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Soil fertility of afforested arable land compared to continuously forested sites

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Abstract

In Finland, over 220,000 ha of arable land has been afforested in recent decades. To meet the goals of forest management on afforested fields, information on the effects of former agricultural land use on soil fertility is needed. In this study, we examine the soil fertility of 12 former arable fields afforested either 10 or 60–70 years ago with Norway spruce (*Picea abies* (L.) Karst.) and adjacent sites that have been forested continuously. Volumetric soil samples were collected from the organic soil layer and from mineral soil to a depth of 40 cm. Soil samples were analyzed for pH, bulk density, organic matter content and amounts of nutrients (Kjeldahl N, extractable P, K, Ca, Mg, Zn and B). On afforested fields, amounts of nutrients in the mineral soil, especially in 10-year-old afforestations, were higher than on continuously forested sites. In the organic layer plus the 0–40 cm soil layer, the 10-year-old afforestations had 68% more N, 41% more P, 83% more K, 252% more Ca, 6% more Mg, 61% more Zn and 33% more B than the continuously forested sites at a comparable soil depth. In the 60–70-year-old afforestations, the differences were significant only for N, Ca and Zn (20% more N, 121% more Ca and 115% more Zn than on the continuously forested sites). The effects of agriculture on amounts of nutrients were most clearly detected in the former plough layer (0–20 cm) of the 10-year-old afforestations and in the top layer (0–10 cm) of the older afforestations. Amounts of nutrients in the organic layer of the afforested sites were lower, but their concentrations were higher than in the continuously forested sites. On the 10-year-old afforestations, the bulk density of the mineral soil tended to be lower and the organic matter content higher than on the continuously forested sites. On both young and old afforestations, soil pH was higher than on the continuously forest sites. According to these results, changes in soil properties caused by agriculture have increased the soil fertility and therefore probably also the site index. The results also suggest that changes in soil properties due to agricultural land use are quite long lasting.

Introduction

Cultivation of agricultural land alters the physical and chemical properties of soil. Ploughing results in mixing of the topsoil and in Podzols most of the E (eluvial) horizon and sometimes the upper part of the spodic B (illuvial) horizon is mixed into the Ap (plough layer) horizon (Yli-Halla and Mokma, 1999). Cultivation usually decreases the organic matter content of the soil (Johnson, 1992; Mann, 1986), and use of agricultural machinery results in increased bulk density (Domżał et al., 1993; Soane et al., 1981).

After long-term application of fertilizers, their residues can accumulate in soils and the quality and quantity of these residues depend on the soil type, history of fertilizer use and type of agricultural history, including the type of fertilizer used

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(Marrs, 1993). Various effects of previous agricultural use on chemical properties of soil have been reported, for example, increased N content of mineral soil (Compton and Boone, 2000; Koerner et al., 1997; Richter et al., 2000), increased (Compton and Boone, 2000; Koerner et al., 1997) or lowered (Kalisz, 1986) P content, increased K (Goovaerts et al., 1990), Ca (Kalisz, 1986) and Mg (Goovaerts et al., 1990) content, and higher pH (Goovaerts et al., 1990; Kalisz, 1986; Koerner et al., 1997). Afforested peat fields have been shown to have much higher pools of N, P and Ca in the cultivation layer than the adjacent forests (Hytönen and Wall, 1997). These findings consistently suggest that former agricultural use of soil has a long-term effect on soil properties.

The methods used to cultivate agricultural land have undergone major changes over time. In Finland, the application of lime and fertilizers in agriculture has increased considerably from the 1950s to the 1980s. This has led to a marked increase in pH, plant-available amounts of P, Ca, K and Mg in Finnish cultivated soil (Erviö et al., 1990; Kähäri et al.,1987; Kurki, 1982). Thus, due to cultivation practices (ploughing, disking and harrowing, continued fertilization, soil amelioration with lime and growing of agricultural crops) the physical and chemical properties of agricultural soils may differ considerably from those of forest soils even if the soils were similar prior to cultivation.

The general concern about surpluses of agricultural products both in Finland and in other European Union countries has promoted forestry as an alternative land use to agriculture. In Finland, large-scale afforestation of agricultural land, aimed at reducing the area under cultivation in the country, began in the late 1960s. At present, in Finland over 230,000 ha of arable land have been afforested (Finnish Statistical Yearbook of Forestry, 2002). However, the effects of modern agriculture on the production potential of forest soils after change in land use and the duration of these effects are poorly known. In Finland, the production potential of a forest site is estimated on the basis of the floristic-ecological properties of the site (Cajander, 1926). On agricultural land, however, this method is not feasible. Thus, to assess the potential of agricultural land for production of tree crops, information on direct site properties is needed. Upon afforestation of agricultural land, information on soil fertility is needed to meet other objectives of forest management besides wood production, such as preservation of biodiversity, preservation of recreational values, protection of groundwater quality and sequestration of carbon.

Using chemical analysis, we studied soil fertility at sites on former arable land afforested either 10 or 60–70 years ago with Norway spruce and compared their soil fertility to that of adjacent continuously forested sites. To study long-term changes in soil fertility due to agriculture and to determine the effects of afforestation on development of organic layer, we sampled sites afforested some 60–70 years ago. The aims of this study were (1) to examine changes in amounts of soil nutrients and in nutrient distribution within a soil profile due to agriculture and (2) to evaluate the importance of potential changes in soil fertility for forest management.

