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Self-restoration of post-agrogenic Albeluvisols: Soil development, carbon stocks and dynamics of carbon pools

Olga Kalinina [a,*], O. Chertov [c], A.V. Dolgikh [b], S.V. Goryachkin [b], D.I. Lyuri [b], S. Vormstein [a], Luise Giani [a]

[a] Dept. Soil Sci. C-v-O, University of Oldenburg, Oldenburg, Germany
[b] Institute of Geography, Russian Academy of Sciences, Moscow, Russia
[c] Albert-Schweitzer-Str. 20, 26129 Oldenburg, Germany

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ABSTRACT

This chronosequential study focuses on the vegetation succession, pedogenesis, carbon stocks and functionally different carbon pools of post-agrogenic Albeluvisols under self-restoration in the Taiga zone of the European part of Russia. The sites investigated were comparable in terms of climate, soil texture and land-use history, but differed in duration of agricultural abandonment, covering 4, 12, 17 and 68 years of self-restoration. During self-restoration, the vegetation showed a development towards a mesophytic spruce forest. Pedogenesis resulted in recovery of morphological and chemical features with a vertical differentiation typical for the undisturbed Albeluvisols. During self-restoration, new organic surface layer (O) and new humic topsoil horizon (Ah) were developed. At the end of the chronosequence, the bottom of the well visible former ploughing horizon showed eluvial characteristics. Simultaneously, leaching caused a pH decrease of about 1.8 units, loss of the exchangeable cations, depletion of base saturation from 100% to 18%, and loss of nutrients. A vertical differentiation due to redistribution processes was found for soil organic carbon (SOC) and plant available phosphor and potassium. During self-restoration, the measured carbon stocks did not change substantially in the upper 0.5 m, but show a distinct redistribution within different soil layers, causing SOC accumulation from 0.64 to 0.78 kg m^{-2} in the organic surface layers and from 0.75 to 2.64 kg m^{-2} in 0–0.1 m, but SOC loss from 3.60 to 1.71 kg m^{-2} in 0.1–0.5 m. The simulation results showed also minor alterations for the chronosequence time interval, followed by an increasing SOC sink functioning at long terms of up to 200 years. The investigation of functionally different SOC fractions showed a significant enrichment of free particulate organic matter (POM) and occluded POM, hot water extractable carbon (Chwe), and carbon in grain size fractions, significantly following the increase of total SOC during self-restoration. Nevertheless, self-restoration affected the distribution pattern of carbon to functionally different pools, predominantly stimulating SOC sequestration within free POM fraction. Despite all these alterations the study showed no full restoration for the vegetation and the soils within the chronosequential time scale of 68 years.

1. Introduction

Until recently, 2,197,000 km^{-2} of arable land were abandoned in many countries worldwide. About 25% of such abandonments were found in Russia (Lyuri et al., 2010; Ramankutty, 2006). Although a wide range of climatic zones of Russia were affected, 50% of the abandoned sites were documented in the Taiga zone. Predominantly caused by economic crises, most abandonment occurred after 1990 (Agriculture of Russia, 2007; Henebry, 2009; Kurganova et al., 2010; Lyuri et al., 2010). As a consequence of abandonments, self-restoration set in. Self-restoration is a process without any direct human impact and describes the alteration of formerly agricultural or post-agrogenic soils during abandonment (Lyuri et al., 2006).

Preliminary studies of post-agrogenic soils undergoing self-restoration indicated that such soils, as well as the vegetation, were developing towards their natural composition (Kalinina et al., 2009, 2011; Nicodemus et al., 2012; Vladychensky et al., 2009). The dynamics of these changes depends on climatic zones, soil geneses, previous land use history, and the existence of wild plant seeds nearby (Laganiere et al., 2010; Paul et al., 2002). Soil morphological alterations were related to changes of physicochemical properties and resulted in a recovery of the vertical differentiation of the topsoil (e.g. Jug et al., 1999; Kalinina et al., 2009; Smal and Olszewska, 2008).

Soil carbon dynamics during self-restoration are especially important due to their role in terrestrial ecosystem carbon balance and the global carbon cycle. Guo and Gifford (2002) reviewed data of 74 publications and reported an increase of soil organic carbon (SOC) stocks by 53% from changing crop land into secondary forest and by 19% from crop to pasture. Post and Known (2000) estimated an average

* Corresponding author. Fax: +49 441 798 3769.
E-mail address: oykalinina@mail.ru (O. Kalinina).

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rate of SOC accumulation of 33.8 g C m^{-2} y^{-1} and 33.2 g C m^{-2} y^{-1} in post-agrogenic soils after forest and grassland establishment, respectively. Studies from Russia reported that former croplands acted as a stable sink of carbon after abandonment (Kalinina et al., 2009, 2011; Kurganova et al., 2010; Lopes de Gerenyu et al., 2008; Vladychensky et al., 2009). This carbon sink averaged 548 ± 35 Tg C or 34 Tg y^{-1} (Kurganova et al., 2010). Increasing carbon stocks after afforestation or during self-restoration of the former arable land resulted in SOC accumulation in the organic surface layer and plant biomass (e.g. Morris et al., 2007; Richter et al., 1999; Thuille and Schulze, 2006; Vesterdal et al., 2002), while contradictory data have reported for mineral soil layers (e.g. Poulton et al., 2003; Richter et al., 1999; Vesterdal et al., 2002). For sandy soils of the Russian Taiga, SOC gains resulted from SOC accumulation within the organic surface layers and SOC loss occurred within the mineral top soils during self-restoration (Kalinina et al., 2009). Hence, a carbon sink was expected for post-agrogenic loamy soils investigated in this chronosequential study. Nevertheless, SOC sequestration and SOC dynamics may be quite different due to varying interrelations between initial SOC pools and SOC dynamic trends in respect to environmental conditions. Therefore, an appropriate model may support a laboratory approach. Consequently, the SOC model ROMUL (Chertov et al., 2001b) and the forest ecosystem model EFIMOD (Komarov et al., 2003) have also been implemented to calculate long-term trends of SOC changes during self-restoration of post-agrogenic loamy soils in this study. These models consider impacts of litter input, litter quality, soil temperature and moisture on the dynamics of SOC pools.

