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Carbon Sequestration and Nitrogen Status in Arenosols Following Afforestation or Following Abandonment of Arable Land

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Abstract

Over 600 000 ha of agricultural land on infertile soils (mainly Arenosols) are or soon will be abandoned in Lithuania. According to the resolution of the Kyoto Protocol, afforestation of this land could be relevant with the focus on carbon sequestration. The current study was carried out in a long-term permanent experiment in which arable Haplic Arenosols were afforested or before the abandonment were used as arable land during 25-year-long period. Soil chemical changes with an emphasis on organic carbon (C) and total nitrogen (N) pools, and the storages in ground vegetation cover and the roots were compared in 45-year-old Scots pine (*Pinus sylvestris* L.) plantations and abandoned (11 years ago) arable land. The former plaggic Ap horizon was less acid (by 1.3-1.9 pH_{CaCl_2} units) and 2-3 times more saturated with mobile phosphorus and potassium compounds in plots on formerly fertilized abandoned arable land than in afforested with pine plantation plots. The total C pool at 100 cm mineral soil depth (including O horizons) in abandoned arable land (3.81 kg C m^{-2}) was 1.7 times less than in pine plantations (6.52 kg C m^{-2}), mainly because of C accumulation in the forest floor (2.24 kg C m^{-2}). The differences in mineral horizons were not significant, although the root mass in mineral topsoil was more than 10 times larger in pine plantations, except the surface 0-2 cm layer of the former Ap horizon in which the C pool was 3 times larger in pine plantations (0.72 kg C m^{-2}) than in abandoned arable land (0.22 kg C m^{-2}). Total soil N pools were at the same level (0.47-0.54 kg N m^{-2}) because the mineral soil to the depth of 100 cm contained 90% and more of N in both the abandoned arable land and the pine plantations. It was concluded that pine plantations better preserve C and N pools in mineral horizons of Haplic Arenosols, than abandoned arable land that was formerly intensively fertilized with conventional NPK fertilizers and farmyard manure as well.

Key words: Lithuania, Haplic Arenosols, abandoned arable land, afforestation, Scots pine, *Pinus sylvestris*, ground vegetation, roots, soil organic carbon, total nitrogen

Introduction

At present, Lithuanian forests occupy almost 2 million hectares (ME/SFSS 2006). In the future, the forest cover of the country may increase from 30.9% to 37-38%, because over 600 000 ha of agricultural land with infertile soils (mainly Arenosols) are or will soon be abandoned (Riepšas 2002). According to the resolution of the Kyoto Protocol, the afforestation of such land could be relevant, with the focus on carbon (C) sequestration.

Arenosols cover almost 12% of Lithuanian territory and 25-30% of the forest area (Beniušis and Vaičys 2004). Scots pine (*Pinus sylvestris* L.) prevails on Arenosols and Scots pine stands make up more than 36% of the forests.

Afforestation of arable land with coniferous trees, including Scots pine, induces chemical changes in mineral topsoil due to the large amount of the litterfall. The accumulation and decomposition of the organic layer (mor humus) is followed by destruction of former plaggic Ap horizon because of the leaching of organic carbon acids and nutrients (mainly exchangeable cations of potassium, calcium and magnesium), which is reflected by a decreasing pH (Reynolds *et al.* 1988, Карпачевский and Травлеев 1991, Whiteley and Wilson 1991, Kubiniok and Muller 1994, Leth and Breuning-Madsen 1994, Alriksson and Olsson 1995, Andersson *et al.* 2002, Vesterdal *et al.* 2002). These changes occur within several decades mainly in deeper layers of the Ap horizon, because the mineralization of organic layer leads to formation of a thin humic Ah horizon in the surface of mineral soil. As a consequence, C stock increases in the surface 0-5 cm mineral soil layer but decreases in the deeper (5-25 cm) layer. Therefore the initial C pools in mineral topsoil (< 20-30 cm) tend to decrease during the first 5-10 years following afforestation of arable land (Richter *et al.* 1999, Paul *et al.* 2002, Vesterdal *et al.* 2002, Paul *et al.* 2003). In forest plantations older than 30 years, the soil C store has recovered to the original level and starts increasing. Such an increase is especially considerable in the nutrient-poor sandy soils with a low stock of C (Post and Kwon 2000).

These changes in soil C stores following afforestation of arable land have mainly been revealed using a chronosequence approach, *i.e.* by analyzing the data obtained in forest plantations of different age. The objective of the current study was to assess changes in soil carbon stocks (i) following afforestation with Scots pine, and (ii) following abandonment of fertilized arable soils. We hypothesized that the effects of these two forms of land use on soil properties could be modified by: (i) the application of mineral and organic fertilizers in arable land; and (ii) the accumulation of organic matter in the forest floor of the plantations. Assessment of the differences was conducted in the 45-years permanent experiment in which ground vegetation, organic and mineral soil, roots were sampled in Scots pine plantations and on adjacent abandoned arable land.

Material and methods

Study site

The study was carried out at the Perloja Experimental Station of Lithuanian Institute of Agriculture. In 1960, a long-term experiment (hereafter – the Perloja experiment) was established with the aim to compare the productivity of field and forest crops on arable land and arable land afforested with Scots pine (*Pinus sylvestris*) (Kupčinskas 1999).