Materials and methods

Sites

Twelve pairs of afforested former arable fields and adjacent continuously forested sites located in central and southern Finland were chosen for this study (Figure 1). The mean effective temperature sum (threshold 5 °C) of the study sites varies from 1000 °C days (central Finland) to 1300 °C days (southern Finland), and the mean annual precipitation varies from 526 (central Finland) to 620 mm (southern Finland). The criteria used for selecting the study sites were that (i) Norway spruce (*Picea abies* (L.) Karst.) grew almost exclusively on both the afforested field and its adjacent forest, (ii) the adjacent site had been continuously forested and (iii) the afforested field and its adjacent forest had a similar soil texture. At six sites the former fields had been afforested in 1990 and at six sites they had been afforested in the 1930s. Thus, at the time the sample plots were established, plantations were 10 or 60–70-years-old. The history of land use was provided by the landowners. Prior to afforestation the 10-year-old afforested sites had been cultivated for cereals. However, for fields afforested 60–70 years ago, no information on past agricultural practices of the study sites was

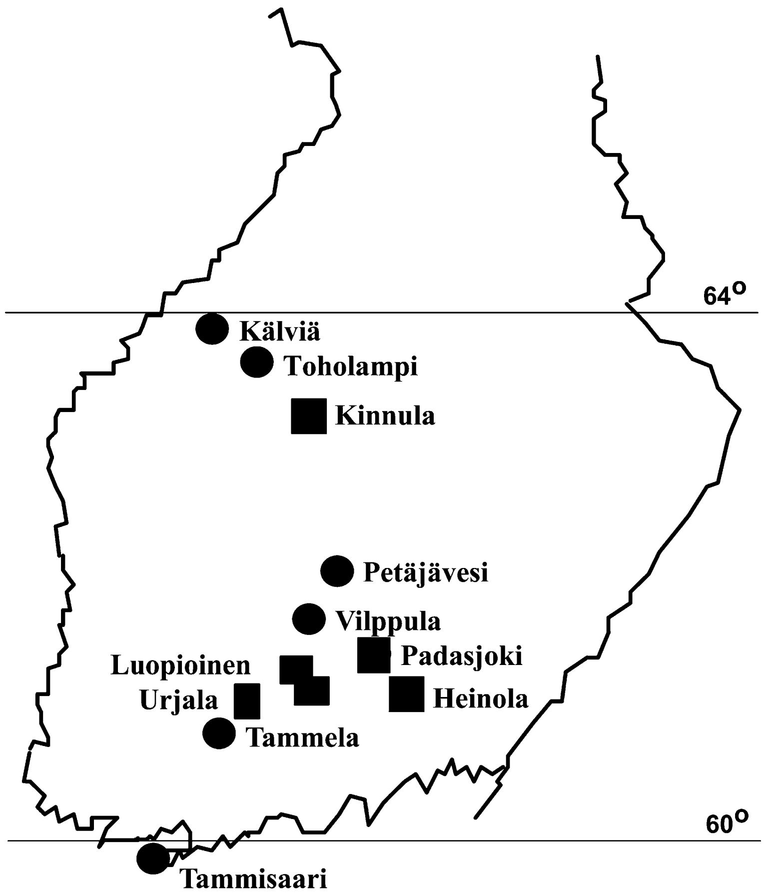

Figure 1. Geographic location of the study sites in Finland. Arable land afforested in 1990 are marked with a circle and afforested in the 1930s are marked with a square.

available. Former land use was also identified by the soil properties. Former cultivation was manifested by the presence of an Ap horizon (plough layer), which clearly differed from the underlying soil due to its darker color, absence of surface stones, level microtopography and ditches. In adjacent continuously forested sites, these characteristic properties of cultivated soils were not found.

The age of the trees, their height and the volume of the stands growing on the study sites are presented in Table 1. At Urjala the trees growing on the afforested field had already been cut and new seedlings planted. The site types of the continuously forested sites described by Cajander's (1926) classification, based on vegetation and the median particle size of the mineral soil and proportion of particle sizes smaller than 60 μm are presented in Table 2. In 10-year-old afforestations, the median particle-size tended to be smaller than in the adjacent forests. The difference in the proportion of fine particles (<60 μm) was minor, except for the site located in Vilppula (Table 2). In 60–70-year-old afforestations, at all locations except Heinola, the particle-size distribution was similar to that of adjacent forests.

Soil sampling

At each location, three circular sample plots, each 0.01 ha in area, were randomly placed 10–30 m from each other both on the afforested fields and on their adjacent forests, except in Tammisaari where only four sample plots were placed. Sample plots were placed at a distance of 20–50 m from the border between the forest and the afforested field. Volumetric soil samples collected during September–October in 1999 from

Table 1. Stand characteristics of the study sites in afforested fields (AF) and their adjacent continuously forested sites (FO)

Location	Age of trees (years)		Height of trees (m)		Stem volume (m^3 ha^{-1})	
	AF	FO	AF	FO	AF	FO
Kälviä	10	55	3.6	20.0	–	170
Toholampi	10	50	4.0	20.0	–	170
Petäjävesi	10	50	4.0	18.0	–	340
Vilppula	10	51	2.9	24.0	–	240
Tammela	10	70	3.6	27.0	–	340
Tammisaari	10	100	3.3	22.0	–	350
Kinnula	65	80	26.0	22.0	280	195
Luopioinen I	65	60	26.0	22.0	510	200
Luopoinen II	65	80	27.0	26.0	660	590
Padasjoki	65	65	25.0	25.0	265	370
Urjala	3	35	0.3	16.0	–	220
Heinola	69	70	31.0	25.0	845	380

Table 2. Particle-size distribution and site type of the study sites sites in afforested fields (AF) and their adjacent continuously forested sites (FO)

