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REGULAR ARTICLE

The effect of afforestation with Scots pine (*Pinus silvestris* L.) of sandy post-arable soils on their selected properties. II. Reaction, carbon, nitrogen and phosphorus

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Abstract Despite the extensive literature on the effect on soil properties of afforestation of former arable land, we still lack full understanding of whether the changes proceed in the same direction and at the same rate, and of how long is required to achieve a state of soil equilibrium typical of a natural forest ecosystem. Therefore, as part of a study comparing post-arable sandy soils (Dystric Arenosols) afforested with Scots pine *(Pinus silvestris* L.) with arable soils and soils of continuous coniferous forests, the range and direction of changes in pH, organic carbon (C_{org}), total nitrogen (N_{tot}), ammonium ($N\text{-}NH_4$) and nitrates ($N\text{-}NO_3$) in soil solution, total (P_{tot}) and available (P_{av}) phosphorus were determined. The studies were carried out in south-east Poland (51°30′-51°37′N, 22°20′-22°35′E). Ten paired sites of afforested soils (five with 14- to 17-year-old stands and five with 32- to 36-year-old stands) with adjacent cultivated fields, and five sites of continuous forest with present stands of ca. 130–150 years old were selected. Soil samples were taken from the whole thickness of master horizons and, in the case of the A horizon of the afforested soils, from three layers: 0–5 (A_{0-5}), 5–10 (A_{5-10}) and 10–20 cm (A_{10-20}). The cultivated soils in the Ap horizon showed higher pH (by ca. 1.0 unit), lower C_{org} and C:N, similar N_{tot}, lower $N\text{-}NH_4$, higher $N\text{-}NO_3$, higher P_{tot} and P_{av} contents compared with the Ah horizon of continuous forest soils. The results indicated decreased soil pH in the former plough layer of the afforested soils, with the greatest decrease observed in the 0–5 cm layer. In these soils, the C_{org} content was considerably higher in the A_{0-5} layer, but lower in the two deeper layers and in the whole A horizon (0–20 cm) compared with the Ap horizon of the arable soils. The results indicate that the C_{org} content, after an initial phase of decline, again achieved a level characteristic of arable soils. The N_{tot} content in all layers of the A horizon of the afforested soils was lower than in the Ap horizon of the arable soils, and showed a reduction with stand age, especially in deeper layers. The C:N ratios in the mineral topsoil increased with stand age. $N\text{-}NH_4$ content increased and $N\text{-}NO_3$ decreased after afforestation. The P_{tot} and P_{av} contents in all layers and in the whole A horizon of the afforested soils, on stands of both ages, was lower than in the Ap of the cultivated soils. From the results, it could be concluded that, after more than 30 years of tree growth, the soils of the A horizon were still more similar to arable than to continuous forest soils with respect to C_{org}, P_{tot} and P_{av}. With respect to pH, $N\text{-}NH_4$ and $N\text{-}NO_3$, especially in the 0–5 cm layer, they were more similar to continuous forest soils than to

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cultivated soils, but with respect to N_{tot} and C:N ratio they were somewhere in between.

Keywords Afforestation · Carbon · Nitrogen · pH · Phosphorus · Post-arable soils

Introduction

Abandonment and afforestation of agricultural soils has been one of the major land use changes in many European countries in recent decades (Vesterdal et al. 2002; Wall and Hytönen 2005; Uri et al. 2007).

In the past, cultivation of virgin soils (forest, grassland) usually resulted in a substantial increase in soil pH (Honnay et al. 1999) and decline in organic carbon content (Ellert and Gregorich 1996; Verheyen et al. 1999; Guo and Gifford 2002; Martens et al. 2003). The loss of organic matter caused by agricultural management can be related to lower input of crop plant residue and the increased rate of mineralisation (Carter et al. 1998), and the increase in soil pH due to lime application. In contrast to carbon, the content of soil phosphorus increase upon conversion of forest land to arable use, as shown in several studies (Ellert and Gregorich 1996; Honnay et al. 1999; Compton and Boone 2000). The effect of agriculture on soil nitrogen is more difficult to establish. According to Ellert and Gregorich (1996), the mean mass of N across all sites of cultivated soils in Ontario was 19% less than that in adjacent forest areas. However, the cultivation-induced declines in soil N were detectable only at 7 of the 15 sites examined. The authors suggest that variability among decreases at the various sites likely reflected differences in the management of N inputs. Moreover, Carter et al. (1998) indicated a possible dependence on soil type, as cultivation decreased the mass of total N (10%) in the soil profile of Podzolic soils, whereas it increased (37%) in Cambisols and Gleysolic soils. Generally, a narrowing of the C:N ratio when forest soils were cleared and cultivated for agriculture has been observed in many studies (Ellert and Gregorich 1996; Verheyen et al. 1999).

Afforestation of agricultural land may cause substantial changes in the chemical properties of the soil. These may be expected to occur within a few decades after plantation establishment (Binkley et al. 1989), although slow but continuous changes in important soil parameters are induced immediately after afforestation (Jug et al. 1999). A known effect of the afforestation of agricultural land is a decrease in soil pH, either shortly after forest establishment (Jug et al. 1999) or over several decades (Alriksson and Olsson 1995; Parfitt et al. 1997; Compton et al. 1998; Ritter et al. 2003).

Studies indicate that a land use change from agriculture to forest is a significant contributor to aboveground carbon (Garten 2002) and nutrient (Uri et al. 2007) sequestration. However, reports on carbon and nutrient accumulation in soils caused by conversion of former agricultural land to forest are more diverse. For carbon, some studies indicate relatively large increases in surface soil C stocks (Schiffman and Johnson 1989; Garten 2002) while others have concluded that there is a very limited capacity for soil C accumulation (Richter et al. 1999). Extensive literature data on this subject reviewed by Paul et al. (2002) show that findings are highly variable, with soil C either increasing or decreasing, particularly in young (<10 year) forest stands. Generally, the authors concluded that, on average, soil C in <10 cm (or <30 cm) layers decreased during the first 5 years of afforestation, and eventually recovered to C contents found in agricultural soils by 30 years. In practice then, soil C may either decrease, increase, or not change at all depending on a range of site factors (previous land use, climate and type of forest established) and management practices (Paul et al. 2002, 2003).

Trees planted on agricultural soils influence soil properties, and the former homogenous plough horizon starts to differentiate into an Ah horizon with a distinct gradient in soil reaction and base characteristics as well as organic matter and nitrogen concentration (Jug et al. 1999). However, these changes also depend on the effects of previous land use, which can be very long lasting. The findings of Compton and Boone (2000) suggest that cultivation-increased soil N and P levels persisted long after the agricultural period ended. This view is supported by Wall and Hytönen (2005), who stated that, for 60- to 70-year-old afforestations, agricultural land use had 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 soil. Falkengren-Grerup et al. (2006) also concluded that differences in land use persist over long periods

of time and that their impact on the ecosystem is considerable. Koerner et al. (1997) compared soil properties between ancient forests and previous farmlands afforested with conifers a century ago in France, and found that soils in all former agricultural lands contained more available P and had lower C:N ratios than continuously forested areas.

Despite the fact that changes in soil organic carbon and nutrient pools following the conversion of cultivated soils to forest are well documented, there are not many studies comparing afforested soils both with the cultivated land and with soils of continuous forests of stabilised ecosystems all located within one area.