The Perloja experiment site (total area 40 ha) is situated in a flat area (elevation 110 m) in southern Lithuania (54°10' N, 24°25' E). It included three treatments – plots of (i) abandoned arable land, (ii) planted and (iii) naturally regenerated Scots pine stand repeated in four blocks (Fig. 1). The soil is a well-drained Haplic Arenosol (ISSS-ISRIC-FAO 1998) developed on glaciofluvial sandy deposits from Weichselian glaciation. The soil consists of coarse sand with a high proportion (10-20%) of coarse particles (>2 mm) and a low clay + fine silt content (less than 5%). Before the establishment of Perloja experiment small farmers used the site under crop production for some centuries. The depth of the plaggic Ap horizon was 20 cm (pH_{CaCl2} 4.8-5.6) with low concentrations of nutrients and C: 0.30-0.38 mg N g^{-1}; 39-77 μg K_2O g^{-1}; 51-70 μg P_2O_5 g^{-1}; and 4.8-7.0 mg C g^{-1} (Gudaitienė *et al.* 1984).

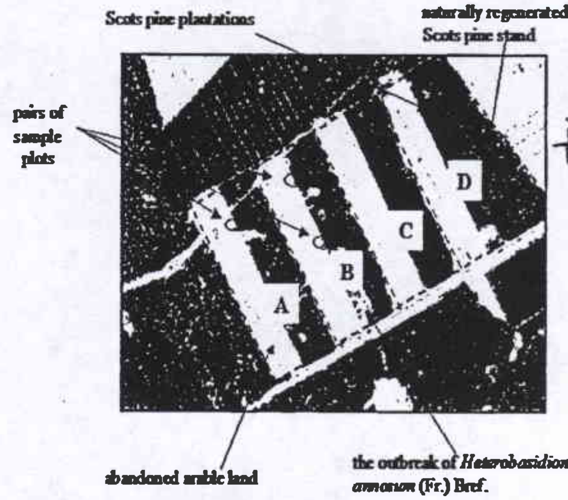

Figure 1. Diminished ortho-photo map of the Perloja experiment (total area – 40 ha, A–D – four blocks with abandoned at present arable land, planted and naturally regenerated Scots pine stands, 1-3 – pairs of adjacent sample plots)

The mean annual precipitation of the area is 682 mm. The mean annual temperature is 6.2°C, with a mean January temperature of -5.4°C and a mean July temperature of 18.6°C.

Pure Scots pine plantations were planted in 1961 while Scots pine stands of natural origin had started to regenerate 12 years before; no thinnings have been carried out until 2005 in the afforested part of the Perloja experiment. The Scots pine plantations had an initial planting density of 10 000 trees per ha and there are no deciduous tree species. An outbreak of root rot (*Heterobasidion annosum* (Fr.) Bref.) has affected about 20% of the plantation area (Armolaitis *et al.* 2005). In 2004, the standing density in the pine plantation sample plots was about 3000 trees ha^{-1}, mean tree height was 16.9 m, mean DBH was 12.8 cm, stem volume was 340 m^3 ha^{-1}, and fallen dead stem wood volume was 31 m^3 ha^{-1}. It is worth noting that no damages caused by root rot have occurred in the naturally regenerated Scots pine stands, which have a much lower standing density (450-650 trees ha^{-1}).

The productivity of the agricultural land in the Perloja experiment was studied in 1961-1994. In the first part of the period (in 1960-1973) the crop rotations included potatoes (*Solanum tuberosum* L.), maize (*Zea mays* L.), lupin (*Lupinus luteus* L.), winter rye (*Secale cereale* L.), oats (*Avena sativa* L.) and perennial grasses, mainly a mixture of clover (*Trifolium pratense* L. and *T. repens* L.), timothy-grass (*Phleum pratense* L.) and meadow fescue (*Festuca pratensis* Huds.). Conventional NPK fertilizers were applied annually (34 kg N, 60 kg P, and 80 kg K per ha) with or without the addition 60 Mg ha^{-1} of cattle manure every six years. In the second part of the period (in 1974-1994) the rotation was simplified: maize – winter rye – oats. Two doses of mineral nitrogen (15 + 30 kg or 30 + 60 kg N ha^{-1}) in combination with phosphorus (60 kg P ha^{-1}) and potassium (90 kg K ha^{-1}) fertilizers were applied annually with or without the addition of manure (30 Mg ha^{-1} every three years or 60 Mg ha^{-1} every six years).

In 1995, investigations in agricultural land of the Perloja experiment were interrupted, because despite the abundant mineral and organic fertilization it was stated that the arable land was non-productive (Lukšienė 1997, Kupčinskas 1999). The arable land was totally abandoned only in blocks A and B of the experiment; in blocks C and D this land was occasionally used as farmland and even for tillage competitions.

For our study, in 2005 we selected two contrasting treatments of the Perloja experiment: (i) non-fertilized Scots pine plantations; and (ii) former arable land not cultivated for the last 11 years, on which the largest amounts of fertilizers had been applied before abandonment. To avoid the mentioned disturbances of abandoned arable land the sample plots were placed in blocks A and B (Fig. 1). It was calculated that before abandonment total nutrient additions to the arable land were about 1.4 Mg N ha^{-1}; 2.0 Mg P ha^{-1}; and 2.9 Mg K ha^{-1} using mineral fertilizers, and 28.8 Mg C ha^{-1}; 1.6 Mg N ha^{-1}; 0.7 Mg P ha^{-1}; and 1.8 Mg K ha^{-1} using manure (calculated according to Tripolskaja 2005).

Field sampling

Three circular plots of 400 m^2 (R = 11.29 m) were established in the Scots pine plantations and three in the adjacent abandoned arable land in blocks A and B (Fig. 1).