Location	Afforestation Year	Media particle size (μm)		Particle size <60 μm (%)		Site type
		AF	FO	AF	FO	FO
Kälviä	1990	197	437	29.1	36.3	VMT
Toholampi	1990	5	18	94.0	95.3	MT
Petäjävesi	1990	127	464	37.7	21.5	MT
Vilppula	1990	24	168	68.8	11.2	MT
Tammela	1990	136	107	35.7	39.1	OMT
Tammisaari	1990	357	434	35.0	22.7	MT
Kinnula	1930s	552	467	20.6	21.2	MT
Luopioinen I	1930s	243	363	23.0	21.1	MT
Luopoinen II	1930s	276	635	19.8	17.3	MT
Padasjoki	1930s	418	307	11.5	14.2	OMT
Urjala	1930s	842	1294	10.5	13.7	MT
Heinola	1931	260	734	28.0	18.0	OMT

the sample plots were taken from the organic layer on top of the mineral soil (litter, fermentation and humus layer) and mineral soil at soil depths of 0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm. At the Tammela location, soil samples deeper than 10 cm could not be taken due to the hardness of the soil on two sample plots. Thickness of the organic layer was measured when soil samples were taken. The soil samples were taken with a soil corer (either 5.5 cm × 4.4 cm or a cylindrical corer 5.65 cm in diameter) from five points on each plot (one in the center, the other four on the circumference of the plot) and bulked into one composite sample for each soil depth and sample plot. Soil morphological horizons were not used in sampling since ploughing of the former fields had disturbed the horizons.

Soil analyses

Prior to analysis, samples from the organic horizon were ground (2 mm), mineral soil samples were sieved through a 2 mm mesh, roots were removed, and the samples were air-dried and stored at room temperature. The total N concentrations of the soil samples were determined by the Kjeldahl method. After extraction with 0.5 M NH_4OAc (pH 4.65) (Halonen et al., 1983), concentrations of extractable P, K, Ca, Mg and Zn were determined with inductively coupled plasma emission spectrometry (ICP). After digestion of the soil samples with HNO_3–H_2O_2 in a microwave oven, the concentration of extractable B was determined with ICP. In 31 soil samples, the B concentration was below the limit of detection (0.002 mg kg^{-1}); and for those samples, the B concentration was given as half the limit of detection. Bulk density of the soil samples was calculated as the ratio of dry mass (dried at 105 °C) to the volume of the sample. The concentration of organic matter was estimated as loss-on-ignition at 550 °C for 8 h. Amounts of nutrients at different soil depths were calculated on the basis of oven-dry (105 °C) weight of the soil samples using bulk densities and expressed on an area basis for the sampling depth. Amounts of organic matter for each soil depth were calculated by multiplying the concentration of organic matter by the bulk density and were expressed on an area basis for the sampling depth. Soil pH was measured in distilled–deionized water from dried soil samples using a 1:2.5 soil:solution suspension. After removal of organic matter from the samples with H_2O_2, the particle-size distribution was determined by a dry-sieving and sedimentation method (Elonen, 1971).

Statistical analyses

Differences between former fields and forests were tested separately for each soil depth for the measured soil properties with ANOVA (MIXED) as a multilocation trial (Littel et al., 1996). In the analysis the focus was on land-use effects averaged over entire populations represented by the various locations. The statistical model used was

$$y_{ijk} = \mu + T_i + L_j + (TL)_{ij} + e_{ijk},$$

where y_{ijk} is the observation, μ is the overall mean, T_i is the treatment effect, L_j is the location effect, TL_{ij} is the treatment-by-location interaction and e_{ijk} is the residual error. In the models the locations were considered to be random, the treatments to be fixed and the location-by-treatment interaction to be experimental error. The homogeneity of the variances was tested and transformations were made for K and Ca to stabilize the variances. Sites of different afforestation ages were not compared because it was assumed that, owing to the changes in cultivation methods over time, they were not the same at the end of cultivation.

Results

Morphology of the soil horizons

On 10-year-old afforestations, a 1-cm-thick litter layer formed the uppermost soil horizon and a plough layer formed an Ap horizon, which due to its darker color, was clearly distinct from the underlaying soil. The thickness of the plough layer was, on average, 22 cm. On 10-year-old afforestations, four sites had a spodic B-horizon in the soil profile and were classified as Haplic Podzols (FAO, 1988). In these Podzols the E horizon was missing. Two of the sites had no diagnostic horizons and were classified as Regosols. The continuously forested sites had a soil type similar to their adjacent formerly arable field but had raw humus on top of the mineral soil forming the O horizon, which was, on average, 6 cm thick.

On 60–70-year-old afforestations, raw humus formed the O horizon, which was, on average, 4-cm thick. The plough layer, which was 17-cm thick, had a darker color than the underlaying soil. On 60–70-year-old afforestations, the E horizon was missing and all soils were Podzols. Their adjacent continuously forested sites were also Podzols and had raw humus forming the O horizon, which was, on average, 6-cm thick.

Soil chemical characteristics

On the 10-year-old afforestations, at all soil depths the mean amount of total N, extractable nutrients and nutrient concentrations contained in the mineral soil tended to be higher than in adjacent continuously forested sites (Figures 2 and 3; Table 3). However, the differences in amounts of nutrients in mineral soil between afforested sites and continuously forested sites were significant for most nutrients only at soil depths of 0–10 cm and 10–20 cm. The variance component estimates of the location-by-land-use interaction indicated that there were