We conducted an investigation aimed at determining the direction and rate of changes in selected soil properties, i.e. physical, physicochemical and chemical properties in the soil profile of former arable soils as affected by afforestation. Post-arable sandy soils (Distric Arenosols) afforested with Scots pine *(Pinus silvestris* L.*)* were compared to the adjacent arable soils and to soils of continuous fresh coniferous forests. Two groups of afforestations, i.e. 14- to 17-year-old stands and 32- to 36-year-old stands were included.

This paper presents the results on soil reaction, soil contents of organic carbon, total nitrogen, an ammonium and nitrate nitrogen in the soil solution, and total and available phosphorus.

Materials and methods

Study region and locations

The investigations were performed in the Lublin region of south-east Poland (51°30′-51°37′N, 22°20′-22°35′E). In this region, soils of low and medium agricultural value dominate (Turski et al. 1993). Habitats of fresh coniferous forests occur in the majority, followed by fresh mixed coniferous forests and fresh mixed forests (Trampler et al. 1990). The mean annual temperature (1951–1990) is 7.4°C, and precipitation is 550 mm. In the vegetation period, from April to October, the mean temperature is 13.2°C and precipitation is 400 mm (Kaszewski et al. 1995).

Ten paired sites of former arable soils afforested with Scots pine, with adjacent cultivated fields, were selected for investigation. At five sites the stand age was 14–17 years (young stands); we made the assumption that changes in some soil properties can be observed after about 15 years of afforestation. At the five other sites the stands were about twice as old, i.e. 32–36 years (older stands). This age span was selected as, according to the literature, soil properties can change substantially, i.e. revert to the level resembling the soil of mature forest ecosystems, three to four decades after tree planting. Moreover, afforestations of this age occur frequently in the study region. Five sites of semi-natural (continuous) forests, with stands of ca. 130- to 150-years-old, were included for comparison and to provide information on possible long-term changes in soil properties. These stands are situated 100–500 m from the afforested sites. Although they cannot be regarded as native or undisturbed, these forest areas represent stable, mature forest ecosystems and may be treated as an ecological reference (control) against which the afforested soils may be compared. In these stands, Scots pine trees dominate with the addition of a very few English oak trees (*Quercus robur*). The distribution of the study sites is given in Olszewska and Smal (2008).

Unfortunately, details of the historical management practices at the sites are not known as no documented records are available. Therefore, interviews and personal communications constituted the main source of information. The selection of sites followed consultation with forest survey personnel and landowners to ascertain that soils had been ploughed prior to afforestation, and that the cropping system and management intensity was typical for the region, i.e. similar to presently cultivated soils. It was also ascertained that all selected soils were used agriculturally at least for 100 years before afforestation, and that Scots pine trees were planted no more than 1–2 years after tillage termination. Management practices across the sites were similar.

All soils are formed on water-glacial sands and are classified as Distric Arenosols according to WRB classification (FAO-ISSS-ISRIC 1998). Regarding habitat type, all continuous forest communities of the studied soils were classified as sub-continental fresh coniferous forest (*Peucedano-Pinetum*) (for more details, see Olszewska and Smal 2008). The forests had not received any fertilisation or weed control treatments. The trees of the young stands had not been thinned.

On all the studied fields, crop rotations were similar and had remained the same for several decades. In the year of sampling, rye, oat and bird's-foot were grown at seven, two and one locations, respectively. Fertilisation rates were generally low and comparable at all sites (for more details, see Olszewska and Smal 2008). None of the cultivated fields had been limed within the last 5 years.

The site selection criteria allowed the assumption that each pair of plots had similar soil characteristics prior to afforestation, and that the cultivated soils could be considered as a control.

Sampling

To avoid direct fertilisation and vegetation effects, soil sampling was performed in the late summer, when fields were lying fallow after harvesting and were unfertilised. At each site, representative arable and forest profiles were excavated. For soil description, morphology and texture, see Olszewska and Smal (2008). At the young stand sites, shallow but distinct depressions in the rows could be seen. In these sites, profiles perpendicular to rows, i.e. from one row to the next width-wise, were dug. Samples were taken from the whole width of the profile to obtain soil material proportionally from the row and inter-row areas.

Soil samples (ca. 10 kg each) were taken from each master horizon from its whole thickness. An exception was the humus horizon of the afforested soils, from which samples were collected from three layers, i.e. 0–5 (A_{0-5}), 5–10 (A_{5-10}) and 10–20 cm (A_{10-20}). The organic horizon was sampled as one block from the whole thickness in the afforested soils and from the Oi and Oea layers in soils of continuous forests.

Analyses

The samples were air dried, passed through a 2 mm sieve and stored at room temperature. Part of the sample designated for organic carbon, total nitrogen and total phosphorus analyses was ground in an agate mortar.

Soil pH in soils was measured in distilled-deionised water and in 1 M KCl from dried samples in a 1:2.5 soil:water (solution) ratio in mineral soils and a 1:10 ratio in soil of organic horizons, and measured electrometrically using a pH meter.

The content of organic carbon (C_{org}) was determined by a wet oxidation method with $K_2Cr_2O_7$; in the mineral soils according to the modified Tiurin procedure (Arinuskina 1961), and in samples of organic horizons according to the Alten method as described by Bednarek et al. (2004).

The total nitrogen content in the soil was measured by a modified Kjeldahl method using a unit from the TECATOR company (oven 2006 and distillation unit 1002).

A soil solution was obtained by centrifugation following incubation of soil for 48 h at field capacity moisture and room temperature in darkness. Time of incubation was taken from Qian and Wolt (1990). Centrifugation was performed using double-bottomed tubes, at 3,500 rpm for 20 min. Soil solution samples were filtered through a 0.45 μm membrane filter before analysis. The NH_4 content was determined calorimetrically with Nessler reagent and NO_3 by ion chromatography. The concentration of N-NH_4 and N-NO_3 in mg dm^{-3} were recalculated as mg kg^{-1} of soil dry mass using soil moisture.

The content of total phosphorus (P_{tot}) was determined using the ICP-AES method (Leemman PS 950 apparatus) following digestion in a mixture of concentrated nitric acid and 70% perchloric acids, followed by HCl leaching. The available phosphorus (P_{av}) was measured in an extract of calcium oxalate solution acidified to pH 3.6 with HCl solution according to the procedure of Egner et al. (1960).

Statistics

Statistical analysis (arithmetic mean and standard deviation) was performed separately for each parameter, and separately for each horizon. Analysis of variance was also performed to determine whether there was significant differentiation in the studied soil properties depending on the land use. After verification of the general hypothesis, detailed comparisons were performed with Tukey's HSD post-hoc tests (α=0.05). In the present paper, the mean values for the horizons/layers of the forest soils were compared with the respective horizons of the arable soils within the separate stand sites. The mean values for the respective horizons of the forest soils between stand age classes were also compared. Calculations were performed using the program STATISTICA 6.0.

Results

pH

All soils were acidic throughout the soil profile (Fig. 1). The pH values in mineral soils were lowest in the A horizon and increased with depth. In the organic horizons of the afforested and continuous forest soils, the pH was generally higher than in the underlying horizon, i.e. the $A_{0–5}$ layer in the former and the Oea horizon in the latter case.

The average pH_{KCl} in the Ap horizons of the arable soils was 4.11 and 4.20 in soils from the 14–17 and 32–36 year stand sites, respectively. These values were higher than in the Ah horizon of the continuous forest soils (3.17).