Ground vegetation, soil and root sampling was carried out in September 2005. Composite soil samples (n = 3) were collected from the L (litter) and F (fermented) + H (humic) horizons of the organic O layer, and in the former plaggic Ap (from 0-2; 2-10 and 10-20 cm deep layers) and illuvial B (30-40; 50-60 and 80-90 cm) mineral horizons in each plot at 10 systematically distributed points along the 20 meters transects. The organic layer was sampled using a 1000 cm^2 metallic circular frame. The total fresh weight of the L and F+H horizons was determined (n = 5 in each plot) and subsamples were collected for laboratory determination of the moisture content. Mineral soil was sampled using metallic augers of different diameters (2-4 cm). In addition, the samples (n = 3) for determination of fine mineral soil (<2 mm) bulk density were taken with metallic cylinders (volume 188 cm^3).

Ground vegetation and root mass sampling (in the upper 0-30 cm mineral soil layer) were conducted in one pair of adjacent sample plots (Fig. 1, 1 pair). Two replicate square plots (1 x 1 m) were set up at a distance of 6 m and 12 m from the edge in Scots pine plantations and at 12 m and 18 m from the pine plantations in abandoned arable land. The sampling was conducted from two sampling points (0.25 x 0.25 m, n = 8 in each land use) located in the opposite corners of each square plot. Ground vegetation species composition was recorded.

Chemical analyses

For chemical analyses the organic and mineral soil, ground vegetation and root (after washing) samples were dried at 40°C, besides, mineral soil samples were sieved through a 2 x 2 mm sieve. In all samples, organic carbon (C) concentration was determined with a Heraeus apparatus (ISO 10694, dry combustion at 900°C), and total nitrogen (N) was analyzed using the Kjeldahl method (ISO 11261). Concentrations of mineral nitrogen in organic and mineral soil samples were determined by the spectrometric method (ISO 14256-2) in 1 M KCl extraction: NH_4-N using sodium phenolate and sodium hypochlorite, and NO_3-N using sulfanilamide. Mobile potassium (K_2O) and mobile phosphorus (P_2O_5) were determined by the Egner-Riehm-Domingo (A-L) method (Egner *et al.* 1960). Also, pH was potentiometrically measured in a 0.01 M $CaCl_2$ suspension (ISO 10390).

For the determination of oven-dry weight (kg m^{-2}) of organic horizons and root mass in the upper 0-30 cm mineral soil layer, as well as for the dry bulk density (kg m^{-3}) of the fine soil fraction (<2 mm), the samples were dried at 105°C.

Pools of C and N in above-ground soil vegetation cover, roots and soil organic horizons (g m^{-2}) were calculated by multiplying the mean concentrations of C and N (mg g^{-1}) by the mean mass (kg DW m^{-2}) of organic matter. C and N pools (kg m^{-2}) in the mineral soil layers were calculated by multiplying mean C and N concentrations (mg g^{-1}) with fine soil bulk density (Mg m^{-3}) and the thickness (m) of sampled layer. For the calculation of the total pools of C and N in mineral soil to a depth of 100 cm the pools for the not-sampled layers Ap (20-30 cm) and B_2 (90-100 cm) were equated to the pools measured for the layers Ap (10-20 cm) and B_2 (80-90 cm) respectively, while for not-sampled other layers B_1 (40-50 cm) and B_2 (60-80 cm) were obtained by the averaging the values from neighbouring layers.

Data analysis

All the parameters of organic or mineral soil, ground vegetation, and roots separately were treated by one-way ANOVA. The statistical significance of the difference between the data obtained in Scots pine plantations and abandoned arable land was tested using an independent sample *t*-test.

Results

Soil pH, nutrients and carbon concentrations

In the Haplic Arenosols studied we found the following organic horizons: L – litter (containing unaltered dead remains of needles, twigs and small branches, cones and bark in pine plantations and dead grass fall in abandoned arable land); F – fermented (containing only the remains of the autumn of the previous years grass cover in abandoned arable land); and H – humic (absent in abandoned arable land).

Data presented in Table 1 show striking differences in the accumulation rate of the organic layer. The mean mass of the L and F+H horizons was 7 and 14 times larger in Scots pine plantations (0.73 kg m^{-2} and 4.75 kg m^{-2}) than in abandoned arable land (0.10 kg m^{-2} and 0.34 kg m^{-2}).

The data presented in Table 1 allow also to compare the chemical properties of Haplic Arenosol in Scots pine plantations and abandoned arable land. Therefore, it is not reasonable to compare in detail the concentrations of the nutrients and especially C in the organic layer of the soils because of the reported large differences in the mass. However, it should be noted that the organic horizons in plantation plots were significantly more acidic (by 1.4-1.9 pH_{CaCl2} units), and contained higher concentrations of C (by 50%) and NH_4-N (up to 2-fold) in comparison with the abandoned arable land. Meanwhile, the concentrations of K_2O and P_2O_5 were 4-7 and 2-3 times, respectively, higher in dead grass fall of abandoned arable land.