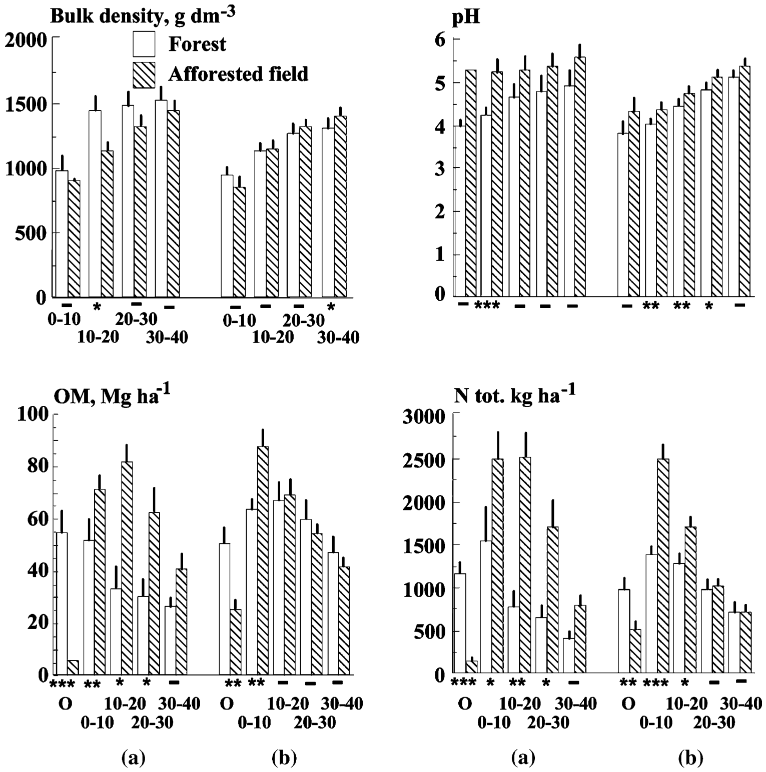

Figure 2. Bulk density, amount of organic matter, pH and amount of total nitrogen in organic layer (O) and in mineral soil in 10 cm increments on 10-year-old afforestations and their adjacent forests (a) and on 60–70-year-old afforestations and their adjacent forests (b). The standard error of the mean is presented as line bars. Stars represent probabilities of the difference between afforested sites and continuously forested sites averaged over all locations: ***significant at 0.001 probability level; **significant at 0.01 probability level; *significant at 0.05 probability level.

location-specific differences in nutrient amounts and concentrations, which was seen in the difference in amounts of nutrients between afforestations and continuously forested sites at different locations.

On the 10-year-old afforestations, the amount of total N and extractable nutrients contained in the organic layer was lower than the nutrient content of the underlying mineral soil and also lower than the organic layer of continuously forested sites (Figures 2 and 3). In adjacent continuously forested sites, among the sampled soil depths with the exception of B, the organic layer contained the greatest amount of extractable nutrients. Both on afforested sites and on continuously forested sites, the B content increased with increasing soil depth.

On the 10-year-old afforestations, the organic layer plus mineral soil to a depth of 40 cm contained, on average, 3106 kg ha^{-1} more N (68% more), 21 kg ha^{-1} more P (41% more), 150 kg ha^{-1} more K (83% more), 2329 kg ha^{-1} more Ca (252% more), 27 kg ha^{-1} more Mg (6% more), 2 kg ha^{-1} more Zn (61% more) and 5 kg ha^{-1} more B (33% more) than did the adjacent continuously forested sites. Without the location of Toholampi, which had exceptionally high levels of Ca and Mg in the soil of the continuously forested site, the differences in these nutrients would have been much higher (Ca 702% more and Mg 359% more than in adjacent forest sites).

On the 60–70-year-old afforestations, the amounts and concentrations of total N, extractable Ca and Zn contained in mineral soil were significantly higher than on continuously forested sites in the uppermost soil depths (Figures 2 and 3; Table 3). For extractable P, K, Mg and B, the differences in amounts of nutrients between afforested sites and continuously forested sites were