Functionally different carbon fractions correspond to land use change (John et al., 2005). Thus, organic carbon (OC) enrichment for active and passive carbon pools were found after afforestation or during self-restoration processes of former arable land, reflecting the total SOC dynamics (Del Galdo et al., 2003; Kalinina et al., 2010; Six et al., 2002). Active and intermediate carbon pools are mainly affected (e.g. John et al., 2005; Kalinina et al., 2010, 2011; Six et al., 2002). Hence, increasing input of new organic matter (OM), changing OM decomposability, increasing above-ground inputs, changing soil organism destructors, and enhanced physical protection through aggregate formation were documented for soils after conversion from cultivated uses to forests (Kalinina et al., 2009, 2010; Six et al., 2002; Susyan et al., 2011). For these reasons, quantitative alterations are expected for the fractions of free and occluded particulate organic matter (POM) as well as for the fraction of hot water extractable carbon (Chwe).

To get insight into self-restoration processes of post-agrogenic loamy soils of the Russian Taiga, the objective of this chronosequential study was first to determine the temporal development of the vegetation and the soil properties of post-agrogenic loamy soil under self-restoration in the Taiga zone of the European part of Russia, secondly to measure the carbon sink or loss functioning of these soils, thirdly to model the long-term dynamics of the carbon stocks during self-restoration, and finally to determine the changes of SOC sequestration within the different functional carbon fractions.

2. Materials and methods

2.1. Site of investigation

The study was conducted close to the villages Sirchini and Gogli, located in the Taiga zone of the European part of Russia ca. 80–85 km north-east of the city of Kirov (Fig. 1).

The region has a moderately cool climate, with a mean annual precipitation of 550 mm, a mean annual air temperature of 1.0 °C, and a frost-free period of 105–110 days. The mean air temperatures in January and July are −16 °C and +17 °C (Lyuri et al., 2010). The region is in a transitional zone between frigid and cryic soil temperature regimes. Geologically, the studied area consists of silt loam deposits from the late Weichselian glacial period. The recent geomorphology shows gentle undulations. Clay translocation under periglacial conditions caused stagnic conditions, reduction of the iron compounds and albeluvic tonguing, resulting in the formation of Stagnic Cutanic Albeluvisols.

For the chronosequential approach of this study, sites differing in self-restoration time but comparable in soil texture, climate and land-use history were required. Hence, sampling sites were selected according to information obtained from topographic maps and personal communications with local authorities and indigenous people.

Having located the most suitable locations, five sites of different self-restoration ages were sampled in July 2010. The positions of the soil profiles were chosen randomly and then recorded using a Garmin Etrex GPS Navigator. Frequent Purckhauer drilling (generally ca. 20 drillings) indicated uniform soil conditions at the different sites. The uniform grain-sized sediments confirmed the pedological relationship of the sampling sites (data not shown). The chronosequential catena included soils of 4, 12, 17 and 68 years of self-restoration, as well as one native and one arable soil. Although this chronosequential approach is based on soil differences among locations and not on changes over time, a time-shifting development or space-for-time substitution (Walker et al., 2010) was hypothetically assumed, resulting in the use of time-shifting terms, although soil differences among locations were made.

The natural Albeluvisol and the soils of 4, 12, 17, and 68 years of self-restoration are located inside a radius of 1.5 km from the village Sirchini. The arable Stagnic Cutanic Albeluvisol (Hypereutric Siltic) (59°12′ N, 50°42′ E), being under agricultural land use for at least 100 years, is located at a distance of about 16 km from the village Sirchini. At the site of the natural Stagnic Cutanic Albeluvisol (Epidystric, Siltic) (59°13′ N, 50°26′ E), no soil working was practiced in former times, but sporadic wood cutting was performed by local people until 30–40 years ago. The abandonment of the Stagnic Cutanic Albeluvisol (Epidystric, Siltic) with 68 years of self-restoration (59°13′ N, 50°26′ E) in 1942 was due to World War II. Since 1990, the economic depression in the country caused the abandonments of the other two sites with Stagnic Cutanic Albeluvisol (Endoeutric, Siltic) that had been in the process of self-restoration for 12 years (59°13′ N, 50°26′ E) and 17 years (59°13′ N, 50°26′ E). The abandonment from ordinary agricultural land use of the Stagnic Cutanic Albeluvisol (Orthoeutric, Siltic) with 4 years of self-restoration (59°13′ N, 50°26′ E) took place in 1996 for economic reasons, too. Since oat seeding was used as bait for bear hunting until 2006, this year was determined as the starting point of self-restoration.

Following the drilling, a representative site was chosen for ground opening and soil morphological description which was done according to the Russian classification system (Shishov et al., 2004) and according to the World Reference Base of Soil Resources (WRB) (IUSS, 2006). The texture of all soils was loam, comprising about 20% sand, 55% silt and 25% clay in the top and about 40% silt and 40% clay in the subsoil (data not shown). Bulk samples were taken from each horizon. Core cutter samples were taken in quintuplicate from the organic surface layers and in duplicate from the other horizons. Additionally, three spots were randomly chosen at each site to sample the uppermost organic and organo-mineral horizons for further C and N measurements.

In the Kirov area, agricultural land use started in the 18th century, but was fragmental and located near the villages (Tsvetkov, 1957). Early in the 19th century, 9% of the area was agriculturally used (6% arable land and 3% pasture). By the end of the 19th century, the agricultural land use reached its maximum, comprising of 36% of the area (27% arable land, 9% pasture and hayfield). Cereals were cultivated with a dominance of barley. The land management was characterised by a low level of organic fertilisation and ploughing to a depth of 12–15 cm (Tsvetkov, 1957). The extensive abandonment of agricultural land began in 1941 due to depopulation of the area during World

Fig. 1. Location of the investigation site on global scale (http://www.weltkarte.com/uploads/pics/landkarte_russland.jpg).