In the mineral soil profiles, we visually distinguished the former plaggic Ap (0-30 cm) and illuvial B_1 (30-60 cm) and B_2 (60-140 cm) horizons. As one can see from Table 1, the mean bulk density of the former Ap horizon (1.26-1.36 Mg m^{-3}) was not significantly lower ($p > 0.05$) as compared with the deeper 30-40 cm layer of the B_1 horizon in either the plantations or

Table 1. Mean characteristics of Haplic Arenosols in Scots pine plantations (*pl*) and adjacent abandoned former arable land (*ab*) of the Perloja experiment

Horizon (depth, cm)		Organic layer mass (kg DW m^{-2}) or bulk density of fine (<2 mm) mineral soil (Mg m^{-3})	pH($CaCl_2$)	NH_4-N (µg g^{-1})	NO_3-N (µg g^{-1})	K_2O (µg g^{-1})	P_2O_5 (µg g^{-1})	N (mg g^{-1})	C (mg g^{-1})
L[1]	*pl*	0.73 (0.16)**C	3.7 (0.2)*A	87.5 (2.8)***B	1.1 (0.0)B	584 (49)***B	325 (37)**B	9.4 (1.1)AB	545.7 (6.0)***C
	ab	0.10 (0.02)A	5.6 (0.2)C	42.0 (2.4)A	1.0 (0.0)A	2593 (101)C	650 (30)C	10.9 (0.7)B	360.6 (17.2)B
(F+H)[2]	*pl*	4.75 (0.59)***D	3.6 (0.2)***A	59.6 (23.6)A	1.0 (0.0)*** B	384 (5)***A	247 (6)**A	8.1 (1.7)A	386.7 (26.0)**B
	ab	0.34 (0.04)B	5.0 (0.1)B	40.1 (6.2)A	2.1 (0.0)C	2815 (142)C	660 (35)C	9.3 (0.4)A	252.5 (16.5)A
Ap (0-2)[3]	*pl*	1.26 (0.04)a	3.6 (0.2)**a	22.7 (2.5)***e	2.2 (0.1)*b	146 (18)e	58 (8)***ab	2.3 (0.2)*e	28.7 (1.6)***g
	ab	1.32 (0.07)ab	5.5 (0.2)c	5.0 (0.6)d	3.8 (0.5)c	179 (4)f	136 (8)c	1.3 (0.1)d	8.4 (1.0)f
Ap (2-10)	*pl*	1.26 (0.04)a	4.7 (0.4)***b	3.0 (0.1)b	1.7 (0.1)a	51 (2)***a	50 (5)***a	0.5 (0.1)*b	6.5 (0.3)e
	ab	1.32 (0.07)ab	6.0 (0.2)d	3.6 (0.5)bc	2.0 (0.2)ab	114 (4)d	148 (11)c	1.0 (0.1)d	5.7 (0.3)d
Ap (10-20)	*pl*	1.31 (0.04)ab	5.5 (0.5)*bcd	3.5 (0.2)c	1.8 (0.1)a	48 (2)***a	46 (5)**a	0.4 (0.0)b	4.6 (0.4)c
	ab	1.36 (0.02)b	6.9 (0.2)e	3.3 (0.2)bc	1.8 (0.1)a	111 (6)d	153 (12)c	0.6 (0.1)c	4.6 (0.7)c
B_1 (30-40)	*pl*	1.31 (0.06)ab	6.3 (0.6)e	2.7 (0.4)b	1.8 (0.1)a	53 (4)*ab	54 (12)ab	0.2 (0.1)a	1.6 (0.2)a
	ab	1.32 (0.13)ab	6.8 (0.2)e	2.9 (0.3)b	1.7 (0.1)a	85 (6)c	85 (22)b	0.4 (0.1)b	1.4 (0.3)a
B_1 (50-60)	*pl*	1.47 (0.23)bc	6.7 (0.5)e	2.3 (0.3)a	1.7 (0.0)a	57 (3)**b	50 (15)*ab	0.2 (0.0)a	2.0 (0.1)b
	ab	1.51 (0.19)c	7.1 (0.2)e	2.3 (0.3)a	1.7 (0.0)a	114 (10)d	83 (7)b	0.2 (0.0)a	1.9 (0.9)ab
B_2 (80-90)	*pl*	1.45 (0.20)bc	7.4 (0.1)e	1.7 (0.1)a	1.7 (0.0)a	61 (3)**b	76 (3)b	0.2 (0.0)a	1.5 (0.6)ab
	ab	1.52 (0.21)c	7.6 (0.2)e	2.2 (0.3)a	1.6 (0.1)a	103 (8)d	89 (7)b	0.2 (0.0)a	1.3 (0.6)a

Standard errors of means (n = 3) are given in parenthesis. Significant differences ($p<0.05$) in organic horizons are marked with different upper case letters, in mineral soil – with different lower case letters. Asterisks denote significant differences between data obtained in Scots pine plantations and abandoned arable land (*pl* and *ab*): * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

[1] L – litter horizon of organic layer; [2] F+H – fermented (F) and humic (H) horizons of organic layer, H horizon was not found in abandoned arable land; [3] Ap – former plaggic mineral horizon

former arable plots. However, some chemical differences between the former Ap and B horizons were obvious. For a general comparison, it is reasonable to exclude the uppermost 0-2 cm layer, which was, as will be stated later on in this section, peculiarly transformed because of differences in the decomposition rate of the organic layer and (possibly) in microclimatic conditions. For example, in pine plantations this uppermost mineral layer was mostly acid (pH_{CaCl2} 3.6) and contained 4-6-fold higher concentrations of C (28.7 mg g^{-1}) and N (2.3 mg g^{-1}) as compared with the underlying layers of the Ap horizon.