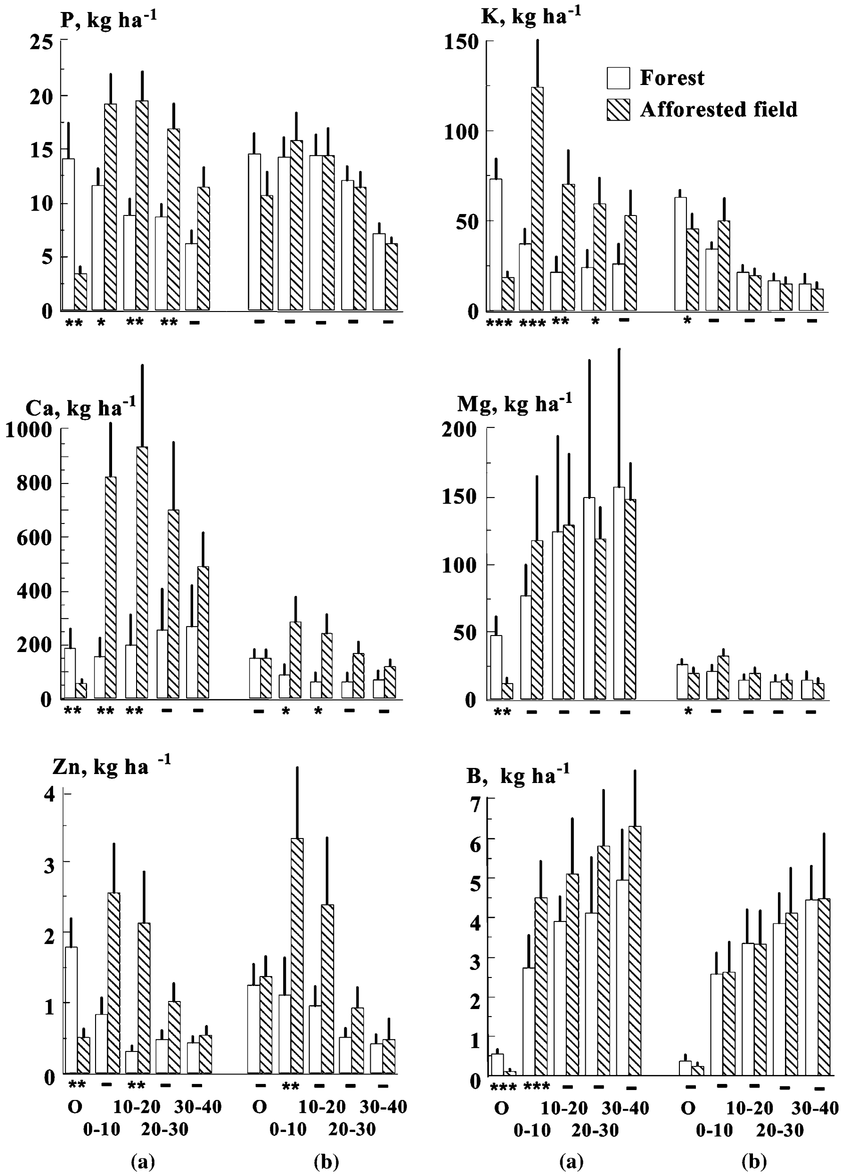

Figure 3. Extractable amounts of P, K, Ca, Mg, Zn and B in the organic layer (O) and in mineral soil in 10 cm increments on 10-year-old afforestations and their adjacent forests (a) and on 60–70-year-old afforestations and their adjacent forests (b). The standard error of the mean is presented as line bars. Stars represent probabilities of the difference between afforested sites and continuously forested sites averaged over all locations: ***significant at 0.001 probability level; **significant at 0.01 probability level; *significant at 0.05 probability level.

not significant. However, on afforested sites the nutrient concentrations for P and Mg were significantly higher at a soil depth of 0–10 cm. The variance component estimates of the location-by-land-use interaction indicated that there were location-specific differences in amounts and concentrations of nutrients.

In the organic layer, the amount of extractable K was significantly lower in 60–70-year-old afforestations than on continuously forested sites; but for other nutrients, the differences were not significant (Figures 2 and 3). In the organic layer, however, nutrient concentrations for K, Ca, Zn and B were significantly higher on afforested

Table 3. Nutrient concentrations (means ± standard error of the mean) in the organic layer (O) and in mineral soil in 10 cm increments in locations with 10-year-old afforestations (A) and 60–70-year-old afforestations (B)

Depth (cm)	A		*P*-value	B		*P*-value
	AF	FO		AF	FO	
Organic matter (%)						
O	33.4 ± 3.0	57.0 ± 5.0	0.0026	60.5 ± 3.0	59.4 ± 7.0	0.8498
0–10	8.5 ± 0.6	6.5 ± 1.8	0.1905	10.7 ± 1.0	7.5 ± 0.5	0.0123
10–20	7.8 ± 0.7	2.8 ± 0.9	0.0001	6.2 ± 0.3	6.1 ± 0.6	0.8630
20–30	5.0 ± 0.6	2.4 ± 0.6	0.0157	4.2 ± 0.2	4.7 ± 0.5	0.4019
30–40	3.1 ± 0.5	2.0 ± 0.4	0.0766	3.2 ± 0.2	3.7 ± 0.4	0.4479
N (%)						
O	0.88 ± 0.13	1.15 ± 0.06	0.1319	1.12 ± 0.08	1.10 ± 0.12	0.8196
0–10	0.28 ± 0.04	0.19 ± 0.07	0.1963	0.30 ± 0.02	0.15 ± 0.01	0.0005
10–20	0.23 ± 0.03	0.06 ± 0.02	0.0045	0.15 ± 0.01	0.11 ± 0.01	0.0118
20–30	0.13 ± 0.02	0.05 ± 0.01	0.0137	0.08 ± 0.00	0.08 ± 0.01	0.9557
30–40	0.06 ± 0.01	0.03 ± 0.01	0.0572	0.05 ± 0.00	0.05 ± 0.01	0.7214
P (mg kg^{-1})						
O	201 ± 39	159 ± 38	0.3168	230 ± 37	184 ± 32	0.1088
0–10	22 ± 3	12 ± 2	0.0352	18 ± 2	15 ± 3	0.0471
10–20	18 ± 2	71 ± 1	0.0007	12 ± 2	13 ± 2	0.6774
20–30	13 ± 2	71 ± 1	0.0023	9 ± 1	9 ± 1	0.3710
30–40	7 ± 31	4 ± 1	0.1024	4 ± 0	6 ± 0	0.0179
K (mg kg^{-1})						
O	1088 ± 213	777 ± 125	0.1260	990 ± 78	758 ± 61	0.0260
0–10	140 ± 30	40 ± 8	0.0002	58 ± 10	38 ± 4	0.0752
10–20	67 ± 16	15 ± 4	0.0024	17 ± 3	19 ± 2	0.5912
20–30	44 ± 12	15 ± 5	0.0260	11 ± 3	13 ± 3	0.5294
30–40	35 ± 8	16 ± 6	0.0777	9 ± 2	12 ± 3	0.3367
Ca (mg kg^{-1})						
O	3042 ± 368	1928 ± 411	0.0047	3296 ± 192	1773 ± 328	0.0080
0–10	941 ± 216	154 ± 54	0.0009	333 ± 102	93 ± 42	0.0038
10–20	938 ± 267	105 ± 68	0.0009	201 ± 50	55 ± 15	0.0136
20–30	576 ± 161	123 ± 85	0.0327	125 ± 29	50 ± 18	0.0552
30–40	336 ± 74	128 ± 86	0.0871	86 ± 11	50 ± 22	0.1866
Mg (mg kg^{-1})						
O	623 ± 115	476 ± 145	0.0408	455 ± 64	302 ± 25	0.0575
0–10	126 ± 45	71 ± 44	0.3855	39 ± 9	22 ± 4	0.0357
10–20	98 ± 43	59 ± 50	0.9760	17 ± 3	12 ± 2	0.3281
20–30	75 ± 34	68 ± 59	0.9971	11 ± 2	11 ± 3	0.9025
30–40	82 ± 40	72 ± 60	0.8925	9 ± 1	11 ± 4	0.5469
Zn (mg kg^{-1})						
O	25 ± 6	18 ± 4	0.3548	31 ± 6	14 ± 1	0.0081
0–10	3 ± 1	1 ± 0	0.0964	4 ± 1	1 ± 0	0.0028
10–20	2 ± 1	0 ± 0	0.0110	2 ± 1	1 ± 0	0.1558
20–30	1 ± 0	0 ± 0	0.0382	1 ± 0	0 ± 0	0.3338
30–40	0 ± 0	0 ± 0	0.5177	0 ± 0	0 ± 0	0.8665
B (mg kg^{-1})						
O	7 ± 1	5 ± 1	0.0010	5 ± 1	4 ± 0	0.0201
0–10	5 ± 1	3 ± 1	0.0086	3 ± 1	3 ± 0	0.4104
10–20	5 ± 1	3 ± 0	0.3779	3 ± 1	3 ± 1	0.7516
20–30	4 ± 1	3 ± 1	0.0721	3 ± 1	3 ± 0	0.8337
30–40	4 ± 1	3 ± 1	0.0719	3 ± 1	3 ± 0	0.4931