The results indicate that interruptions in soil tillage and the planting of pine trees resulted in soil reaction changes. These were related mainly to the humus horizon and were not observed in the B and C horizons. Afforested soils, in both the young and older stands, showed stronger acidity (as measured by pH) in all layers and in the whole humus horizon than in the corresponding Ap horizons of the arable soils. Moreover, the differences were clearer for $A_{0–5}$ than for $A_{5–10}$ and $A_{10–20}$ layers and for soils from 32–36 compared to 14–17 year stands (Fig. 1).

Comparison between afforested and continuous forest soils showed the following order of increasing acidity in the A horizon: young stands (pH_{KCl} 3.89) < older stands (pH_{KCl} 3.57) < continuous forests (pH_{KCl} 3.17). It is worth pointing out that pH values in the $A_{0–5}$ layer of soils under the older stands (pH_{KCl} 3.37) were close to the values found in the Ah horizon of the old forest soils. No differences in pH between any groups of forest soils were noted in the deeper horizons.

Organic carbon

In all soils, the content of C_{org} was highest in the organic horizons (Ap in the case of arable soils) and decreased with depth (Table 1, Fig. 2a). C_{org} content was similar in the O horizons of soils from the young and older afforestations and throughout the O horizon of the continuous forests, i.e. at a level slightly exceeding 400 g C kg^{-1} (Table 1).

The C_{org} content of the Ap horizon of arable soils was 7.88 and 9.85 g C kg^{-1} at the young and older stands, respectively, and was about 2.5 times lower

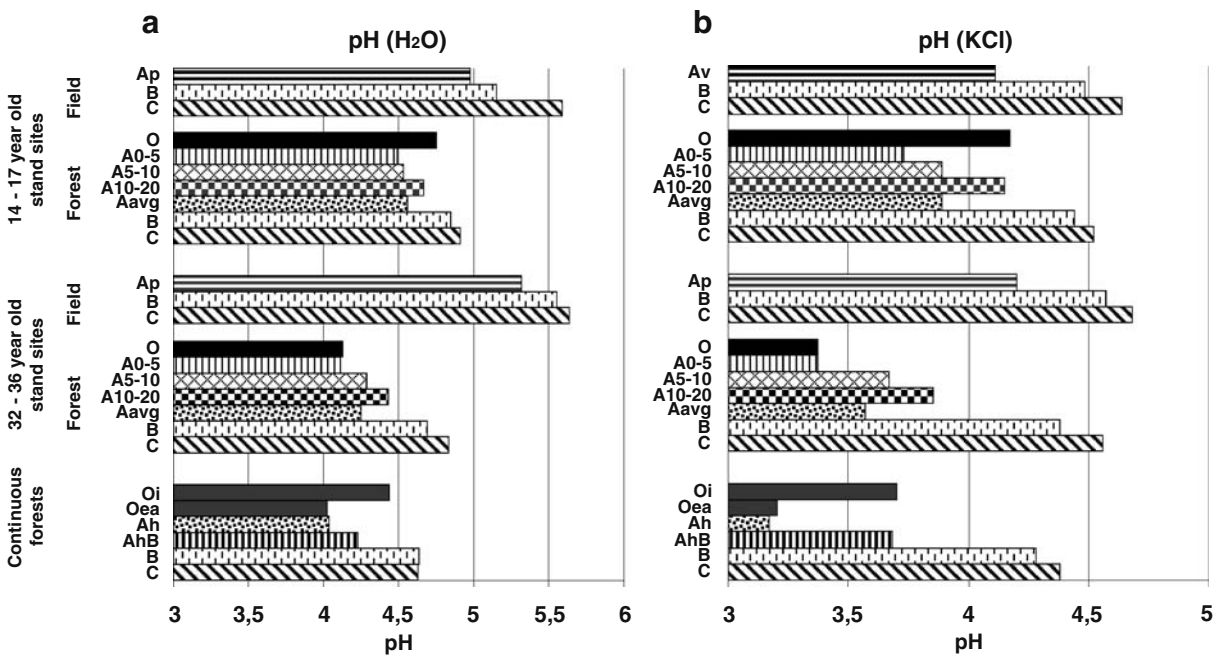

Fig. 1 Mean pH values in the studied soils, calculated as −log from mean H^+ concentrations. n=5 for Ap, B, C, O, Oi, Oea, $A_{0–5}$, $A_{5–10}$, $A_{10–20}$ and AhB; n=15 for A_{avg}

Table 1 Mean (standard deviation) content of organic carbon, total nitrogen, total phosphorus in organic horizon of the forest soils. For all stand classes, n=5

Horizon/layer	C_{org} (g C kg^{-1})	N_{tot} (g N kg^{-1})	P_{tot} (mg P kg^{-1})
14–17 year old stands			
O	423.08 (118.38)	12.11 (2.97)	751.3 (127.1)
32–36 year old stands			
O	413.07 (65.13)	14.04 (2.42)	712.5 (72.8)
Continuous forests			
Oi	458.24 (112.83)	13.59 (2.08)	828.8 (163.9)
Oea	359.45 (111.43)	12.77 (3.45)	655.0 (143.9)

(significantly) compared with values in the Ah horizon of continuous forests (Table 3).

In the afforested soils, the C_{org} content in the humus horizon was dependent on the layer and on the stand age. A clear relationship was observed for both stand ages: the highest content of C_{org} was seen in the $A_{0–5}$ layer, intermediate in $A_{5–10}$ and the lowest in $A_{10–20}$. The mean content in the $A_{0–5}$ layer was 9.5 and 12.9 g C kg^{-1} for soils of the young and older stands, respectively (Fig. 2a). These values were considerably higher (although not statistically significant) than in the Ap horizon of the cultivated soils. In contrast to $A_{0–5}$, in the deeper layers, in both groups of stands, the C_{org} contents were lower than in the corresponding Ap horizons (difference not significant). Finally, in the whole humus horizons of the afforested soils, the content of C_{org} was lower compared with the respective Ap horizons, but not significantly. However, it is worth noting that these differences decreased with stand age.

A comparison of the forest soils showed that the content of C_{org} in all layers and in the whole humus horizon increased in the following order: soils of young stands (A_{avg}=7.08) <older stands (9.35) <continuous forests (21.75 g C kg^{-1}). The differences between two first means were not significant. In turn, the mean content of C_{org} in all layers and in the whole humus horizon in both groups of afforested soils was significantly lower ($P \leq 0.001$) than in the Ah horizon of continuous forests (Table 4).

The C_{org} content was similar in the B and C horizons of the pairs of arable and afforested soils, whereas in the continuous forests it was significantly higher ($P \leq 0.05$) than in the corresponding horizons of arable soils (Table 3).