On excluding the uppermost layer, i.e. according to the data obtained in the 2-20 cm mineral layer, in the former Ap horizon (in both the plantation and abandoned arable land) the concentrations of C (4.6-6.5 mg g^{-1}) and total N (0.4-1.0 mg g^{-1}) were on average up to 2-5 times higher than in the underlying B_1 horizon. Besides, the former Ap horizon in abandoned arable land did not differ significantly in pH and was 1.7-1.8 times more saturated with P_2O_5 and up to 30-40% more saturated with K_2O. In comparison to the B_1 horizon, the former Ap horizon in pine plantations was more acidic by 0.8-2.0 pH_{CaCl2} units, while the mobile nutrient (P_2O_5 and K_2O) concentrations were similar.

The concentrations of the nutrients in mineral horizons of the soils could be compared, because the soil bulk density of separate sampled layers in Scots pine plantations was not significantly ($p>0.05$) lower than in abandoned arable land (Table 1). To compare with pine plantations, in formerly intensively fertilized abandoned arable land the mineral soil was 1.6-2.3 times more saturated with K_2O (to a depth of 90 cm), except for the uppermost (0-2 cm) mineral layer. Other significant differences in soil chemical properties were determined only in the former plaggic Ap horizon. In pine plantations, the Ap horizon was more acidic (by 1.3-1.9 pH_{CaCl2} units) and contained 2-3 times lower concentrations of P_2O_5. Meanwhile, significant differences for NH_4-N, NO_3-N, total N and organic C were found only in the top 2 cm layer of the mineral soil. The NO_3-N concentration was 70% higher in the abandoned arable land than in the plantation. In contrast, at a depth of 0-2 cm the concentrations of NH_4-N and C were 3-4 times higher and total N was 1.7-1.8 times higher in pine plantations.

It would have been interesting to compare the concentrations of nutrients and C in the former Ap horizon with the data documented (see Material and methods) before establishing the Perloja experiment. However, because of the lack of detail and the variable initial data (4.8-7.0 mg C g^{-1}) no changes in the C concentrations could be confirmed. Meanwhile, in the abandoned arable land, which had been intensively fertilized, there was a 2-3-fold increase in P_2O_5 (from 51-70 to 148-153 µg g^{-1}) and up to 3-4-fold increase in N and in K_2O concentrations (from 0.3-0.4 to 0.6-1.3 mg g^{-1} and from 39-77 to 111-114 µg g^{-1}, respectively). In the Scots pine plantations there was some significant decrease of pH in the former Ap horizon.

C and N concentrations in ground vegetation and roots

In the abandoned arable land plots, 27 herbaceous species were found: grass cover (mainly *Hieracium pilosella* L., *Trifolium arvense* L., *Achillea millefolium* L., *Artemisia vulgaris* L.) comprised about 53-54% of the surface area. In Scots pine plantation plots, ground vegetation cover was composed of mosses (mainly *Pleurozium schreberi* (Brid.) Mitt. and *Hylocomium splendens* (Hedw.) Schimp.) and reached 60% (data on ground vegetation cover are not shown).

The mean mass of ground vegetation cover in abandoned arable land (0.08 kg m^{-2}) was almost 7 times less than in pine plantations (0.55 kg m^{-2}). Meanwhile, the total root mass (mainly of Scots pine) in the upper 30 cm thick mineral layer was on average 11 times higher in pine plantations (6.16 kg m^{-2}) as compared with grass root mass (0.56 kg m^{-2}) in abandoned land.

In contrast to the large differences in the biomass, the concentrations of total N and C were quite similar (Table 2). For example, the mean concentration of N differed insignificantly ($p>0.05$) in grass and moss

Table 2. Mean C and N concentrations in the biomass of the grasses, mosses and roots in Scots pine plantations (*pl*) and abandoned arable land (*ab*) of the Perloja experiment

Organic matter		Weight, kg DW m^{-2}	N, mg g^{-1}	C, mg g^{-1}
Grass cover	*pl*	0.00[1]	-	-
	ab	0.08 (0.03) a	18.0 (2.1) c	472.7 (30.7) b
Moss cover	*pl*	0.55 (0.11) b	17.9 (1.1) c	538.0 (8.0) c
	ab	0.00[2]	-	-
Roots[3]	*pl*	6.16 (0.38)***c	11.8 (0.1)*a	452.2 (10.0)*b
	ab	0.56 (0.04) b	13.9 (0.6) b	414.0 (4.4) a

Standard errors of means are given in parenthesis. Organic matter parameters significantly differed at 0.05 level are marked with different letters. Asterisks denote significant differences between data obtained in Scots pine plantations and abandoned arable land (*pl* and *ab*): * $p < 0.05$, *** $p < 0.001$.
[1] The weight of grass as well as shrub and seedling covers was less than 5 g m^{-2} in pine plantations.
[2] The weight of moss cover was less than 5 g m^{-2} in abandoned arable land.
[3] Total grass and / or pine roots mass in upper 30 cm thick mineral layer.

covers and comprised 17.9-18.0 mg g^{-1}, while in the roots N concentrations were on average about 20-30% lower (11.8-13.9 mg g^{-1}). The differences in mean C concentrations did not exceed 8-14% in separate compartments of the vegetation. In the above-ground mass of ground vegetation, the mean concentrations of C were 473-538 mg g^{-1}, and in the roots were 12-16% lower (414-452 mg g^{-1}).

C and N pools in ground vegetation cover, roots, organic and mineral soil

General comparison of the data calculated for the organic materials studied shows that for both the plantation and former arable land plots the roots and soil organic layers contained the highest C and N pools, while these pools in the above-ground mass of ground vegetation cover were 3-10-fold lower (Table 3). Meanwhile, in the mineral soil the former Ap horizon accumulated on average 1.3-1.5 times more C and the same or up to 25% greater content of N than the underlying B_1 and B_2 horizons.