AF – Afforested field, FO – adjacent forest, *P*-value – probabilities of the difference between afforested sites and continuously forested sites averaged over all locations.

sites; but for P and Mg the differences in nutrient concentrations were not significant (Table 3). On afforested sites, the 0–10 cm soil depth contained the greatest amount of extractable nutrients among the sampled soil depths; but on continuously forested sites, the organic layer contained the greatest amount of extractable nutrients.

On the 60–70-year-old afforestations, the organic layer plus the mineral soil to a depth of 40 cm contained, on average, 1097 kg ha^{-1} more N (20% more), 536 kg ha^{-1} more Ca (121% more), 11 kg ha^{-1} more Mg (13% more) and 4 kg ha^{-1} more Zn (115% more) than continuously forested sites. For amounts of P, K and B differences between afforested sites and continuously, forested sites were minor.

Organic matter content, bulk density and pH of soil

On the 10-year-old afforestations, the organic matter content of the mineral soil was significanly higher at soil depths of 0–10 cm, 10–20 cm and 20–30 cm but lower in the organic layer than on continuously forested sites (Figure 2). On the 10-year-old afforestations, the organic layer plus mineral soil to a depth of 40 cm contained, on average, 67,350 kg ha^{-1} more organic matter (32% more) than the adjacent forests. On afforested sites, the mean annual rate of accumulation of organic matter in the organic layer was 587 kg ha^{-1} over the 10-year period. At the soil depths sampled the bulk density of mineral soil on the 10-year-old afforestations was lower than in the adjacent continuously forested sites, but the difference was significant only for the 10–20 cm soil depth (Figure 2). At a soil depth of 0–10 cm the pH value of the soil was significantly higher in the afforestations than in the adjacent forests, but in deeper soil the differences were not significant (Figure 2).

On the 60–70-year-old afforestations, the organic layer contained significantly less organic matter than the continuously forested sites did; but at a depth of 0–10 cm, the amount of organic matter was greater (Figure 2). In deeper soil, the organic matter content did not differ between afforested sites and continuously forested sites. In the 60–70-year-old afforestations and continuously forested sites, the organic layer plus mineral soil to a depth of 40 cm contained, on average, 298,000 kg ha^{-1} of organic matter. On afforested sites, the mean annual accumulation rate of organic matter in the organic layer was 426 kg ha^{-1} over the 65-year period. At a soil depth of 30–40 cm the bulk density of the 60–70-year-old afforestations was lower than that of continuously forested sites but at other soil depths did not differ (Figure 2). With increasing soil depth the bulk density increased consistently on afforested sites and continuously forested sites, whereas the organic matter content decreased. At soil depths of 0–10 cm, 10–20 cm and 20–30 cm the pH value of the soil was significantly higher on the afforested sites than on the continuously forested sites (Figure 2).

Discussion

According to the present results, the soils of the 10-year-old afforestations contained more total N, extractable nutrients and organic matter and had higher pH than the adjacent continuously forested sites. This means that cultivation has not depleted the nutrient pools in the soil. On the contrary, cultivation had increased them, probably due to use of organic amendments and inorganic fertilizers during the cultivation period. Furthermore, liming has most likely increased the Ca and Mg content of the soil, in addition to increasing the pH. In Finland, use of liming in order to decrease soil acidity is common practice in agriculture owing to inherently acidic soils. The mean amount of lime (as $CaCO_3$) used for fields has been 400 kg ha^{-1} per annum (Erviö et al., 1990).

In addition to differences in the amount of nutrients, the afforested fields studied here differed from continuously forested soils in terms of distribution of nutrients within a soil profile. In mineral forest soils, the organic horizon is the layer richest in extractable (plant-available) macronutrients (Urvas and Erviö, 1974) and therefore the main source of nutrients for plants. In the afforested field studied here, the mass of the organic layer was low compared to continuously forested sites, and the organic layer contained a relatively small amount of nutrients. Therefore, the former plough layer (0–20 cm) was the main source of nutrients, even in the 60–70-year-old afforestations. The larger amounts of P, K, and especially Ca, on afforested sites in the 30–40 cm soil depth compared to the continuously forested sites suggest that these nutrients have been translocated deeper into the soil from the former plough layer. Furthermore, the nutrient concentrations of the organic layer in the 60–70-year-old afforestations were higher than in continuously forested sites, which suggests that on afforested fields nutrients from the mineral soil appear to have been transferred to the trees and then to the organic layer via litterfall.