War II and afterwards increased due to migration of the rural population to the urban areas (Agriculture of Russia, 2007; Lyuri et al., 2010). Due to the huge extent of abandonment at that time also soils with relatively high fertility were affected. From the 1930s, when mechanical ploughing was introduced, the ploughing depths increased to 22–24 cm. Forage crops appeared in the crop production (Agriculture of Russia, 2007; Lyuri et al., 2010). The level of fertilisation reached a maximum in the 1980s (approximately 3 t ha^{-1} of organic manure and 30 kg ha^{-1} of mineral fertilisers) (Russian Statistic Yearbook, 1995). Since the economic crises in the 1990s–2000s, the agricultural area has been reduced to 17% (9% arable land and 8% pasture and hayfield). Fertilisation declined to about 0.9 t ha^{-1} of organic manure and about 13.8 kg ha^{-1} of mineral fertilisers. The crop composition comprised of 50% forage crops, 40% cereals and 10% vegetables (Agriculture of Russia, 2007; Lyuri et al., 2010).

2.2. Analytical methods

2.2.1. Standard methods

All soil samples were homogenised and passed through a 2 mm sieve. Bulk density was calculated on gravimetrically obtained volume data; pH was electrometrically measured with a glass electrode in 1:2.5 soil water solutions of bi-distilled water and 0.01 M $CaCl_2$ for the organic-mineral horizons and in 1:6.5 soil water solutions for the organic surface layer. Particle-size fractionation was done according to Schlichting et al. (1995). Carbon (C) and nitrogen (N) contents in dry soil pellets were determined after combustion and spectrometric measurements with a C/N/S analyzer (CHNS-Analyzer Flash EA). Total phosphorus (Pt) content was measured photometrically (Shimadzu Uv mini-1240) in an extract tinged with vanadate–molybdate reagent after combustion at 800 °C and HNO_3 treatment. Plant-available phosphorus and potassium were extracted with a 0.02 M Ca-lactate/ 0.02 M HCl solution. Subsequent plant-available K was measured spectrometrically in AAS (Varian SpectrAA 300) and plant-available P was measured photometrically (Shimadzu Uv mini-1240) in an extract tinged with ammonium-heptamolybdate and ascorbic acid reagent. Exchangeable cations were measured spectrometrically in AAS (Varian SpectrAA 300) after extraction of 10 g soil with three portions of 25 ml 0.1 M $SrCl_2$, buffered with Triethanolamin to pH 8.2, in a column procedure. Afterwards, the soil columns were treated with three portions of 25 ml 0.1 M $MgCl_2$ and the obtained Sr was measured spectrometrically in AAS (Varian SpectrAA 300), representing the cation exchange capacity (CEC). Measurement of dithionite-soluble iron was done in modification according to Mehra and Jackson (1960).

Briefly, 0.5 g soil was treated in a water bath at 82 °C with two portions of 40 ml 0.3 M Na-citrate solution and 0.5 g Na-dithionite in 3 ml 1.25% NaOH. Dithionite-soluble iron was measured spectrometrically in AAS (Varian SpetrAA 300) after centrifugation at 1000 ×g and filtration. If not explicitly stated, the methods were performed according to Schlichting et al. (1995). The vegetation was estimated according to Braun–Blanquet's method (Dierschke, 1994).

2.2.2. Carbon stocks

To avoid the influence of changing bulk densities on the carbon, phosphorus, and potassium stocks that produce dilution effects during self-restoration (Ellert and Bettany, 1995), the stocks were calculated on the basis of the equivalent soil mass approach (Ellert and Bettany, 1995), by using the following formulae:

$$Diff_{cm} = \frac{(Mass_L - Mass_{LNC})}{BD_{deepest\ part\ of\ layer} \times 10} \quad (1)$$

$$C_{stocks} = C_{conc1} \times BD_1 \times H_1 + \ldots + C_{conc\,n} \times BD_n \times (H_n - (Diff_{cm} \times 0.01)) \quad (2)$$

where $Diff_{cm}$ is mass difference converted to cm, $Mass_L$ is mass of the layer (kg m^{-2}), $Mass_{LNC}$ is mass of the layer in natural Albeluvisol (kg m^{-2}), BD is bulk density (g cm^{-3}), C_{conc} is carbon (g kg^{-1}), H is thickness of a soil horizon (m), n is number of soil horizons, and C_{stocks} is carbon on the basis of the equivalent soil mass approach (kg m^{-2}). The stocks were calculated for a soil depth of 0–0.2 m.

2.2.3. Aggregate separation

Aggregate separations were done by wet sieving in the soil layer 0–0.1 m. The method used for aggregate-size separation was adapted from Hartge and Horn (1989) and Six et al. (2000). Briefly, 100 g of air-dried soil were capillary-rewetted for 5 min on a 2000 μm sieve with filter paper. Filter paper was removed and the soil suspension was passed through 2000, 200 and 63 μm sieves for 2 min with 50 repetitions of hand shaking with up and down movements of 3 cm. All fractions were recollected from the sieves, dried at 40 °C and weighed. The wet sieving was conducted in five replicates. The mean weight diameter (MWD) of each sample was calculated by

$$MWD = \sum_{i=1}^{n} X_i W_i \quad (3)$$

where X_i is the mean diameter of each size fraction and W_i is the proportion of the total sample weight in the corresponding size fraction.