However, the most important point in our study was to compare the pools in Scots pine plantations with those in abandoned arable land. Because of the considerably greater mass in Scots pine plantations (see Tables 1 and 2), the most pronounced differences between the land uses regarding C pools were found in ground vegetation cover, roots and especially in soil organic horizons. In the pine plantation, the mean C pools of the above-ground vegetation (0.30 kg C m^{-2}) and the root mass (2.79 kg C m^{-2}) were 7.5 and 12 times higher than in the grass cover (0.04 kg C m^{-2}) and root mass (0.23 kg C m^{-2}) of abandoned arable land (Table 3). Meanwhile, the total C pool in the organic layer (L+F+H horizons) was about 17 times greater in pine plantations (2.24 kg C m^{-2}) than in abandoned arable land (0.13 kg C m^{-2}). Despite the reported differences in organic horizons and root mass, changes of organic C in mineral soil were significant only in the surface 0-2 cm layer of the former Ap horizon. In this uppermost mineral layer the C pool was on average more than three times greater in pine plantations (0.72 kg C m^{-2}) than in abandoned arable land (0.22 kg C m^{-2}).

In comparison with C pools, the N pools differed to a smaller extent in the study plots (Table 3). Significantly different N pools were detected only in vegetation compartments and O horizons (L+F+H). The most important point is that the N pools in root mass (0.07 kg N m^{-2}) and organic horizons (0.05 kg N m^{-2}) in pine plantations were on average 7-12 times larger than in abandoned land (0.01 kg N m^{-2} and 0.004 kg N m^{-2}). However, in all mineral layers to the depth of 90 cm, despite some perturbations in the former Ap horizon, N pools differed insignificantly.

Table 3. Organic C and total N pools, and C/N pool ratios in ground vegetation cover and root mass, organic and mineral horizons of Haplic Arenosols in Scots pine plantations (*pl*) and abandoned arable land (*ab*) of the Perloja experiment

Vegetation compartments or soil layers		C, kg m^{-2}		N, kg m^{-2}		C/N ratio	
		pl	*ab*	*pl*	*ab*	*pl*	*ab*
Above-ground vegetation cover		0.30 (0.06)[x] A	0.04 (0.02) A	0.01 (0.00)[1xxx] A	0.00 (0.00)[1,2] A	30	40
Roots in upper 30 cm thick mineral soil layer		2.79 (0.23)[xx] C	0.23 (0.02) C	0.07 (0.01)[xx] C	0.01 (0.00)[1] B	40	23
Soil horizons:	L	0.40 (0.09)[xx] A	0.04 (0.01) A	0.01 (0.00)[1xxx] A	0.00 (0.00)[1,2] A	40	40
	F+H	1.84 (0.35)[xx] B	0.09 (0.02) B	0.04 (0.01)[xxx] B	0.00 (0.00)[1,2] A	46	30
	Ap (0-2 cm)	0.72 (0.06)[xx] b	0.22 (0.04) a	0.06 (0.01) b	0.03 (0.00)[1] a	12	7
	Ap (2-10 cm)	0.66 (0.05) b	0.60 (0.06) b	0.05 (0.01) b	0.11 (0.02) b	13	5
	Ap (10-20 cm)	0.60 (0.07) b	0.63 (0.10) b	0.05 (0.00)[1] b	0.08 (0.01) b	12	8
	Ap (20-30 cm)[3]	*0.60 (0.07) b*	*0.63 (0.10) b*	*0.05 (0.00)[1] b*	*0.08 (0.01) b*	*12*	*8*
	B_1 (30-40 cm)	0.21 (0.04) a	0.18 (0.06) a	0.03 (0.01) a	0.05 (0.02) a	7	4
	B_1 (40-50 cm)[4]	*0.25 (0.05) a*	*0.24 (0.12) a*	*0.03 (0.01) a*	*0.04 (0.01) a*	*8*	*6*
	B_1 (50-60 cm)	0.29 (0.06) a	0.29 (0.17) a	0.03 (0.00)[1] a	0.03 (0.00)[1] a	10	10
	B_2 (60-80 cm)[4]	*0.51 (0.09) a*	*0.49 (0.14) a*	*0.06 (0.00)[1] a*	*0.06 (0.00)[1] a*	*8*	*8*
	B_2 (80-90 cm)	0.22 (0.12) a	0.20 (0.12) a	0.03 (0.00)[1] a	0.03 (0.00)[1] a	7	7
	B_2 (90-100 cm)[3]	*0.22 (0.12) a*	*0.20 (0.12) a*	*0.03 (0.00)[1] a*	*0.03 (0.00)[1] a*	7	7

Standard errors of means are given in parenthesis. Significant differences ($p < 0.05$) are marked with different letters (see abbreviations in Table 1).

[1] SE was less than 5 g m^{-2}.

[2] The pool was less than 5 g m^{-2} in abandoned arable land (in above biomass of ground vegetation cover as well as in L horizon – 0.001 kg N m^{-2}, in F+H – 0.003 kg N m^{-2}).

[3] The pools that were equated to the pools measured in neighbouring layer within separate horizons (presented *in italic*).

[4] The pools that were obtained by averaging the values from neighbouring layers (presented *in italic)*.