The higher organic matter content of the soil on afforested sites found in this study, compared to continuously forested sites, is in contrast to the conclusion based on information in literature reviews that in most cases cultivation results in loss of organic C from the soil compared to the original C content (Davidson and Ackerman, 1993; Mann, 1986). These reviews show results mainly from the temperate zone, and studies from the boreal zone are few. Low temperatures and water logging are two conditions that lead to accumulation of organic matter (Oades, 1988); the former one appears most likely to contribute to high content of organic matter in the soil in our study region, given the fact that arable fields are commonly drained. In addition, the residues and below-ground litter from agricultural crops and the use of organic amendments during the cultivation period may have incorporated organic matter into the soil and thus contributed to the high organic matter content. Furthermore, liming of fields during the agricultural period may have stabilized the decomposition of organic matter, thus contributing to accumulation of organic matter (Oades, 1988).

Use of machines in agricultural operations can result in increased compaction, bulk density and physical degradation of soil (Alakukku, 1999; Domżał et al., 1993; Soane et al., 1981). Our findings showed no indication of physical degradation of the soil. In contrast to our findings, Messing et al. (1997) found that the bulk density of soil was lower in soils under forests than in soils under field crops. Also Compton et al. (1998) found that increased bulk density is the persistent legacy of agriculture. The lower bulk density of mineral soil in afforested fields found here compared to forest soils is probably a legacy of agriculture because tillage decreases the bulk density of soil and increases total porosity (Lindstrom and Onstad, 1984). Changes in soil porosity due to cultivation occur mainly in the larger pore-size range (Ahuja et al., 1998; Lindstrom and Onstad, 1984; Mapa et al., 1986). However, these changes diminish gradually with time due to reconsolidation caused by the impact of water drops and by wetting and drying of the soil (Cassel, 1983; Makeschin, 1994; Onstad et al., 1984; Rousseva et al., 1988). Furthermore, the increased organic matter content of soil in former fields also results in decreased bulk density due to the inverse relationship between organic matter content and bulk density (Adams, 1973; Federer et al., 1993).

The mean concentrations of extractable P, K and Ca in the 0–20 cm soil depth of cultivated fields in 1987 in southern Finland were 10, 109 and 1277 mg dm^{-3}, respectively (Erviö et al., 1990). These values for P and K are close to those for the soils of 10-year-old afforestations in our study; but the Ca concentration of the soil was markedly higher than in our study, as was the mean pH for cultivated fields (5.75). According to the soil fertility classification used in agriculture, which is based on the pH level of the soil (Kähäri et al., 1987), the afforested arable fields studied here would be classified as soils of rather poor fertility. This may have resulted from a lower inherent soil pH of the afforested fields because fields of low fertility are more likely to become afforested than are fields of high fertility (Selby, 1980). It is also possible that afforested fields have received less lime during the former cultivation period than fields still under cultivation or that the effect of liming has decreased since afforestation.

In Finnish upland forests, the timber production capacity is positively correlated with the content of exchangeable Ca in the surface soil (Aaltonen, 1937; Lipas, 1985; Tamminen, 1993; Urvas and Erviö, 1974; Valmari, 1921; Viro, 1951). In 10-year-old afforestations, the extractable Ca content in the 0–10 cm soil layer was more than twice that reported in forest soils for the OMT site type (high fertility class) in the corresponding soil layer in southern Finland (Tamminen, 1991; Urvas and Erviö, 1974). This suggests that modern agricultural practices have increased the capacity for timber production.

This suggestion was supported by the high volume of trees in the 60–70-year-old afforestations compared to adjacent 60–80-year-old stands. In Sweden, trees growing on former farmland have also been reported to have a high growth potential (Johansson, 1996; Karlsson et al., 1997).

Based solely on the higher N and Ca content of soil, however, it is not possible to reach the definite conclusion that afforested arable fields are much more fertile than continuously forested sites due to several possible adverse factors which might limit tree growth such as nutritional imbalances and nutrient-based growth disturbances (Birk, 1991; Carlyle et al.,1989; Hytönen and Ekola,1993, Zas and Serrada, 2003), vigorous growth of weeds (Ferm et al., 1994; Gilmore and Boggess, 1963), acute N deficiency (Richter et al., 2000) and low soil aeration (Wall and Heiskanen, 2003).

A crucial question for sustaining the soil fertility of afforested fields is: How persistent are the changes in soil properties and soil fertility induced by former agricultural land use? After afforestation the nutrient cycling of former agricultural land changes from a system that is heavily influenced by humans towards the natural state inherent to forest ecosystems. Substantial changes in the chemical properties of the soil may be expected to occur within a few decades after afforestation (Binkley et al., 1989). However, studies have shown that after abandonment or afforestation of agricultural land, agricultural influences on soil may be significant, lasting at least several decades and even centuries (Goovaerts et al., 1990; Compton and Boone, 2000; Koerner et al., 1997; Richter et al., 2000; Sandor and Eash, 1995), but there have also been contradictory results (Kalisz, 1986). Our results for 60–70-year-old afforestations support the view that agricultural land use has a long-term influence on soil properties, although differences in soil properties between former fields and continuously forested sites were limited to the upper 0–10 cm of soil. The soils of 60–70-year-old afforestations contained less nutrients than 10-year-old afforestations; however, it is not possible to conclude that amounts of soil nutrients have decreased after afforestation. The increase in the intensity of agricultural practices (fertilization regime, liming rates, use of machinery) during the past 60 years has most likely contributed to the difference in soil properties between young and old afforestations.

