CARBON ACCUMULATION AND HUMIFICATION IN SOILS OF ABANDONED FORMER AGRICULTURAL LANDS IN THE HEMIBOREAL ZONE

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Abstract. *Abandonment of the agricultural land is a common, topical problem in many post-soviet countries, including Latvia. These changes impact nutrient cycling, soil properties. The results of the study of abandoned agricultural lands in the hemiboreal zone in Latvia validated the theory that after afforestation, in long term, soil accumulates organic carbon (C_{org}). During the first 30 years of abandonment, C_{org} content in mineral topsoil does not present a significant increase; it varies from 42 to 43 t ha^{-1}. More rapid C_{org} content increase was observed in the territories where the age of the forest land had exceeded 30 years; the mean C_{org} content in 31-60 years old forest stands reached 51.3 t ha^{-1}. The C_{org} content which has been accumulated in litter increases in older forest sites. In spruce and mixed forest stands, where age of the forest had exceeded 60 years, the mean C_{org} content in litter was 17.8 t ha^{-1}. Afforestation also changes the content of humic substances and the humification rate in the mineral topsoil. In agricultural lands C of humic substances (C_{hs}) constituted 65% of total topsoil C_{org}. In sites where age of the forest land was more than 30 years C_{hs} exceeded 75% of total C_{org} amount.*

Key words: *Afforestation, land use, change, humic substances.*

INTRODUCTION

Abandonment and afforestation of agricultural land (AL) are common in many European countries [3], [20]. Land use change affects soil genesis, soil morphology, soil chemical and physical properties [2],[16].

Afforestation of agricultural land in the long-term leads to increased organic mattter (OM) and C content [17],[24]. However, organic carbon (C_{org}) content in soil does not change or even may decrease during the first years of afforestation. More intense C accumulation starts in a later period, which may differ for forest types, but, usually occurs when annual C inflow from litter is larger than C loss due to degradation [17],[24].

Furthermore, afforestation of AL affects the structure and chemical properties of soil OM and humification processes [6]. Land use change also leads to changes in soil moisture and temperature regime, that affects intensity of OM degradation [17]. The main changes occur in topsoil within the A horizon. Inherited OM properties from agricultural land use decline with the age of the forest stands [6].

C sequestration and OM humification processes in soil after AL afforestration are affected by climate [14]. There is minimal information on these processes in the hemiboreal zone, where the climate is more humid than in the nemoral zone (e.g. summers are shorter, and winters are longer and colder). The main tree species are the conifers spruce (*Picea abies*) and pine (*Pinus silvestris*), and the deciduous species birch (*Betula sp*) and aspen (*Populus tremula*). The broad-leaved tree species oak (*Quercus robur*), ash (*Fraxinus excelsior*) and lime (*Tilia cordata*) occur in lower amounts. In Latvia, large-scale abandonment of the agricultural lands and overgrowing by trees starts in the first half of the 20th century, but more intensive afforestation occured after 1990 with the collapse of the Soviet Union [18],[20]. In the beginning of the 20th century, forests covered only 25.2% of Latvia's total land area [18], but in 2007 forests covered 56% of state's total area. During the last decade, agricultural land area decreased by 1.4%, while forest area increased by 0.8%. Thus Latvia provides a good model territory where the impact of the afforestation of the former agricultural land on the landscape, biodiversity and soil can be determined.

The aim of the study was to estimate changes of soil C_{org} content and OM properties in topsoil (O and A horizons), in territories with different age of the forest land in moraine upland in hemiboreal zone.

MATERIALS AND METHODS

Field studies and soil analysis

Field work was carried out from 2009 till 2013. Sampling plots were established on abandoned agricultural land, afforested former agricultural land and forest land with different age. A total of 58 sampling plots were described. In forested sites, tree species were recorded and tree age was estimated using a Pressler's auger. The age of the oldest stands was determined from forest inventory material and historical maps.

Soil profiles were described according to the international FAO WRB classification system [10]. Soil samples from litter O and mineral Ap, Ah horizons (from the upper 5 cm and from the middle part of the A horizon) were collected in all sampling plots.