From the data presented in Table 3, it could be calculated that the mean total organic C pools to soil depth of 100 cm, including the organic layer, were 6.52 kg m^{-2} and 3.81 kg m^{-2} in pine plantations and abandoned land, respectively (Fig. 2). Such considerable (1.7-fold) differences resulted from a more intensive accumulation of the organic layer in pine plantations. Therefore, about 34% of the total C pool in the 100 cm of the soil was accumulated in the organic layer of the soil in pine plantations, while in abandoned land this figure was only 3.4%. In mineral soil (down to 100 cm), the differences between the land uses were not significant ($p>0.05$) because of the large standard errors. The data variability was less in the former plaggic Ap (0-30 cm) horizon where about 57-60% of total mineral soil C pools were locked: on average 2.58 kg C m^{-2} in pine plantations and 2.08 kg C m^{-2} in abandoned arable land.

Total soil N pools to the depth of 100 cm, including O horizons, were at the same level (0.47-0.54 kg m^{-2}) for both land uses, because the mineral soil (0-100 cm) contained about 90% (in pine plantations) and even 99% (in abandoned arable land) of total N pools (Fig. 2).

In general, the C/N ratio decreased with increasing depth in the soil profile in both the plantations and the former arable land (Table 3). Meanwhile, only in F+H and former Ap horizons, as well in root biomass the ratios of C and N pools were 1.5-2.6-fold higher in pine plantations than in abandoned arable land.

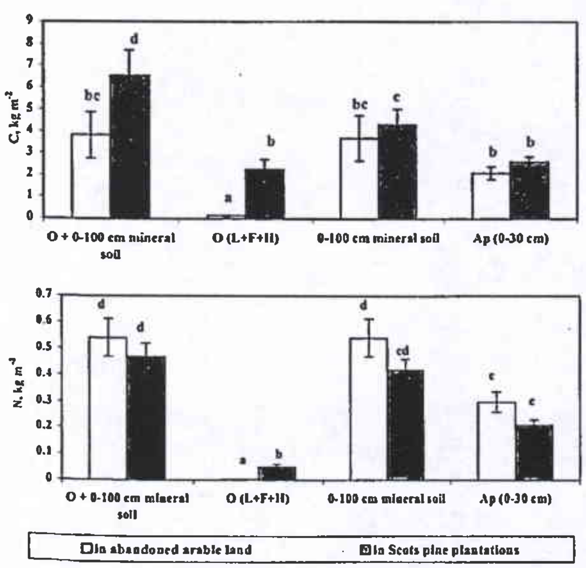

Figure 2. Distribution of soil C and N pools in Scots pine plantations and abandoned arable land of the Perloja experiment. Standard errors of means are shown on the columns by bars. Significant differences ($p < 0.05$) are marked with different letters. See abbreviations in Table 1

Discussion

In our case study, Haplic Arenosols in the Perloja experiment were poor in N and C in arable land afforested with Scots pine as well as in arable land abandoned for the last 11 years after many years of intensive fertilization. Even in the former plaggic Ap horizon, the total N concentrations in general ranged within 0.6-1.3 mg g^{-1}, and C concentration within 4.6-8.4 mg g^{-1}, while in the surface mineral layer of forest soils, both in Europe and in Lithuania, they mainly vary within 0.5-5.0 g N kg^{-1} and 0.5-50:0 g C kg^{-1} (Vanmechelen *et al.* 1997, Vaičys 1999). Meanwhile, our data correspond well to the average N (0.7 mg g^{-1}) and C (9.4 mg g^{-1}) concentrations in horizon A of forest Dystric Arenosols reported from Denmark with similar climatic conditions (Vejre *et al.* 2003).

The changes and the differences in chemical properties of mineral soil horizons (mainly in the upper plaggic Ap horizon) in the Scots pine plantations and the abandoned arable land could be attributed to the accumulation and decomposition of forest floor and greater root mass in pine plantations, while in abandoned arable land the changes could be attributed to the former intensive fertilization regime. Due to the high planting density in the 45-year-old pine plantations studied, the total mass of acid (pH_{CaCl2} 3.6-3.7) organic O layer exceeded 5.5 kg m^{-2} and was 1.5-1.7-fold greater than the average value in 40- to 110-year-old Scots pine stands in Lithuania (3.3-3.7 kg m^{-2}, unpublished soil monitoring data of 1992 and 1998). As in other studies (Reynolds *et al.* 1988, Alriksson and Olsson 1995, Grieve 2001, Andersson *et al.* 2002), in the underlying former Ap horizon a decrease in pH and mobile K_2O was observed. Besides, below the forest floor, in a thin (0-2 cm) mineral layer, C and N concentrations increased considerably (4-6-fold). In the abandoned formerly intensively fertilized arable land, in spite of the leaching and removal of nutrients with harvested crop biomass, increased concentrations of P_2O_5 and K_2O were found. However, there were no changes in C concentrations, though the former application of farmyard manure could lead to an increase of soil organic matter (Powlson *et al.* 1998). The abovementioned changes resulted in the fact that during our study the former Ap horizon was less acid (by 1.3-1.9 pH_{CaCl2} units) and 2-3 times more saturated with mobile P and K in abandoned arable land than in pine plantations.

Calculated to a 100 cm mineral soil depth (including O horizons), soil C and N pools were relatively low in both the pine plantations (6.52 kg C m^{-2} and 0.47 kg N m^{-2}) and in abandoned arable land (3.81 kg C m^{-2} and 0.54 kg N m^{-2}). According to a global estimation, in cool temperature moist forests the median C content in mineral soil (although the forest floor was excluded) reaches 10.1 kg C m^{-2} (Post *et al.* 1982), while N content on the worldwide scale in different mineral soils ranges from 0.52 kg N m^{-2} (Arenosols) to 1.39 kg N m^{-2} (Podsols) (Batjes 1996). Even C pools reported for Arenosols in Danish conifer forests (10.5-13.4 kg C m^{-2}) are significantly higher (Vejre *et al.* 2003). Meanwhile, our data on N contents are quite similar to those estimated for a 95-100 cm soil depth (including O horizons) in Denmark (0.57-0.66 kg N m^{-2}) (Vejre *et al.* 2003) and southwestern Sweden (0.50-0.65 kg N m^{-2}) (Eriksson and Rosén 1994) with similar forests and climate.