Trees affect the soil via the associated microclimate that is formed under tree cover, by elements in the throughfall, by their above- and below-ground litter, and by their root activities. Afforestation of agricultural land may ameliorate soil conditions through increased organic matter content of soil, improved bulk density and hydraulic conductivity, and increased levels of exchangeable calcium and magnesium (Rolfe and Boggess, 1973; Wilde, 1964). On the other hand, afforestation can also result in a general decline in soil fertility, manifested as lower concentrations of subsoil and litter nutrients (Johnson et al., 1988). After conversion of pasture or grassland to forest in New Zealand, soil exchangeable cations were found to increase, decrease or remain at the same level (Alfredson et al; 1998; Chen et al., 2000; Davis, 1995; Parfitt et al., 1997).

After afforestation of arable land, changes in amount and distribution of organic matter in the soil are important for soil fertility because organic matter is related to the cation exchange capacity, pools of N, P and S, soil structure, bulk density and water-retention characteristics. After afforestation, soil organic matter increases both aboveground and belowground (Alriksson and Olsson, 1995; Johnson, 1992; Romanyà et al., 2000). After afforestation, organic carbon content has been found to increase in the surface soil, while in deeper in the soil profile, the carbon content has been found to decrease (Jug et al., 1999; Makeschin, 1994; Vesterdal et al., 2002). In the 0–10-cm soil depth, organic C has been reported to decline directly after abandonment of agricultural land and to begin to accrue after the decline (Zak et al., 1990). In the subtropical climate in the southern USA, the development of the forest floor and accumulation of organic matter towards natural equilibrium is rapid during the early stage of vegetation succession, which covers 45 years after abandonment of a field and reaches maximum levels during middle succession in 45–100 years after abandonment (Switzer et al., 1979). In the afforested fields studied here, 60–70 years was not long enough to build up an amount of organic matter in the organic horizon equal to that of continuously forested sites. In contrast, Kalisz (1986) found that 60 years of forest growth after abandonment of old fields in the USA was enough to build up a humus horizon corresponding to forest soils; Schiffman and Johnson (1989) also reported similar results. The mean accumulation rate of organic matter (426 kg ha^{-1} per annum) found in this study implied that 122 years would be needed to regain the organic matter content stored in the organic horizon of continuously forested sites. Assuming that 58% of the organic matter is in the form of organic carbon, the accumulation rate for organic carbon found here is lower than the 360 kg ha^{-1} of organic carbon per annum reported for abandoned meadows in Italy. (Thuille et al., 2000).

A well-known effect of the afforestation of pastures and arable fields is a decrease in soil pH over several decades (Binkley et al., 1989; Giddens et al., 1997; Gilmore and Matis, 1981; Noble et al., 1999; Ovington and Madgwick, 1957; Parfitt et al., 1997). Afforestation of agricultural land initiates slow development towards a new acidity status, which is determined above all by the buffering capacity of the soil (Jug et al., 1999). In the 60–70-year-old afforestations studied here, the value of soil pH was still higher, especially in the top layers, than in the adjacent forests. Thus in the studied afforestations, the natural acidification process associated with the ageing of the stands (Troedsson, 1980) had not led to the same pH level as in the continuously forested sites even 60 years after afforestation. This suggests that the new acidity status of soil in afforested arable land is markedly higher than the inherent acidity status. The pH of the organic layer in afforested arable land was also higher than in continuously forested sites, which is probably a result of elevated Ca in the organic layer due to Ca uptake of trees from the mineral soil and transference of some of it to the organic layer through the forest litter.

The methods used to compare soil properties on afforested sites and continuously forested sites may have introduced some bias. It is possible that farmers had chosen land use according to the original fertility of the soil: agriculture on the richest soil and forestry on the poorest. The assumption that soils on adjoining sites were initially similar could not be tested. However, the particle-size composition of the soil indicated that initially at most locations the inherent soil fertility in former arable land and forestland was similar. Furthermore, soils were sampled to a fixed depth in the studied sites; but it is possible that not exactly the same genetic horizons were sampled in afforested sites and their adjacent forests, because on afforested sites there appears to have been a increase in thickness of the soil and a decrease in bulk density in the uppermost part of the soil profile due to cultivation. Comparisons of management-induced changes in nutrient contents in a soil layer of fixed depth are subject to errors if the masses of the soils being compared are not equivalent (Ellert and Bettany, 1995). Comparisons of nutrient concentrations of soil on cultivated and on continuously forested sites are unreliable because the concentrations do not adequately reflect the nutrient masses per unit volume (Ellert and Bettany, 1995). On the other hand, for nutrient comparison of soils with differing organic matter content (as was the case in our study), volumetric expression of soil nutrients is generally more appropriate than gravimetric expression (Westman et al., 1985). However, we compared soil nutrients using both gravimetric and volumetric expressions of soil nutrients; and since both comparisons produced essentially the same results, the conclusions based on these comparisons are reliable.

In conclusion, according to our results, former agricultural land use has significantly increased pH level, amounts of organic matter, total N and extractable nutrients of soil and probably the site index of afforested arable land. It appears that afforested sites have reached higher soil fertility and higher site index compared to the inherent soil fertility, which may remain high for at least several decades. Such a change in soil properties presents a special challenge for sustainable forest management if the new human-imposed level of soil fertility is to be sustained. In afforested arable land, potential risks for reduced soil fertility over time, such as leaching of nutrients from the soil, immobilization of nutrients in organic layer and biomass and acidification of soil, should to be studied.

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