Nitrogen

Similarly to C_{org}, the N_{tot} content was highest in the top soil and decreased with the depth of the profile

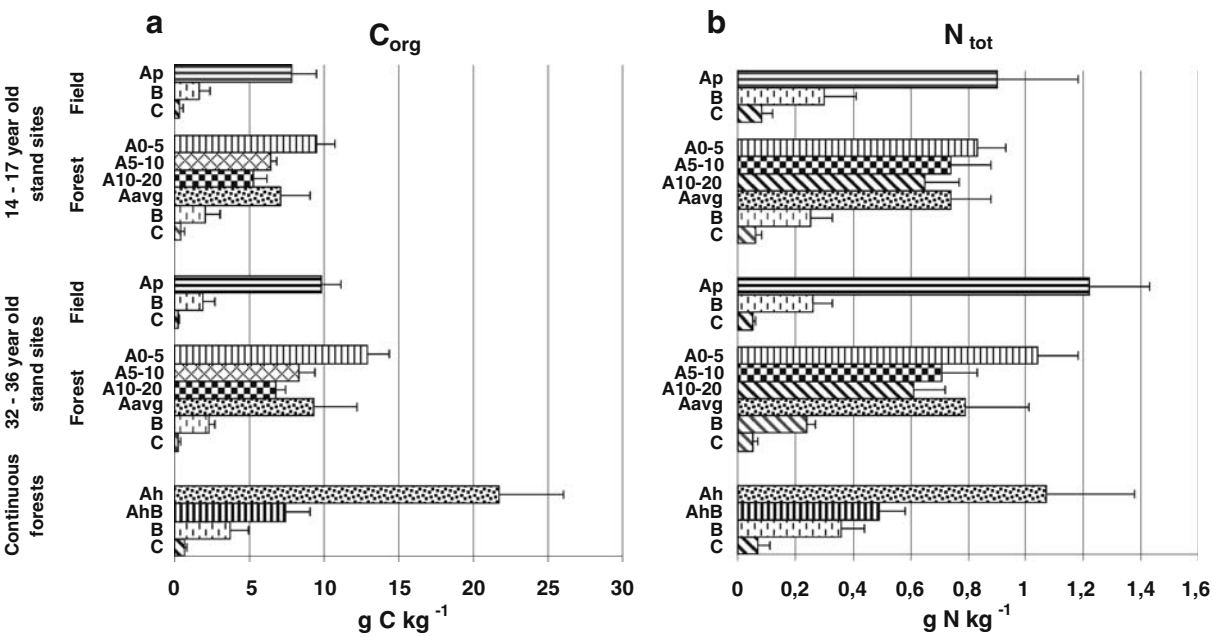

Fig. 2 Mean content of organic carbon (**a**), total nitrogen (**b**) and standard deviation (*error bars*) of the studied soils by soil horizon/layer. n=5 for Ap, B, C, $A_{0–5}$, $A_{5–10}$, $A_{10–20}$, Ah and AhB; n=15 for A_{avg}

Table 2 Mean (standard deviation) C:N ratio, content of soil solution N-NH_4 and N-NO_3 in the studied soils. n=5 for Ap, B, C, O, Oi, Oea, $A_{0–5}$, $A_{5–10}$, $A_{10–15}$, Ah and AhB; n=15 for A_{avg}

Horizon/layer	C:N	N-NH_4 (mg N kg^{-1})	N-NO_3 (mg N kg^{-1})
14- to 17-year-old stand sites			
Field			
Ap	8.94 (1.15)	1.47 (0.31)	2.41 (2.39)
B	6.85 (1.66)	0.28 (0.07)	0.67 (0.13)
C	5.27 (2.79)	0.11 (0.04)	0.20 (0.09)
Forest			
O	34.97 (4.56)	nd[a]	nd
$A_{0–5}$	11.48 (1.44)	3.89 (1.62)	1.11 (0.77)
$A_{5–10}$	8.97 (2.09)	2.07 (0.64)	0.21 (0.18)
$A_{10–20}$	8.32 (1.78)	1.34 (0.39)	0.08 (0.07)
A_{avg}	9.59 (2.18)	2.43 (1.46)	0.47 (0.64)
B	8.12 (1.62)	0.37 (0.14)	0.37 (0.36)
C	6.46 (2.19)	0.12 (0.04)	0.24 (0.43)
32- to 36-year-old stand sites			
Field			
Ap	8.15 (1.09)	1.05 (0.35)	1.82 (1.71)
B	7.12 (1.69)	0.31 (0.19)	0.61 (0.39)
C	4.90 (1.39)	0.16 (0.06)	0.16 (0.07)
Forest			
O	29.50 (1.37)	nd	nd
$A_{0–5}$	12.56 (1.72)	3.26 (1.30)	0.72 (0.72)
$A_{5–10}$	12.04 (1.76)	1.64 (0.30)	0.34 (0.49)
$A_{10–20}$	11.45 (2.07)	1.26 (0.27)	0.28 (0.48)
A_{avg}	12.02 (1.78)	2.06 (1.16)	0.45 (0.57)
B	9.98 (0.83)	0.56 (0.22)	0.38 (0.47)
C	5.01 (1.38)	0.21 (0.08)	0.21 (0.30)
Continuous forests			
Oi	34.03 (7.50)	nd	nd
Oea	27.90 (2.95)	nd	nd
Ah	20.82 (2.25)	3.84 (1.92)	0.21 (0.36)
AhB	14.67 (1.78)	1.26 (0.49)	0.08 (0.09)
B	10.08 (1.41)	0.22 (0.13)	0.04 (0.02)
C	7.41 (0.83)	0.06 (0.02)	0.02 (0.01)

[a] Not determined

(Table 1, Fig. 2b). The results revealed differences in the N_{tot} content between afforested and arable soils. In the Ap horizon of the cultivated soils, the mean N_{tot} content was 0.90 and 1.22 g N kg^{-1} for soils from young and older stand sites, respectively. As with C_{org}, the N_{tot} concentrations in the humus horizon of the afforested soils were highest in the $A_{0–5}$ layer, and decreased with increasing horizon depth. In the soils of both stand ages, in all layers and, on average, through the whole humus horizon they were lower than in the corresponding Ap horizon of the cultivated soils. In all layers, the differences were larger for soils under older than under young stands. Moreover, significant differences were observed between the mean content of N_{tot} in $A_{5–10}$ ($P \leq 0.01$), $A_{10–20}$ ($P \leq 0.001$) and in the whole A horizon ($P \leq 0.05$) of the 32- to 36-year-old forests and Ap of the arable soils (Table 3).

The N_{tot} content in Ah of the continuous forests was 1.07 g N kg^{-1} on average, similar to the values of Ap of the cultivated soils (no statistical difference).

As for C_{org}, in the afforested soils of both stands, the mean N_{tot} content of all layers and through the whole A horizon was substantially lower than that in the Ah of the continuous forests, although the difference was not as large as for C_{org} and was statistically insignificant.

The N_{tot} content was similar in the B and C horizons of all soils, and none of the compared pairs of means showed a statistically significant difference (Table 3).

Table 3 Comparison (Tukey's test; *P* value) of the mean values of the soil features of the horizon/layer of the forest soils with those of the corresponding horizon of the arable soils, within the separate stand sites

Horizon/ layer compared	C_{org}	N_{tot}	C:N	N-NH_4	N-NO_3	P_{tot}	P_{av}
14- to 17-year-old stand sites							
$A_{0–5}$ vs Ap	ns[a]	ns	ns	0.0287	ns	ns	ns
$A_{5–10}$ vs Ap	ns	ns	ns	ns	ns	ns	ns
$A_{10–20}$ vs Ap	ns	ns	ns	ns	ns	ns	ns
$A_{avg.}$vs Ap	ns	ns	ns	ns	ns	ns	ns
B vs B	ns	ns	ns	ns	ns	ns	ns
C vs C	ns	ns	ns	ns	ns	ns	ns
32- to 36-year-old stand sites							
$A_{0–5}$ vs Ap	ns	ns	0.0101	ns	ns	0.0013	ns
$A_{5–10}$ vs Ap	ns	0.0059	0.0401	ns	ns	0.0008	ns
$A_{10–20}$ vs Ap	ns	0.0004	ns	ns	ns	0.0009	ns
$A_{avg.}$vs Ap	ns	0.0369	0.0426	ns	ns	0.0010	ns
B vs B	ns	ns	ns	ns	ns	ns	ns
C vs C	ns	ns	ns	ns	ns	ns	ns
Continuous forests							
Ah vs Ap[b]	0.0001	ns	0.0001	0.0447	ns	0.0003	0.0494
B vs B[b]	0.0216	ns	0.0324	ns	0.0516	ns	ns
C vs C[b]	0.0479	ns	ns	ns	ns	ns	ns

[a] Not significant

[b] n=10

C:N ratio

The mean C:N values in the organic horizon of the forest soils were similar and ranged from 29.5 to 35.0 (Table 2). Among the humus horizons, the highest C:N value (mean 20.8) was observed for the Ah of the continuous forests. This mean value was significantly higher ($P \leq 0.001$) than the C:N in the Ap horizon of the arable soils (Table 3).