The present study has confirmed that the afforestation of nutrient-poor sandy soils could result in an increase of soil C stores within a short period (Post and Kwon 2000, Vesterdal *et al.* 2002). As compared with the adjacent abandoned arable land, C pools were considerably greater in pine plantations, mainly because of the accumulation of forest floor. In the horizons of mineral soil the differences were in general not significant, although root mass was more than 10 times greater in pine plantations. It has been noted that fine root turnover may substantially increase the C content in the soil (Kurz *et al.* 1996, Paul *et al.* 2002). In our opinion, the leaching of organic carbon acids caused by the low pH could suppress such an increase in pine plantations. Meanwhile, despite the low decomposition rate of soil organic horizons (C/N pool ratios were 40-46), a significant increase in C pools was found in a 0-2 cm surface mineral layer in pine plantations. In abandoned arable land the C pools and N pools were about 3 times less in this mineral uppermost layer than in the underlying layers of the Ap horizon. The reason could be more intensive microbial activity, which was reflected by the low C/N = 5-8 ratio. Many studies have emphasized that sandy soils in abandoned agricultural land due to more intensive distribution of precipitation, higher soil temperature, better aeration and higher pH contribute to a large and more active soil microbial community as compared with forest area (Hopkins *et al.* 1993, Reich *et al.* 1997, Krankina *et al.* 1999, Van der Putten *et al.* 2000, Priha *et al.* 2001, Griffiths *et al.* 2002, Fierer *et al.* 2003, Stevenson *et al.* 2004). The above facts imply that the estimation of C pool changes in the soil after afforestation should be focused on the organic layer and mineral topsoil, *i.e.* on the former plaggic Ap horizon. However, even in this quite thin (about 20-30 cm) mineral horizon a precise and more stratified sampling could be relevant. Besides, along with C determination, it is essential to define the pH, nutrient and microbial status of the mineral soil. The long-term permanent experiment presented in this study is suitable for such a complex research.

Our comparative study carried out in a cold temperate climate shows that the afforestation of nutrient-poor Haplic Arenosols under Scots pine plantations leads to a significant sequestration of C, mainly in the organic horizons of the soil. On the other hand, the accumulation and low decomposition rate of forest floor as well as root turnover result at least in the maintenance of C sequestration and N status in the underlying mineral soil horizons while such preservation did not occur in formerly intensively fertilized arable land.

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СЕКВЕСТРАЦИЯ УГЛЕРОДА И НАКОПЛЕНИЕ АЗОТА В АРЕНОСОЛЯХ ПРИ ОБЛЕСЕНИИ ИЛИ ПРИ ЗАПУЩЕНИИ ПАХОТНЫХ ЗЕМЕЛЬ

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Резюме

Более чем 600 000 га угодий с неплодородными почвами (в основном Ареносолями) уже не используются или в ближайшем будущем не будут использованы в Литве для сельского хозяйства. В свете Киотского протокола облесение таких земель имеет преимущественное значение для секвестрации углерода. Данное исследование проводилось в долголетнем эксперименте, заложенном на пахотных землях (Haplic Arenosols), одна часть которых была облесена, а другая в течении 25 лет использовалась для выращивания сельскохозяйственных культур. Во время исследований изменение химических свойств почвы, преимущественно накопление органического С и общего N в почве, а также в живом напочвенном покрове и в корнях сравнивались в 45-летних культурах сосны (*Pinus sylvestris* L.) и в 11-летней залеже.

Установлено, что бывший пахотный горизонт Ар в залеже был на 1,3-1,9 pH_{CaCl_2} единиц менее кислый и в 2-3 раза более насыщенный подвижными соединениями фосфора и калия, чем в культурах сосны. Вследствие накопления С в лесной подстилке (2,24 кг С $м^{-2}$), в 100-сантиметровом слое минеральной почвы (включая лесную подстилку) накопление С в культурах сосны (6,52 кг С $м^{-2}$) было в 1,7 раза более значительное, чем в залеже (3,81 кг С $м^{-2}$). При этом разница в минеральных горизонтах в основном была незначительной за исключением самого верхнего 0-2 см слоя бывшего Ар горизонта, в котором органического С в культурах сосны (0,72 кг С $м^{-2}$) накопилось в 3 раза больше, чем в залеже (0,22 кг С $м^{-2}$). Установлено также, что в лесных культурах, в поверхностном слое минеральной почвы, корневая масса растений была в 10 раз больше. Накопление общего N в обеих биотопах было на одинаковом уровне (0,47-0,54 кг N $м^{-2}$), поскольку 90 % и больше N содержалось в верхнем 1-метровом слое минеральной почвы. Сделано заключение, что лесные культуры сосны в большей степени сохраняют накопленные С и N в минеральных горизонтах Haplic Arenosols по сравнению с залежью, которая раньше интенсивно удобрялось не только минеральными (NPK), но и органическими удобрениями (навозом).

Ключевые слова: Литва, Haplic Arenosols, запущенные пахотные земли, облесение, *Pinus sylvestris*, живой напочвенный покров, органический углерод, общий азот.