Physical and chemical analyses (soil texture, soil pH_{KCl}, exchangeable cations: calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), total organic carbon (C_{org}), humic substances (C_{hs}), index of humification (HIX)), of soil samples were conducted in the Soil Laboratory of the Faculty of Geography and Earth Sciences, University of Latvia.

Soil texture by size fractions were determined by pipette analysis [25] and according to USDA soil textural classes. Soil pH was measured with a glass electrode in 1M KCl (1:2.5 mass to volume ratio). Total organic carbon (C_{org}, %) was determined using a total carbon analyzer „Shimadzu TOC-Vcsn".

Humic substances were purified according to International Humic Substance Society (IHSS) standard methods [23]. Organic carbon content in humic substances (C_{hs}, %) was determined with a „Shimadzu TOC-Vcsn" total carbon analyzer.

Alkaline extracts of humic substances were analyzed for humification index. Fluorescence spectra were used to determine the organic matter humification index (HIX) according to methodology [11].

Data analysis

For data analysis purposes, all sampling plots were divided into groups by age of the forest land: 1) unmanaged AL, without tree vegetation; 2) afforested AL, age of trees less than 15 years; 3) afforested AL, age of trees from 16 to 30 years, O horizon has begun to form; 4) new forest land, age of forest land from 31 to 60 years; 5) forest land, where age of the forest land is from 61 to 100 years; 6) relatively old forest land, age of the forest land exeeds 100 years.

One-way analysis of variance (ANOVA) was performed to compare properties (C_{org}, C_{hs}, $C_{hs}/C_{org,}$ HIX, pH_{KCl}, BD) of the mineral soil between the AL, afforested AL and forest land. Tukey and Scheffe HSD post-hoc tests (α=0.05) were made to determine the significance of differences betveen groups. Calculations were performed using SPSS PASW Statistics 18 software.

Principal component analysis (PCA) using PC-ORD 5.0 software was carried out to determine relationships between afforestation age (years) and the topsoil properties.

RESULTS AND DISCUSSION

Organic matter and C content

The mean C_{org} concentration in the studied AL topsoil was 1.3 (±0.4)%. In areas overgrowing by trees, dense grass vegetation with *D. glomerata*, *F. pratensis*, *Taraxacum officinalisun* and *Ahillea millefolium* dominated, and O horizon was absent. Litter patches of 1-year-old leaves had started to accumulate on the soil surface when age of trees exceeded 10 years. Mean C_{org} concentration in mineral topsoil of young tree stands was 1.49%. Higher C_{org} concentration (>2%) occurred in silty clay loam soils under and overstorey of aspen and gray alder (table 1).

In 16- to 30-year-old tree stands, where the AL was under *Betula pendula*, *Alnus incana* and *Picea abies*, max thickness of the O horizon reached 2.0 cm, litter mass was 23.1 (±1.34) $t\ ha^{-1}$. In the 20-year-old *Betula pendula* and 25-year-old *Alnus incana* stands a continuous O horizon had not formed. The lowest C_{org} concentration (mean 1.59%) was in sites overgrowing by *Picea abies*, and the highest concentration in *Alnus incana* stands, where it reached a mean of 2.5%.

The thickness of the O horizon in sites where the age of the forest land exceeded 30 years was dependent on the tree species. Thinner litter layers occurred in *Alnus incana* stands. Thickness of the litter layer varied from 0.3 to 0.5 cm, and mass from 2.5 to 7.8 $t\ ha^{-1}$ in 35- to 40-year-old *Alnus incana* stands. The thickest litter O horizons, as well as the highest litter amount were found in *Picea abies* stands, where the O horizon depth was up to 10 cm and mass of the litter was 134 $t\ ha^{-1}$.

Table1

Changes of the soil morphological properties. Mean thickness of O and A horizons, litter weight and bulk density in the studied soils.

Standard deviations (error bars) of the means are shown in parentheses.