In the A horizon of afforested soils, higher C:N values were generally observed in comparison with the corresponding horizon of the cultivated soils. In soils from young stands, the mean value (11.5) was higher (not significantly) in the $A_{0–5}$ layer, whereas in the $A_{5–10}$ and $A_{10–20}$ the mean value was close to that of the Ap horizon. As a result, in the whole former plough layer, the C:N ratio (9.6) was 0.7 higher (not significant) than in the corresponding humus horizon of the arable soils. In turn, in soils from older stands the mean C:N values in all layers (with the exception of $A_{10–20}$) and in the whole humus horizon were significantly higher ($P \leq 0.05$) than in the Ap of the corresponding arable soils (Table 3).

Comparison of the afforested soils revealed that the mean C:N values in specific layers as well as in the whole A horizon under young stands were lower than the corresponding values in soils of older stands. However, only the difference between the mean values for the whole A horizon of these sites was significant ($P \leq 0.05$). In turn, in the afforested soils of both stand ages in all layers, the C:N ratio was significantly lower ($P \leq 0.001$) than in the Ah horizon in the continuous forest soils (Table 4).

The C:N ratios in the B horizons of all soils were lower than in top soils, and lower in the C horizons than in the B horizon. It was also observed that the C:N values in the B horizon of the three categories of forest soils were higher (for continuous forests, the difference was significant, at $P \leq 0.05$) in comparison with the corresponding horizon of the arable soils (Table 3).

Soil solution N-NH_4 and N-NO_3

In all soil profiles, the contents of N-NH_4 and N-NO_3 were highest at the surface and decreased with soil depth (Table 2).

In the Ap horizon of the cultivated soils, the mean N-NH_4 content was 1.47 and 1.05 mg N kg^{-1} for soils at the 14–17 and 32- to 36-year-old stand sites, respectively. The N-NO_3 content in soil solution of these horizons was higher than that of N-NH_4 (2.41 and 1.82 mg N kg^{-1}, respectively). The values for N-NH_4 were about three times lower (significant at $P \leq 0.05$) while those for N-NO_3 were about ten times higher (not significant) than in the corresponding Ah horizon of the continuous forest soils (Table 3).

The results clearly show that, in the arable soils (in all horizons), nitrates prevailed over ammonium

Table 4 Comparison (Tukey's test; *P* value) of the mean values of soil features for the corresponding horizon/layer in the forest soils, between stand age classes

Horizon/ layer compared	C_{org}	N_{tot}	C:N	N-NH_4	N-NO_3	P_{tot}	P_{av}
14–17 vs 32–36 year old stands							
$A_{0–5}$ vs $A_{0–5}$	ns[a]	ns	ns	ns	ns	ns	ns
$A_{5–10}$ vs $A_{5–10}$	ns	ns	ns	ns	ns	ns	ns
$A_{10–20}$ vs $A_{10–20}$	ns	ns	ns	ns	ns	ns	ns
$A_{avg.}$ vs $A_{avg.}$	ns	ns	0.0181	ns	ns	0.0500	ns
B vs B	ns	ns	ns	ns	ns	ns	ns
C vs C	ns	ns	ns	ns	ns	ns	ns
14– to 17-year-old stands vs continuous forests							
$A_{0–5}$ vs Ah	0.0001	ns	0.0001	ns	ns	0.0395	0.0396
$A_{5–10}$ vs Ah	0.0001	ns	0.0001	ns	ns	0.0486	0.0422
$A_{10–20}$ vs Ah	0.0001	ns	0.0001	ns	ns	ns	ns
$A_{avg.}$vs h	0.0001	ns	0.0001	ns	ns	ns	ns
B vs B	0.0459	ns	ns	ns	ns	ns	ns
C vs C	ns	ns	ns	ns	ns	ns	ns
32- to 36-year-old stands vs continuous forests							
$A_{0–5}$ vs Ah	0.0001	ns	0.0001	ns	ns	ns	ns
$A_{5–10}$ vs Ah	0.0001	ns	0.0001	ns	ns	ns	ns
$A_{10–20}$ vs Ah	0.0001	ns	0.0001	0.0453	ns	ns	ns
$A_{avg.}$vs Ah	0.0001	ns	0.0001	ns	ns	ns	ns
B vs B	ns	ns	ns	0.0161	ns	ns	ns
C vs C	0.0281	ns	ns	0.0012	ns	ns	ns

[a] Not significant

nitrogen and that , in contrast, the N-NH_4 content was much higher than the N-NO_3 content in soils of the continuous forest.

Afforested soils under young stands showed a higher content of N-NH_4 in the $A_{0–5}$ (significant at $P \leq 0.05$) and $A_{5–10}$ layers, whereas N-NH_4 content was slightly lower in the $A_{10–20}$ layer of the A horizon in comparison with the Ap horizon of the cultivated soils. As result, the N-NH_4 content in the whole former plough layer was 45% higher than in the Ap horizon. Similarly, in soils of the older stands, the N-NH_4 content in the soil solution from all layers and from the whole A horizon was much higher than in the solution from the corresponding horizon of the arable soils, although the difference was not statistically significantly. The N-NO_3 content showed the opposite pattern to the values seen for N-NH_4. The N-NO_3 content was considerably lower in all layers and in the whole A horizon of both groups of the afforested soils (not significant), compared with the Ap horizon of the adjacent cultivated soils.

Comparisons between forest soils showed that the contents of ammonium nitrogen in the uppermost layer of the afforested soils of both stand ages were similar to the values found in the Ah horizon of the continuous forest soils, whereas in the deeper layers they were lower than in Ah. In turn, the nitrate nitrogen contents in the whole humus horizon of soils of both the young and older stands (0.47 and 0.45 mg N kg^{-1}, respectively), were on average higher compared with the Ah horizon of the continuous forest soils (0.21 mg N kg^{-1}), although not significantly (Table 4).

In the B and C horizons of the afforested soils (of both stand ages) the N-NH_4 contents were slightly higher than in the corresponding horizons of the arable soils. The N-NH_4 contents were also higher compared with those of the B and C horizons of the continuous forest soils, and the differences for soils from the 32- to 36-year-old stands were significant ($P \leq 0.05$ and $P \leq 0.01$ for the B and C horizon, respectively) (Table 4). The contents of N-NO_3 in the B and C horizons of the afforested soils tended to be higher than in corresponding horizons of the cultivated and continuous forest soils.

Phosphorus

In all soils, the content of P_{tot} and P_{av} was highest in the top horizons and lowest in the C horizons (Fig. 3). It is also worth stressing the relatively high values in the B horizons of all soils.