2.2.4. Soil organic matter (SOM) fractionation methods

The procedure was conducted in duplicate to obtain free POM, occluded POM of the light fraction (<1.8 g cm^{-3}) and OM of the heavy fraction associated with particle size fractions (>1.8 g cm^{-3}) according to Steffens et al. (2009). Briefly, a 15 g air-dried soil sample <2 mm was transferred into a metal container with a diameter of 7.5 cm together with 120 ml sodium polytungstate (TC-Tungsten Compounds, Germany) at a density of 1.8 g cm^{-3}. The free POM fraction was withdrawn by suction after 16–18 h, filtered through a cellulose nitrate filter (pore size 1.2 μm) and washed with bi-distilled water until the electrical conductivity was <0.5 mS cm^{-1}. To obtain the fraction of the occluded POM in aggregates, the subsequent heavy fraction (>1.8 g cm^{-3}) was treated by ultrasound (HF-Generator GM-2200, Sonotrode VS 70 T, Bandelin). An energy input of 150 J ml^{-1} was used (treatment times were adjusted to sample volume, approximately 15 min) to disrupt all macroaggregates and to obtain highest similarity of clay yields compared to standard particle size analysis, but to minimise the production of artefacts following heavy ultrasonication (Schmidt et al., 1999). The instrument was calibrated calorimetrically every 4 weeks according to North (1976). Subsequently, the suspension was centrifuged at 13,000 ×g for 15 min and the formerly occluded light fraction now floating on the liquid surface was withdrawn by suction. The occluded POM fraction was removed and washed intensively with deionised H_2O onto a 20 μm sieve until the electrical conductivity was <0.5 mS cm^{-1}. To get occluded POM of the suspension which passed through the 20 μm sieve, the solution was centrifuged at 13,000 ×g for 15 min and then the sample was filtered through a cellulose nitrate filter (pore size 1.2 μm) and washed with bi-distilled water until the electrical conductivity was <0.5 mS cm^{-1}. The residue of the density fractionation procedure, comprising particle size fractions associated OM of the heavy fraction (>1.8 g cm^{-3}), was passed through a 63 μm sieve to obtain the sand fraction. Finer particles were separated by sedimentation (Atterberg) into coarse and medium silt (63–6.3 μm), fine silt (6.3–2.0 μm) and clay (<2.0 μm). The clay fraction was gained by centrifugation at 3000 ×g for 18 min and washed with bi-distilled water until the electrical conductivity was <0.5 mS cm^{-1}. All fractions were dried at 105 °C, weighed and analysed for total C and N (CHNS-Analyser Flash EA).

2.2.5. Hot water extractable carbon (Chwe)

Chwe was gained by reflushing 5 g of soil with 25 ml of $H_2O_{dest.}$ for 60 min following VDLUFA (2003). Subsequently, the sample was cooled down to room temperature in a water bath, two droplets of $MgSO_4$-solution (490 g l^{-1}) were added, and samples were centrifuged at 2600 ×g for 10 min. The supernatant was filtered through a 0.45 μm nitrocellulose filter (Millipore), acidified to pH 2 and stored at −18 °C. The Chwe concentration was measured using a TOC analyzer (TOC-V CSH, Shimadzu).

2.2.6. Model description

For modelling, the ROMUL model in combination with the EFIMOD model was used. The ROMUL model of SOC dynamics was described in detail previously (Chertov et al., 2001a,b, 2007). The input parameters include an unlimited number of above- and below-ground litter fall cohorts (leaves, branches, fine roots, stems and coarse roots for every tree species), as well as C and N stocks of the 0–50 cm topsoil. The conversion of this biomass into soil carbon stocks was calculated on data of litter nitrogen and ash content, soil temperature, soil moisture, and soil texture. The EFIMOD model (Komarov et al., 2003) was introduced to calculate litter fall cohorts, not measured within this study. The EFIMOD was previously calibrated and used for West Europe (Kahle et al., 2008), Canada (Bhatti et al., 2009), Central European Russia, Leningrad district and Komi Republic (Shanin et al., 2011).

A recently abandoned impoverished plough soil with 10.0 g kg^{-1} SOC in Ap was selected for the simulation (in 50 cm topsoil SOC and N stocks are 4.35 and 0.108 kg m^{-2}). Climatic scenarios to run the model were compiled by a soil climate generator SCLISS (Bykhovets and Komarov, 2002) that transforms standard meteorological data in the format of the model's input attributes as a matrix of soil temperature and moisture. The initial birch tree density at the simulation was set to 5000, 15,000, and 30,000 seedlings ha^{-1} with a following spruce regeneration. No disturbances (cutting, fires, insect attacks and storms) were modelled.

2.2.7. Data analyses and statistics

Unless stated otherwise, the data were based on three replicates; the standard deviations were always less than 10% of the mean. The correlation coefficient (R^2) was calculated by the statistic programme SPSS 17.

3. Results

3.1. Plant succession and soil development

The arable land was cropped with barley (Fig. 2). The ploughing horizon showed a clod subangular blocky structure and was subdivided into a well rooted top with a bulk density of 1.07 g cm^{-3} and two deeper layers with bulk densities of 1.41 and 1.46 g cm^{-3}, representing different ploughing depths (Table 1). After 4 years of self-restoration, a meadow stage with dominant *Agrostis tenuis* (41%), *Equisetum pratense* (18%), and *Poa pratensis* (12%) had developed. Pedogenesis resulted in the formation of an Ah horizon with a bulk density of 1.20 g cm^{-3}. The former ploughing horizon showed a coarse subangular blocky structure with a bulk density of 1.45 g cm^{-3}. After 12 years of self-restoration, a meadow with a *Chamaenerion angustifolium* (100%) and single small birch trees was documented. The former ploughing horizon showed a subangular blocky structure with a bulk density of 1.38 g cm^{-3}. After 17 years of self-restoration, a young birch forest (*Betula pubescens*) with about 20,000 trees per hectare and an herbal cover of 18% was established. Soil development resulted in the formation of a 2 cm thick organic surface layer of moder and a well rooted Ah horizon with a fine subangular blocky structure. The former ploughing horizon showed a platy subangular blocky structure with a bulk density of 1.22 g cm^{-3}. After 68 years of self-restoration, the vegetation had changed into birch–spruce forest with an herbal cover of about 47% coverage and young spruce trees (*Picea abies*) in the underwood. The organic surface layer of moder was about 3 cm thick; the Ah horizon with a bulk density of 0.79 g cm^{-3} consisted of very fine granular elements. The top part of the former ploughing horizon with a bulk density of 0.94 g cm^{-3} showed a fine subangular blocky structure; the deeper part had a platy subangular blocky structure and a bulk density of 1.25 g cm^{-3}. A birch–aspen (*B. pubescens*; *Populus tremula*) forest with an herbal cover and young spruces in the underwood was observed at the site with the natural Albeluvisol. Local people reported on sporadic cuttings about 30–40 years ago. The soil showed a typical Albeluvisol O–A–E–Bt–Bg profile without any ploughing features with a dark surface horizon over an albic subsurface horizon that tongues into an underlying brown clay illuviation horizon. The eluvial–albic horizons and the Ah–E horizon were characterised by a platy subangular block structure.