Forest land age	Sampling plots	O horizon depth, cm	Litter mass, $t\ ha^{-1}$	A horizon depth, cm	Soil density $g\ cm^{-3}$, 0-5 cm
AL	5	-	-	30.6 (±6.8)	1.21 (±0.12)
1-15	25	0.01 (±0.06)	0.1 (±0.6)	28.9 (±4.9)	1.12 (±0.24)
16-30	6	0.51 (±0.77)	7.9 (±9.1)	25.3 (±5.7)	1.01 (±0.09)
31-60	10	2.38 (±3.22)	20.0 (±32.1)	22.8 (±6.5)	1.06 (±0.06)
61-100	8	4.25 (±2.72)	60.5 (±48.8)	15.9 (±4.2)	1.05 (±0.15)
>100	4	3.1 (±2.10)	60.8 (±46.6)	15.0 (±10.1)	0.93 (±0.15)

The A horizon was thinner in the oldest forest sites. Among forest sites of age >60 years, a lower C_{org} concentration (1.5%) occurred in the mineral topsoil in the Ergli sampling site in Arenosols and Cambisols soils, where signs of podzolization were detected. Comparing mean C_{org} concentrations within forest land age groups (table 2), a gradual increase of C_{org} concentration was detected. During the first years of afforestation there was no significant change in C_{org} concentration in soil. Increase in C_{org} concentration was observed in 16- to 30-year-old forest sites. However, due to high variability, these differences were not statistically significant ($p<0.05$).

OM properties were less variable and age of forest land had greater effect on observed properties. The concentration of humic substances in soil OM (C_{hs}/C_{org}) in AL soils was 65%, compared to 73% in young afforested soils. A lower C_{hs}/C_{org} ratio (mean 59%) occurred in Stagnosols and Gleysols soils. In the oldest forest sites, C_{hs}/C_{org} ranged from 65 to 89%, and there was no significant relationship between index and dominant tree species, soil group, and soil texture. Mean C_{hs}/C_{org} was higher in the older groups (table 2), and was significantly ($p<0.05$) higher in forest soils in forest land with age more than 30 years, compared to AL soils.

Afforestation caused changes in the mineral soil OM humification rate. There was no direct correlation between age of the forest land and OM humification index (HIX) ($r^2=0.3043$), but the OM humification rate in topsoil slightly increased with age of the forest land. In the abandoned AL and in the overgrown AL mean HIX values (0.64 and 0.62) did not exceed the lowest HIX values of the old forest soils. Also, mean HIX values in the AL and in the 1-15 years old afforested soils were significantly lower than in the sites where age of the forest land exceeded 60 years (table 2).

Forest evolution on AL was significantly related with soil reaction. Mean pH_{KCl} values changed from 5.5-5.6 in AL and 1- to 15-year-old site soils to 4.4 and lower in the oldest forest soils.

Table 2

Characterization of soil properties (mean values).

Different letters (a, b, c...) shows statistically significant differences ($p<0.05$) [according to comparison (Tukey and Scheffe test)].

Age group (age of forest land, years)	0	1-15	16-30	31-60	61-100	>100
C_{org} %	1.3[a]	1.5[a]	1.9[a]	2.7[a]	2.6[a]	2.9[a]
C_{hs} %	1.2[a]	**1.0[ab]**	1.3[a]	**2.3[ac]**	1.9[a]	1.7[a]
C_{hs}/C_{org}, %	**65[a]**	**71[ac]**	77[abc]	**85[bc]**	78[abc]	**80[c]**
HIX	**0.64[a]**	**0.62[a]**	0.61[ab]	0.69[ab]	**0.71[b]**	**0.73[b]**
pH_{KCl}	**5.5[a]**	**5.6[a]**	4.2[ab]	4.3[ab]	**3.7[b]**	**3.9[b]**
BD, $g\ cm^{-3}$	**1.19[a]**	1.25[ab]	1.17[ab]	**1.06[b]**	**1.05[b]**	**1.05[b]**