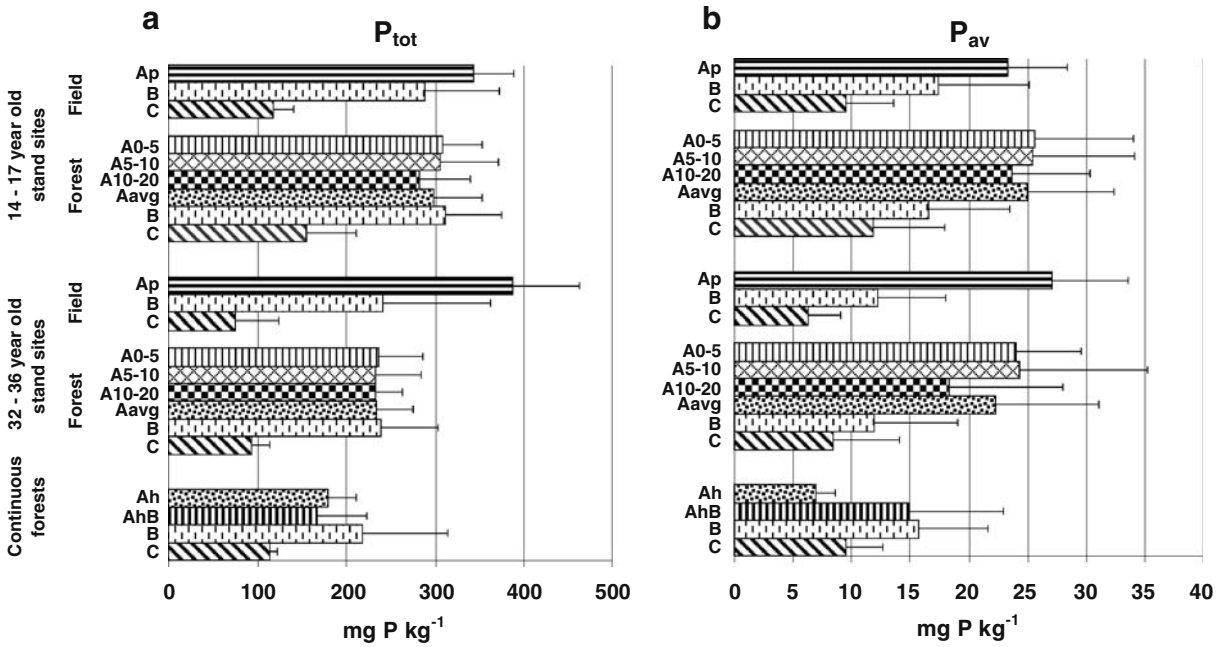

Fig. 3 Mean content of total (**a**) and available (**b**) phosphorus and standard deviation (*error bars*) of the studied soils by soil horizon/layer. n=5 for Ap, B, C, $A_{0–5}$, $A_{5–10}$, $A_{10–20}$, Ah and AhB; n=15 for A_{avg}

The organic horizons showed the highest content of P_{tot}, with the value being similar for all forest soils (mean value ranging from 712.5 to 828.8 mg P kg^{-1}; Table 1).

In the Ap horizon of the arable soils, the mean P_{tot} content was 342.3 and 386.5 mg P kg^{-1} and P_{av} content 23.25 and 27.04 mg P kg^{-1} for soils from the young and older stand sites, respectively. The values of P_{tot} were about 2 times and of P_{av} about 3.5 times higher (both significantly, at $P \leq 0.001$ and $P \leq 0.05$, respectively) than in the Ah horizon of the continuous forest soils (Table 3).

The mean content of P_{tot} in all layers and in the whole humus horizon of the afforested soils was lower compared with the corresponding horizon of the arable soils. The differences were not significant for soils from the young stand sites. Differences were larger for soils from the older stands and for all layers for A_{avg}; significant at $P \leq 0.01$ for $A_{0–5}$, and at $P \leq 0.001$ for $A_{5–10}$, $A_{10–20}$ and A_{avg} (Table 3). Available phosphorus showed a slightly higher content in all layers of the A horizon in soils from young stands, and lower contents (insignificantly) from older stands, than in the Ap horizon of the cultivated soil.

The P_{tot} and P_{av} contents in the humus horizon in forest soils decreased with stand age (Fig. 3). In soils from the young stands the values were higher than in the corresponding soils of the older stands, although not significantly. In turn, the P_{tot} and P_{av} contents in all layers of the A horizon in both groups of the afforested soils were higher in comparison with the Ah horizon of the continuous forest soils. Moreover, the differences in mean contents for both forms of soil phosphorus between the $A_{0–5}$, $A_{5–10}$ layers of the young stands and the Ah horizon of the continuous forest soils were significant.

None of the compared pairs of mean P_{tot} and P_{av} contents in the B and C horizons showed statistically significant differences between soils.

Discussion and conclusions

pH

The results presented here revealed that the pH in the A horizon of afforested soils is lower than that of the corresponding horizon of arable soils, especially in the uppermost layer. Acidification of former arable soils caused by afforestation is typical and has been found by many authors (e.g. Brożek 1993; Alriksson and Olsson 1995; Maciaszek and Zwydak 1996;

Bednarek and Michalska 1998; Compton et al. 1998; Jug et al. 1999; Ritter et al. 2003). The greatest decrease in pH found here was in the 0–5 cm layer of the afforested soils, in agreement with the study of Ritter et al. (2003). These latter authors found that, during a period of about 30 years following afforestation of nutrient-rich arable soils with Norway spruce, pH($CaCl_2$) values decreased by almost two units (from 6 to 4) in the 0–5 cm soil layer, and slightly less at a depth of 5–15 cm.

Acidification of afforested soils could be caused by natural processes related to decomposition of organic matter in organic horizons. Soluble fractions of humus acids migrate to the mineral soil, thus acidifying it. Conifers may also enhance soil acidity through the production of organic acids from their mycorrhizal roots and uptake of nutrients (De Vries et al. 1995). Acidification can also result from release of H^+ ions during uptake of base cations by tree roots (Brożek et al. 1998; Pokojska 1998), although most of the cations taken up by trees are returned to soil in litter and root detritus (Attiwill and Adams 1993). Furthermore, the post-arable soils studied here, already acid prior to afforestation, were subjected to further acidification because of their very low buffering capacity. Buffering capacity is an important factor determining the new acidity status of former agricultural soils influenced by afforestation (Jug et al. 1999). Until buffering capacity is sufficient to bind protons, no changes in soil pH will occur. According to the empirical model proposed by Binkley et al. (1989), a decrease in pH is largely related to reduction in base saturation of the exchange complex with time. In our study the base saturation, throughout the whole humus horizon was, on average, 18.9, 9.0 and 3.0% for the arable soils, and the soils of young and older stands, respectively (Olszewska and Smal 2008). The respective pH_{KCl} values of 4.18, 3.89 and 3.57 were related to these values.

The pH in the humus horizon of the soils under older stands, particularly in its uppermost part, was similar to values seen in the Ah horizon of the continuous forest soils. In contrast to our findings, Wall and Hytönen (2005), studying former arable fields afforested with Norway spruce in Finland, stated that in 60- to 70-year-old stands, the value of soil pH was still higher than on the adjacent continuously forested sites, especially in the top layers.