During self-restoration, the water-stable aggregate-size distribution was dominated by macroaggregates (small 200–2000 μm and large >2000 μm), which averaged 85% of the dry soil weight (Fig. 3). The amount of microaggregates (63–200 μm) was always less than 10% of the dry soil weight. The mineral topsoil of 0.1 m exhibited an increase in the proportions of large macroaggregates and the mean weight diameter of water-stable aggregates within the first 12 years of self-restoration, followed by a distinct decrease. After 68 years of self-restoration, the content of large macroaggregates and the mean weight diameter of water-stable aggregates were smaller than those found in the natural Albeluvisol. Opposite dynamics were found for the small macroaggregates.

The ploughing horizon of the arable soil was characterised by a pH of 6.4 (H_2O) (Table 1). Exchangeable cations were dominated by Ca, exhibiting 9.4 $cmol_c\ kg^{-1}$ (arithmetic mean), and the base saturation was 100%. After 17 years of self-restoration, the mineral topsoil showed a decrease of the pH to 4.5–4.7 (H_2O), a decrease of contents of exchangeable cations (e.g. Ca to 0.2–0.5 $cmol_c\ kg^{-1}$) and of base saturation to 6.0–10.5%. After 68 years of self-restoration, the soil had a pH value of 4.5–4.6, a content of exchangeable Ca of 1.0–2.0 $cmol_c\ kg^{-1}$, and a base saturation of 17.6–18.5% within the former ploughing horizons and a pH value of 4.7, a content of exchangeable Ca of 6.2 $cmol_c\ kg^{-1}$ and a base saturation of 39.5% within the newly built Ah horizon. The natural Albeluvisol showed a pH value of 4.8 (H_2O), a content of exchangeable Ca of 1.6 $cmol_c\ kg^{-1}$ and a base saturation of 22.7% within the Ah–E horizon as compared to a pH value of 5.4 (H_2O), a content of exchangeable Ca of 14.1 $cmol_c\ kg^{-1}$ and a base saturation of 90.1% within the Ah horizon. Nutrient losses occurred within the mineral top soils down to 51.2 mg g^{-1} for plant available K and down to 14.4 mg g^{-1} for plant available P in the former ploughed horizon of the soil restored for 68 years (Table 1). An opposite development in terms of nutrient accumulation in the organic surface layers set in after 17 years of self-restoration. This accumulation was also found for the newly built Ah horizons at the end of the chronosequence. Without chronosequential alterations all studied soils contained 0.87–1.64% of dithionite-soluble Fe.

3.2. Dynamics of soil organic carbon and nitrogen

The SOC contents in the ploughing horizon of the arable soil were 10.4–11.5 g kg^{-1} (Table 1). Within 17 years of self-restoration, the SOC contents of the mineral topsoil were maintained. After 68 years of self-restoration, the SOC contents had increased to 66.7 g kg^{-1} in the newly built Ah horizon, and to 29.6 g kg^{-1} in the following part of the former ploughing horizon, whereas the deepest formerly ploughed part showed 7.2 g kg^{-1}. An additional increase in SOC to

Fig. 2. Vegetation composition and soil profiles of the Albeluvisols under arable, after 4, 12, 17, and 68 years of former arable, and under natural forest.

Table 1
Main properties of the Albeluvisols under arable, after 4, 12, 17, and 68 years of former arable, and under natural forest.