Soil carbon content

C_{org} content in mineral topsoil was mainly related to C_{org} concentration and thickness of the topsoil horizons. In abandoned AL, C_{org} content in the soil A horizon varied from 32.8 to 59.4 $t\ ha^{-1}$. In sites where age of the forest land did not exceed 15 years, C_{org} content in A horizon varied from 16.9 *t ha⁻¹* to 48.5 *t ha⁻¹*. In 16- to 30- year-old forest sites, the lowest C_{org} content (36.6 *t* ha^{-1}) occurred in *Picea abies* stands, and in *Alnus incana* stands C_{org} content reached 45.0 *t* ha^{-1}. The Ergli sampling site, where age of the forest land exceeded 30 years, had soils with the lowest C_{org} content in mineral topsoil. In 60- and 140-year-old *Picea abies* stands, C_{org} content was only 13.1 and 11.2 *t* ha^{-1}. In 60-year-old *Betula pendula* stands, C_{org} content was 21.2 *t* ha^{-1}. In soil of other old forest sites, A horizon carbon content varied from 22.1 to 57.6 *t* ha^{-1}, and in the 70 years old *Picea abies* stand it reached 60.2 *t* ha^{-1}.

During the first years of afforestation, C_{org} content in A horizon increases (figure 1). During the development of forest, in soil, distribution of C_{org} in the A horizon also changed. In abandoned AL and in the young stands, C_{org} was distributed evenly through the profile: the top 5 cm accumulated 19% of total C_{org} in A horizon. In older sites, a greated relative amount of C_{org} occurred in the top 5 cm of mineral soil. In 16- to 30-year-old sites, the proportion of C_{org} in the top 5 cm was 24.2%, in 31- to 60-year-old sites – 30%, and in the oldest sites C_{org} content exceeded 40% of total C_{org} content in the humus A horizon.

Mean C_{org} content significantly ($p<0.05$) differed between AL and 31- to 60-year-old forest soils (figure 1). C_{org} content did not change during the first 30 years of afforestation, but lower C_{org} content in mineral topsoil was observed in 60- to 100-year-old forest land soils.

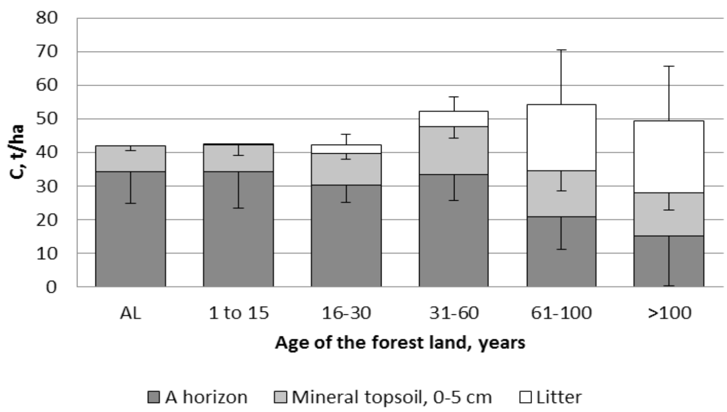

Figure 1. **Mean C content t ha⁻¹ in AL and in forest land of different age**

During forest development significant C_{org} content accumulated in the forest floor. In 30- to 61-year-old forest sites, the forest floor accumulated 1.81 *t* ha^{-1} C_{org} on average. Carbon amounts were 6.1 *t* ha^{-1} in gray alder and aspen litter and 11.7 *t* ha^{-1} in spruce litter. In deciduous tree stands with age of the forest land exceeding 60 years, 4 *t* ha^{-1} C_{org} had accumulated in the litter O horizon. In the oldest spruce stands, mean C_{org} content in the litter layer was 17.8 *t* ha^{-1}.

The natural succession of topsoil properties, alongside those of vegetation, is well shown by principal component analysis (results not shown). The obtained results show that soil properties changed with age of the forest land: decrease in thickness of the A horizon, accumulation of litter horizons, which together lead to C_{org} accumulation in topsoil. These processes decreased soil reaction, as well as increased humification rate of the soil organic matter. These processes depends on soil texture (proportion of sand, clay and silt). The PCA also showed that, alongside age of the forest land, spruce (*Picea abies*) litter promoted formation of the O horizon and the accumulation of C_{org} in this horizon.

