growth rate of forest stands. Our study shows that the need to retain N and C in forest ecosystems is in conflict with traditional amelioration goals. Within multifunctional forestry we have to seek a compromise between competing goals such as having chemical-free forest floors and surface waters with a low nitrate concentration, and sufficiently high growth rates. Based on today's views, the goals of the experiment did not aim high enough, and even more impressive results would have been possible, had a beech and oak dominated forest been established. Beech was especially competitive in this experiment because of its tolerance for shade and its ability to germinate below the canopy of a mature forest. It would have been possible to establish a mixed-species forest, consisting of beech, oak, and Norway spruce. Instead, a secondary pine forest has been replaced by a secondary spruce plantation.

Conclusions

The results of the Dobrowa experiment can be summarized as follows:

(1) Both mineral fertilization and N-fixing plants can ameliorate forest sites that have been degraded by litter raking over centuries.

(2) At high roe deer population densities, their exclusion is a prerequisite for successful stand conversion.

(3) Fertilization treatments have the quickest effect; N-fixing plants can yield results similar to fertilization, but the amelioration is slower.

(4) Degraded forests sequester more C and N in the soil than ameliorated forests.

(5) The need to retain C and N in forest ecosystems is in conflict with traditional amelioration goals.

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