Horizon	Depth	Bulk density	C_{org}	N	C_{org}/N	pH	pH	Dithionite-soluble-Fe	Exchangeable cations				CEC	BS	K_2O	P_2O_5
						H_2O	$CaCl_2$		Na	K	Ca	Mg			Plant available	
	(cm)	(g cm^{-3})	(g kg^{-1})					(%)	(cmol$_c$ kg^{-1})					(%)	(mg kg^{-1})	
Arable soil																
Ap	12	1.07	10.4 (±2.3)	nf	nd	6.2	5.6	1.20	0.3	0.3	8.9	1.8	11.3	100	69.4	461.4
	21	1.41	11.5 (±1.1)	nf	nd	6.4	5.7	1.29	0.3	0.3	10.1	1.9	12.6	100	70.0	473.2
	29	1.46	10.3	nf	nd	6.4	5.7	1.28	0.2	0.3	9.1	1.6	11.2	100	64.9	570.3
E–Bt	37 (45)	1.42	2.4	nf	nd	5.0	4.1	1.28	0.3	0.2	6.3	1.4	8.2	100	49.7	16.0
Bt	58	1.37	1.1	nf	nd	4.9	4.1	1.09	0.4	0.3	12.9	4.3	17.9	100	80.9	44.7
Bg	83 (93)	1.44	0.1	nf	nd	5.2	4.3	0.91	0.4	0.3	16.2	4.8	21.7	100	68.8	68.8
IICr	100+	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
4 years																
Ah	8	1.20	12.3 (±1.5)	0.5 (±0.4)	nd	5.2	4.4	1.01	0.2	0.9	5.3	1.1	9.5	78.6	258.3	34.3
Ap_1	15	1.45	10.9 (±1.6)	nf	nd	5.2	4.2	0.86	0.2	0.4	3.0	0.7	7.7	55.8	137.0	21.1
Ap_2	35	1.52	6.8	nf	nd	5.2	4.2	1.07	0.3	0.3	3.7	0.8	7.0	54.5	97.4	22.9
E–Bt	40	1.44	2.4	nf	nd	5.2	4.2	1.36	0.2	0.2	6.0	1.4	7.8	100	86.6	11.6
Bt	65	1.55	1.6	nf	nd	5.4	4.3	1.47	0.3	0.3	6.9	1.8	9.3	100	83.5	19.6
Btg	100	1.55	0.6	nf	nd	5.6	4.5	1.28	0.2	0.3	7.1	2.5	10.1	100	83.5	50.2
12 years																
Ah	10	1.06	11.6 (±2.0)	0.3 (±0.3)	nd	4.8	4.0	1.07	nf	0.4	1.3	nf	9.6	20.1	190.7	43.5
Ap	27	1.38	11.3 (±2.5)	nf	nd	4.9	4.0	0.97	nf	nd	1.2	nf	10.5	15.0	67.1	45.7
E	28	nd	nd	nf	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Btg	45	1.48	1.4	nf	nd	5.0	4.0	1.26	nf	nd	7.7	1.8	10.4	95.2	78.0	20.1
Bg	75	1.56	0.7	nf	nd	5.2	4.0	1.04	nf	0.3	9.2	2.4	11.9	100	82.2	37.9
Cr	100+	1.66	nd	nd	nd	5.4	4.1	0.98	nf	0.3	7.0	2.4	9.7	100	110.4	61.9
17 years																
O	2+	0.07	397.3	16.9	23.5	5.0	4.7	0.15	nd	nd	nd	nd	nd	nd	1570.5	807.2
Ah	8	1.10	12.7 (±2.4)	nf	nd	4.6	3.8	1.08	nf	nf	0.5	nf	8.8	10.5	71.6	37.6
Ap	21 (28)	1.22	10.6 (±2.7)	nf	nd	4.7	3.8	1.06	nf	nf	0.2	nf	8.4	6.0	64.8	24.5
E–Bt	25 (30)	1.48	1.8	nf	nd	4.9	4.0	1.13	nf	nf	2.6	nd	10.4	34.2	73.0	7.9
Bt	45	1.55	0.9	nf	nd	5.1	4.0	1.16	nf	nf	5.8	2.1	13.2	62.9	65.0	16.3
Btg	80	1.61	0.1	nf	nd	5.1	4.0	1.21	nf	0.3	7.5	2.5	11.5	91.2	66.2	21.5
BCg	125	nd	nf	nf	nd	5.4	4.1	1.15	nf	nd	7.9	2.2	10.2	100	76.1	54.2
Cr	145+	nd	0.2	nf	nd	5.8	4.5	0.87	nf	0.3	6.5	3.7	10.5	100	106.2	55.6
68 years																
O	3+	0.07	400.8	16.3	24.6	5.0	4.8	0.23	nd	nd	nd	nd	nd	nd	1965.8	894.7
Ah	2 (4)	0.79	66.7 (±23.4)	3.2 (±1.6)	20.8	4.7	4.2	1.17	nf	0.3	6.2	0.9	19.3	39.5	113.3	65.9
Ap_1	8 (11)	0.94	29.6 (±16.1)	1.3 (±1.1)	22.8	4.5	3.8	1.30	nf	nf	2.0	nf	16.0	18.5	75.0	35.6
Ap_2	21 (23)	1.25	7.2 (±0.46)	nf	nd	4.6	3.8	1.27	nf	nf	1.0	nf	8.1	17.6	51.2	14.4
E	29 (32)	1.48	2.3	nf	nd	4.8	3.9	1.08	nf	nf	0.4	nf	5.5	12.4	30.0	4.1
E–Bt	45	1.50	1.0	nf	nd	4.9	3.9	1.07	nf	nf	0.9	nf	5.8	26.8	32.3	3.8
Bt	65	1.59	0.5	nf	nd	5.0	3.8	1.22	nf	nf	6.0	2.0	10.6	80.0	69.7	4.6
Bg	80	1.53	nf	nf	nd	5.0	3.8	1.17	nf	0.3	9.4	3.4	13.1	100	80.9	19
BCg	110	nd	0.3	nf	nd	5.2	3.9	0.87	nf	nd	6.8	1.9	8.7	100	52.9	26.5
Cr	130+	nd	nd	nf	nd	5.3	4.1	1.64	nf	0.3	7.2	4.2	11.7	100	99.1	47.8
Natural Albeluvisol																
O	3+	0.08	421.1	17.9	23.8	5.4	5.1	0.13	nd	nd	nd	nd	nd	nd	2225.7	943.3
Ah	2 (4)	0.52	75.9 (±15.0)	3.0 (±1.6)	25.3	5.4	4.8	1.23	nf	1.0	14.1	2.1	19.3	90.1	449.2	138.3
Ah–E	10	0.77	20.8 (±6.3)	0.9 (±0.1)	23.1	4.8	4.1	1.56	nf	nf	1.6	nf	10.8	22.7	78.4	37.25
E_1	16	1.26	5.1 (±0.7)	nf	nf	4.8	3.9	1.48	nf	nf	0.3	nf	6.4	9.3	39.7	16.6
E_2	26	1.51	2.2	nf	nf	4.9	4.0	1.22	nf	nf	0.2	nf	3.5	13.6	26.3	5.9
E–Bt	32	1.56	2.0	nf	nf	4.9	4.0	1.20	nf	nf	1.0	nf	3.4	46.1	31.7	6.8
Btg	45	1.45	1.3	nf	nf	5.0	4.0	1.67	nf	nf	3.2	1.1	11.8	39.8	57.8	14.3
IICr	85+	nd	nd	nf	nd	5.2	4.1	1.64	nf	nf	3.2	1.1	5.9	82.4	43.1	32.3

nd — not determined.
nf — not found.
BS — bases saturation with the exception of shown standard deviations (sd).
sd was <10%.