Discussion

In Latvia moraine hills have high spatial variation of soil texture and soil moisture conditions, which affect C accumulation in soil. Accumulation of OM and C in soil was evident at the beginning of secondary ecological succession, but spatial variation of these indicators was greater and did not allow to detect significant differences in the first years of secondary ecological succession. OM content in topsoil is influenced by many factors, firstly by soil properties and soil geographical conditions (exposition, moisture conditions), and secondly by history of land management. Land management and cultivated crops [7], as well as intensity and properties of fertilisation [1] influence organic matter content in soil. C concentration in arable land is lower than in pastures [8]. Ambiguous C concentration changes during the first years of afforestation may be related to differences of OM content in soil in pastures and arable lands. Some studies have found a decrease of C content during the first 5 years after afforestation [17], or even up to 15 years after natural succession. In other studies [21] a decrease of C was not observed, or there was an increase [25]. The results of our study confirms previous results [16] from the hemiboreal zone which show that AL abandonment and gradual overgrowing do not cause any significant changes in topsoil properties and organic matter content, as well as C accumulation in sandy loam and silty loam soils.

C concentration and content in soil increased during further stages of forest development. More rapid C increase in soil usually correlates with increase of OM production and decrease of degradation intensity. In temperate latitudes, an equilibrium usually occurs after 20 to 25 years of afforestation [5],[16], but in some cases up to 40-60 years may be required to reach equilibrium [13]. High variation of C content in soils, and the fact that most of the studied forest sites in the 31- to 60-year age group was 35 to 40 years, suggests that this kind of production/degradation equilibrium in the hemiboreal zone is reached during the first 40 years after afforestation.

During forest development, the effects of composition of forest tree stands and soil parent material become greater. Study shows that ecological succession on sandy loam, silt loam soils is associated with an increased proportion of spruce in developing forest tree stands. Hansson [9] concluded that, in stands with similar age but different tree species, litter production and C content in mineral soil may differ significantly.

The observed decrease of carbon in mineral topsoil may be related to the podzolization process [17]. A decrease of pH and increasing amount of coniferous litter accelerates podzolization, which promotes leaching of soluble organo-mineral complexes and C to deeper soil layers [15]. Morphological properties of podzolization in nutrient rich glacial till soils in spruce stands in the hemiboreal zone is evident during the first 100 years of afforestation of AL [16].

Differences of thickness of the soil A horizon must be considered in context of the history of land management. A thinner humus horizon in former agricultural lands afforested 60 years ago may be explained not only by podzolozation, but also the practice of scarification of arable land soils only up to a 15 cm depth before 1940, which resulted in undisturbed soil E and B horizons in soils formed on glacial till deposits.

The results of our study, similar to those of Cerli studies [6], show that progress of afforestation process affects not only C content in soil, but also composition and humification rate of soil organic matter. A low soil organic matter humification rate in abandoned AL and in young tree stands is related to high organic matter mineralization in AL soils [4]. The gradual increase of organic matter humification rate in older forest sites can be explained by increased leaching of soluble organic matter from the litter layer, which increases in the later stages of litter decomposition, but not in fresh litter [12].

pH changes and consequent changes in communities of soil meso and micro fauna [19] can explain the increase of proportion of humic substances (C_{hs}/C_{org}, %) in soil. Proportion of humic substances in mineral soil increases by transport of highly oxidized organic matter from soil organic layers [6]. The higher proportion of humic substances in coniferous tree forest soils can be explained by poorer soil fauna, as lack of penetrating fauna does result in mechanic mixing and input of poorly decomposed, non humified organic matter.

CONCLUSIONS

1. Organic carbon concentration varied in mineral topsoil, and was characterized by high variability.
2. During the first years of abandonment and afforestation of AL, there were no significant changes in C_{org} content in soil.
3. A more rapid and significant increase in C_{org} content in mineral topsoil occurred in 30- to 60-year-old forest stands, which was followed by a smaller decrease.
4. In the oldest forest lands dominated by spruce, more C_{org} had accumulated in the litter O horizon.
5. Afforestation of AL caused changes in the proportion of humic substances and humification rate in soil, and humification rate of soil organic matter increased with age of the forest land.

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