Organic carbon

Our investigations have shown that the C_{org} content in the A_{0-5} layer was higher in the afforested soils, under both young and older stands, whereas it was lower in the two deeper layers and, on average, in the former plough layer (0–20 cm) as compared with the corresponding Ap horizon of the arable soils. These findings are in agreement with several studies of mineral soil C changes in temperate climates after forest establishment (Jug et al. 1999; Richter et al. 1999; Vesterdal et al. 2002). In post-arable Danish soils planted with Norway spruce and oak, under comparable climatic conditions (mean annual temperature 7.7°C and precipitation 600 mm), Vesterdal et al. (2002) stated that C concentration and storage increased in the upper 5 cm of the mineral soil but decreased in the 5–15 and 15–25 cm soil layers with increasing stand age. The increase in C content of the upper mineral layer was overshadowed by the decrease in C content of the deeper layers and, as a result, the total C content for 0–25 cm decreased. Consequently, these authors found that, in the 30 years from afforestation, the sequestration of C in forest floors of both tree species and significant increase in C stores of the upper 5 cm was offset by decreasing C content in the lower part of the former plough layer. In contrast, Dovydenko (2004) obtained different results in a study of C content in the mineral 0–10 cm layer of post-agricultural soils afforested with spruce and pine, located in several natural forest regions in Poland and representing stand ages from 1 to 50 years. This latter study distinguished three groups of objects according to the pattern of C changes in the soil during first years following forest establishment. In the first group, the mean carbon content in the Ia age class stand decreased, in the second group it increased at the beginning and later on, for example for the Ib age class stand, it decreased to below the level prior to afforestation. Typical of the third group was a gradual increase in the carbon content. When data for all locations were averaged, the C content in both pine and spruce stands generally declined in the first phase and increased in the second in the course of stand aging.

There are some studies showing that, after afforestation, a slow accumulation of C may occur in the former plough layer (Brożek 1993; Maciaszek and Zwydak 1996; Garten 2002), which differs from our observations.

The initial decrease in soil organic carbon in the studied afforested soils was caused by the cessation of organic matter input resulting from the loss of crop residue input combined with the low input from a young forest stand (Vesterdal et al. 2002; Paul et al. 2003). The inflow of C_{org} with litter fall or roots was too low to balance the loss, especially from the deeper parts of the humus horizon. Following afforestation, C accumulates in surface soil due to non-mixing of litter, while soil C in the lower layers decreases as a result of enhanced decomposition of crop residues (Paul et al. 2002). Vesterdal et al. (2002) explain that carbon input from above- and below-ground litter production is low and spatially unevenly distributed in the transition phase from agriculture to forestry, and it increases until the canopy closes and rooting is complete. The same authors observed a lag period of approximately 10 years before the forest floors develop. Their findings are also supported by Garten (2002), who reported a net loss of mineral C stocks only on one of the studied sites, which was the only plantation that did not have a closed forest canopy.

Thinning may also be an important factor affecting carbon input to the soil, especially when the stems and branches are left on the ground (Carlyle 1995). This was not the case in the present study as trees in the young stands had not yet been thinned.

The decline in soil C could also be ascribed to the methods used for site preparation before tree planting (Johnson 1992; Paul et al. 2002, Dovydenko 2004). Disturbance of soil cover and its structure intensifies organic matter decomposition. Therefore, as Dovydenko (2004) suggests, refraining from intensive soil preparation prior to afforestation may be one way of increasing carbon sequestration in afforested soils and diminishing its emission into the atmosphere. Further studies are needed to quantify this effect.

Some findings suggest that soils with a high initial content of organic matter generally show a decrease in C content (Vesterdal et al. 2002) during the first decade of tree growth, whereas soils with low initial C values often exhibit accumulation of carbon (Garten 2002). Our results do not support this view, as the studied soils had low initial C content but showed a further decline after afforestation.

In the present study, the C_{org} content in all layers of the A horizon in soils of the 32- to 36-year-old stands was higher than in soils at the 14–17 year afforestations. On average, values in the former plough layer were similar (although still lower by 5%) to values for the Ap horizon of the arable soils, possibly indicating that, under the specific conditions of soil, climate and habitat present in this study, the carbon content, after an initial phase of decline, again reaches a level characteristic of arable soils. This view is supported by Vesterdal et al. (2002), who observed a C content similar to that under the previous agricultural systems within the surface 10 cm of soil in plantations older than 30 years.

The results also showed that a much longer time span is needed than undertaken in this study to accumulate C_{org} in afforested soils to levels typical for old forest soils. Even for the uppermost (0–5 cm) mineral soil of the older stands the C content was still 41% lower than in the Ah horizon of the continuous forest soils. This in accordance with data from a study by Falkengren-Grerup et al. (2006), who reported 40% higher C content in all but the litter layer in continuously forested land compared to formerly cultivated soil afforested 40–80 years earlier (see also Maciaszek and Zwydak 1996; Bednarek and Michalska 1998; Vesterdal et al. 2002). In contrast, Wall and Hytönen (2005) found a higher organic matter content in soils on afforested sites compared to continuously forested sites in Finland. They explain this by low temperatures and water logging in the boreal zone leading to greater organic matter accumulation in arable soils than in temperate zones, and also a high organic matter content due to input of residues, organic additions, and liming (decomposition stabilisation).

Nitrogen

The present study revealed that the N_{tot} content in all layers of the A horizon in the afforested soils was lower than in the corresponding Ap horizon of the arable soils. The pattern of N changes is in agreement with observations of Paul et al. (2003), which noted a decrease in soil N storage during 50 years of afforestation of former arable sandy soils in Ohio (USA), measured to a 1 m depth. Also, Alfredsson et al. (1998) found lower contents of total N in the 0–5 cm soil under 17-year-old fir compared with under grassland.

The results of this study indicate that the content of N_{tot} in the former plough layer decreased gradually with time of afforestation, especially in deeper soil. In

contrast, Alriksson and Olsson (1995) found significantly higher concentrations of N in the uppermost section of soils in 40- and 55- year-old stands than in a 20-year old stand.

Some data in the literature also indicate no (Bednarek and Michalska 1998; Brożek et al. 1998) or an unclear (Jug et al. 1999; Ritter et al. 2003) effect of afforestation on the nitrogen status in post-agricultural soils. Ritter et al. (2003) found no significant changes in N concentrations and storage in the 0–15 cm depth with increasing stand age, but a tendency towards decreased N at soil depths below 15 cm. The decline in N_{tot} content could be explained by intensive take-up by fast-growing trees combined with an inadequate supply of N from decomposing forest organic matter and deposition (Szujecki 1990). A decrease in the N pool with time is then understandable, since there is no input of mineral N via manure or mineral fertilisers, and N from the agricultural period of use is incorporated into the growing biomass. A decrease in N indicates that the N demand of the plants was not satisfied by N input, leading to a reduction in N content of the mineral soil during four decades of tree growth.

According to the present investigation, the N_{tot} content of the afforested soils was substantially lower (although not significantly) than that of the Ah horizon of the continuous forest soils. This observation is consistent with data from a study by Falkengren-Grerup et al. (2006), which stated that total N in the soil was higher in continuously forested land than in formerly cultivated fields afforested 40–80 years ago, and that the difference was significant when the whole soil profile was included, but not at any single depth. Also, Paul et al. (2003) reported that the N storage level in afforested soils was about three times lower than in continuous forest. In contrast, Wall and Hytönen (2005) showed more N in 10-year-old and 60- to 70-year-old afforestations on former cultivated fields than in continuously forested sites.

C:N ratio

The proportion of C:N is one of the basic indices reflecting the intensity of organic matter changes. The results presented here showed its dependence on soil horizon, land use and age of stand. It is worth pointing out that low variability in C:N found for particular groups of sites may indicate similar organic matter properties and conditions for decomposition, thereby justifying the choice of study objects.