397.3 g kg^{-1} resulted from the development of organic surface layers, starting after 17 years of self-restoration. During self-restoration SOC contents of the top soils thus developed from a homogenous distribution to a vertical stratification like in the natural Albeluvisol.

Total N content was below the detection limit (0.5 g kg^{-1}) in the arable soil. Within the chronosequence, N was found in the newly built Ah horizon and in the organic surface horizons. Highest N accumulation up to 3.2 g kg^{-1} in the Ah horizon and up to 16.3 g kg^{-1} in the O horizon was documented after 68 years of self-restoration. At that time, the N contents and their vertical distribution were comparable with the natural Albeluvisol. The N stocks in the upper 0.1 m were 0.03 in the soil restored for 17 years, 0.18 kg m^{-2} in the soil restored for 68 years, and 0.12 kg m^{-2} for the natural Albeluvisol (data not shown). The C_{org}/N ratios were in the range of 20–24 and showed no alterations within the chronosequence.

3.3. Carbon stocks

Regarding the standard deviations, the carbon stocks showed minor changes in the upper 0.5 m during self-restoration and in

Fig. 3. Percentage contents of microaggregates 63–200 μm (■), small macroaggregates 200–2000 μm (□), large macroaggregates >2000 μm (■) and mean weight diameter of the aggregates (—) in 0–0.1 m of the Albeluvisols under arable, after 4, 12, 17, and 68 years of former arable, and under natural forest. Standard deviations < 10%.

comparison to the arable and natural Albeluvisol, showing values of 4–5 kg C m^{-2} (Fig. 4). Nevertheless, the data exhibited a vertical redistribution of carbon stocks. The C accumulation within the organic surface layers exhibited 0.64 kg m^{-2} after 17 years and 0.78 kg m^{-2} after 68 years of self-restoration. The mineral topsoils showed an increase of the carbon stocks from 0.75 in the arable soil to 2.64 kg m^{-2} in the soil restored for 68 years in 0–0.1 m and a carbon loss from 3.6 to 1.71 kg m^{-2} in 0.1–0.5 m.

The outcome of the SOM modelling demonstrated the same overall development of carbon stocks for the time interval of the chronosequence as shown by the measured data set (Figs. 4 and 5). The dynamic pattern of SOC pool changes reflected the formation of organic layers with corresponding SOC decrease in the mineral horizons. This decrease was especially intensive when trees began to invade after the 10th time step. On the long term, i.e. up to 200 years, the model predicted a slowly but consistently increasing SOM sink functioning caused by continuously increasing carbon stocks. The fluctuations of SOC pools indicated the impact of varying weather and natural mortality of trees.

3.4. Dynamics of different SOC pools

All fractions increased in the chronosequence. Free POM increased from 0.5 to 0.7 g kg^{-1} in the ploughing horizon of the arable soil to 18.9 g kg^{-1} in the newly built Ah horizon and to 4.2 g kg^{-1} in the upper part of the former ploughing horizon of the soil restored for 68 years (Fig. 6). Occluded POM increased from 3.7 to 4.3 g kg^{-1} in the ploughing horizon of the arable soil to 17.8 g kg^{-1} in the newly built Ah horizon and to 7.8 g kg^{-1} in the top part of the former ploughing horizon of the soil restored for 68 years (Fig. 7). The OC content of the clay fraction increased from 2.9 to 3.7 g kg^{-1} in the arable soil to 11.2–9.3 g kg^{-1} in the soil abandoned for 68 years, and the C content of the sand fraction from 0.4 to 0.7 g kg^{-1}, respectively. The silt fraction showed intermediate chronosequential increase. These increases were significantly correlated with the increase in total SOC content related to the soil mass (Table 2; Figs. 6 and 7), shown by the following coefficients: occluded POM ($R^2 = 0.968$, $P = 0.01$), free POM ($R^2 = 0.951$, $P = 0.01$), clay ($R^2 = 0.853$, $P = 0.01$), fine silt ($R^2 = 0.737$, $P = 0.01$), medium/coarse silt ($R^2 = 0.755$, $P = 0.01$) and sand fraction ($R^2 = 0.686$, $P = 0.01$). Hence, all fractions of the topsoils traced the development of TOC from a homogenous distribution to a vertical stratification during self-restoration.

Related to total SOC, the fractions changed differently. Free POM fraction increased from 5.5 to 7.9% in the arable soil to 33.3% in the newly built Ah horizon and to about 14% in the former ploughing horizon of the soil restored for 68 years. This increase showed a significantly positive correlation with the increase of SOC contents ($R^2 = 0.868$, $P = 0.01$). At the end of the chronosequence, the free POM fraction did not reach the level of the natural Albeluvisol. Occluded POM fraction decreased from 37.9 to 46.3% in the arable soil to 30.7% in the newly build Ah horizon and to about 28% in the former

Fig. 4. Carbon stocks in the organic surface layers (■), in the upper 0–0.1 m of the mineral topsoils (□), and in the upper 0.1–0.5 m of the mineral topsoils (■) of the Albeluvisols under arable, after 4, 12, 17, and 68 years of former arable, and under natural forest.