In the humus horizon of the studied soils, the C:N ratio was lowest in the arable soils, followed by soils of the young stands, older stands and continuous forests. Some literature data show lowering of the C:N ratio due to cultivation as compared with natural forest soils. For example, in a study of native forest soils and adjacent arable soils in Canada, Carter et al. (1998) reported C:N ratios ranging from 8.6 to 14.5, with lower values for cultivated than for forested soils. Compared with forest soil, the surface layers of cultivated soils (averaged for 15 sites) had 34% less C and 19% less N according to a study by Ellert and Gregorich (1996). The authors suggest that decreases in C storage were attributed to reduced C inputs and enhanced rates of plant litter decay, while changes in N storage were dependent on management of N fertility, and that cultivation-induced narrowing of C:N ratios indicated preferential maintenance of N relative to C storage. Ploughing, fertilising and liming cause increases in the biological activity of microorganisms taking part in biochemical processes of organic matter turnover (Bednarek and Michalska 1998).

In the present study, C:N values in the mineral topsoil increased with stand age; for soils beneath 32- to 36-year-old afforestations the values were significantly higher than in the corresponding horizon of the adjacent arable soils. Broadening of the C:N ratio with stand age has been observed by many authors (Alriksson and Olsson 1995; Maciaszek and Zwydak 1996; Bednarek and Michalska 1998; Jug et al. 1999; Compton et al. 1998; Compton and Boone 2000; Ritter et al. 2003).

The observed increase in C:N ratio of the surface soil with time of afforestation is expected to result from the gradual incorporation of young organic material (Alriksson and Olsson 1995). It indicates a lowering of the decomposition rate of organic matter and the accumulation of the latter. In the uppermost layer, the disproportionate increase in organic carbon and decrease of N_{tot} yielded higher C:N ratios. A trend towards increased C:N ratios could be also caused by litter fall in tree plantations with C:N ratios between 30 and 40. Soil C:N ratios were positively correlated with forest floor C:N ratios in the work of Garten (2002).

The C:N ratios in afforested soils were still closer to the values observed in cultivated rather than in

continuous forest soils. Similar relationships were found by Paul et al. (2003). In contrast, Bednarek and Michalska (1998), and Maciaszek and Zwydak (1996) observed C:N values for 47- and 30- to 40-year-old afforestations, respectively, which were typical of native forest soils.

N-NH_4 and N-NO_3

The content of ammonium and nitrate in a soil/soil solution depend on the land use, and contents differ between cultivated and natural forest soils. In afforested soils, these forms of nitrogen can be used as indices of nitrogen changes approaching a state characteristic of a stable forest ecosystem.

The results showed that, in the soil solution of the arable soils, nitrates prevailed over ammonium nitrogen, as also seen in several other studies (Curtin and Smillie 1983; Larsen and Widdowson 1968; Wolt and Graveel 1985), although some studies observed the opposite trend (e.g. Simard et al. 1988; Łabętowicz 1995). In contrast to cultivated soils, in continuous forest soils, of the two forms of soluble nitrogen, N-NH_4 dominated, in agreement with the findings of Prusinkiewicz et al. (1992), Czępińska-Kamińska et al. (1999), and Smal (1999). The opposite relationship was reported by Gooddy et al. (1995) Marques et al. (1996), and Marques and Ranger (1997), while Davis (1990) and Schaaf et al. (1995) found no clear result.

The present results suggest that, after afforestation, the content of soil solution N-NH_4 in the A horizon increased, while N-NO_3 tended to be lower than in the cultivated soils. As a result, ammonium nitrogen prevailed over nitrates in the afforested soils, which is characteristic of continuous forest soils. The observed relationships indicate the restricted nitrification in the afforested soils, most probably due to acidification. It is known that nitrifiers are sensitive to low pH values, although some studies have shown that nitrification is not inhibited by the low pH of many forest soils (Attiwill and Adams 1993). Low-pH-restricted nitrification was observed in the humus layer of stands in Sweden and Norway, with almost no nitrification detected at a pH(H_2O) lower than 4.0 (Persson and Wirén 1995). Compton and Boone (2000) reported that nitrification was strongly influenced by land-use history, with the highest rates in formerly cultivated sites compared to woodlot and pasture.

The level of soluble N-NH_4 and N-NO_3 in forest soils can be interpreted in the light of current questions regarding N pollution. Nitrogen mineralisation and nitrification rates are known to increase in soils affected by decades of enhanced N deposition (Falkengren-Grerup and Diekmann 2003). The low values of NO_3 determined in the soil solution of the forest soils can be related to the low deposition of atmospheric N_{tot} in the study area. According to the data from the closest monitoring station, wet deposition of N_{tot} in the years 1995–2002 was 6.8 kg N ha^{-1} per year on average (GUS 2003). This value is much lower compared with the loads exceeding 25 kg N ha^{-1} $year^{-1}$ that occur in the most polluted areas of Poland or in many other regions in Western Europe (Wright et al. 2001; Holland et al. 2004). It was also lower than the effect-related critical load of N suggested by Falkengren-Grerup and Diekmann (2003) to be set to 7–10 kg N ha^{-1} $year^{-1}$.

Phosphorus

The results of this study showed a higher content of P_{tot} in arable soils than in continuous forest soils, which has also been documented in several other studies (Ellert and Gregorich 1996; Koerner et al. 1997). According to Ellert and Gregorich (1996), the surface layers of the cultivated soils had 24% more P than forested soils, which may result from fertilisation and indicates that application of P fertilisers more than offsets its removal in harvested products, and that much of the P is retained in the surface layers.

The P_{tot} contents were lower in all layers and in the whole humus horizon of the afforested soils in stands of both age groups (significantly for older stands) than in the corresponding horizon of the cultivated soils. The results suggest that, after afforestation, the content of P_{tot} and, to a lesser extent, of P_{av} gradually decreased in the former plough layer. However, after 30–40 years of afforestation they were still higher than in the soils of the continuous forest and more similar to the arable soils. These findings are in agreement with those of Wall and Hytönen (2005), who observed that the nutrient concentrations for P (extractable) at afforested sites were significantly higher at a soil depth of 0–10 cm than under continuous forest. Similarly, in mineral cultivated soil forested 90–120 years ago, Compton and Boone (2000) reported 300 kgP/ha more than in soils of

woodlots. Also, total P and available P tended to be lower in continuously forested land than in the formerly cultivated fields in the study of Falkengren-Grerup et al. (2006). This implies that agricultural use increased the P pool in the soil, probably due to application of organic and inorganic fertilisers during the cultivation period. In mineral forest soils, the organic horizon is the layer richest in macronutrients and is therefore the main source of nutrients to plants (Wall and Hytönen 2005). In the afforested soils studied, the mass of the organic layer, and thus also stocks of nutrients, was low, especially at the young stands, compared to the continuously forested sites. The concentration of P_{tot} decreased after afforestation, indicating that the former plough layer was the major source of P even in the soils of older stands. Moreover, our findings suggest that cultivation-increased soil P levels persist long after the agricultural period has terminated (Compton and Boone 2000).

Final conclusion

This study indicates that, after more than 30 years of tree growth, the soils of the A horizon were still more similar to arable than to continuous forest soils with respect to C_{org}, P_{tot} and P_{av}. With respect to pH, N-NH_4 and N-NO_3, especially in 0–5 cm layer, they were more like the continuous forest soils, and with respect to N_{tot} and C:N they lie somewhere between cultivated and continuous forest soils. Our findings suggest therefore, that former agricultural land use has a long-term effect on soil C and P of afforested soils. On the other hand, the forest vegetation changed the former plough layer with respect to pH and ammonium and nitrates, thus making the afforested soils closer to natural forest soils, in a relatively short time.

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