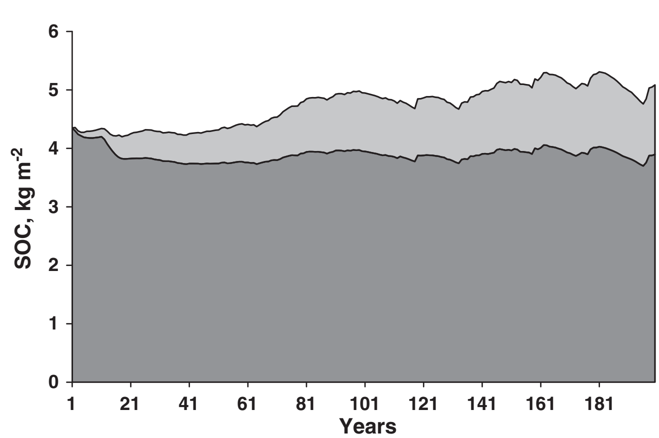

Fig. 5. The simulated SOC dynamics stocks in the organic surface layer (■) and in the upper 0.5 m of the mineral topsoil (■) of the studied soils over 200 year after abandonment for natural afforestation.

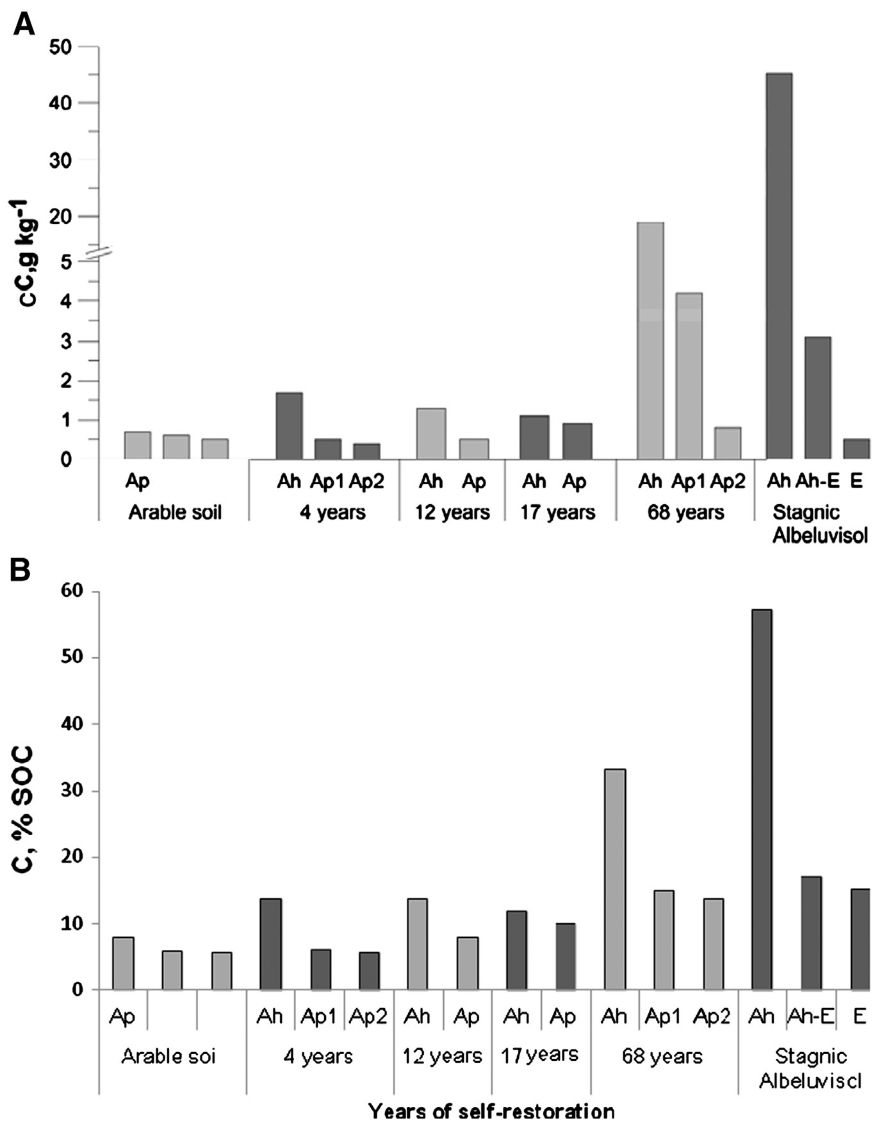

Fig. 6. Contents of total organic carbon (A: g kg^{-1}; B: % of SOC) of the fraction free POM in the density fraction <1.8 g cm^{-3} in the Albeluvisols under arable, after 4, 12, 17, and 68 years of former arable, and under natural forest. Standard deviations < 10%.

ploughing horizon of the soil restored for 68 years. OC of the clay fraction showed the development from a homogenous distribution in the arable soil to a vertical stratification at the end of the chronosequence like the natural Albeluvisol. OC of other grain size fractions showed minor changes.

The N contents of the fractions of free POM, occluded POM, and clay correlated significantly and positively with the C contents ($R^2 = 0.999$, $P = 0.01$; $R^2 = 0.988$, $P = 0.01$; $R^2 = 0.964$, $P = 0.01$, respectively), resulting in similar changes in C and N during the self-restoration process, but with no changes of the C/N ratio. Regardless of the chronosequential development, the C/N ratios of the occluded POM were smaller than those of free POM and the C/N ratios of both fractions were distinctly larger than those of clay (Table 3). From the very beginning, the soils showed increasing C/N ratios with increasing soil depth for the free POM fraction. Vertical differentiation was not observed in the occluded POM fraction before 12 years and in the clay fraction before 68 years of self-restoration.

With a significant positive correlation between Chwe (g kg^{-1}) and total SOC contents ($R^2 = 0.998$, $P = 0.01$) Chwe contents (g kg^{-1}) increased from 1.4 to 3.0 g kg^{-1} in the ploughing horizon of the arable soil to 17.0 g kg^{-1} in the newly built Ah horizon and to 7.8 g kg^{-1} in the upper part of the former ploughing horizon of the soil restored for 68 years (Table 2).

4. Discussion

4.1. Plant succession and soil development

After 68 years of self-restoration, the plant succession reached a birch–spruce forest stage with spruce trees in the underwood (Fig. 2). The young spruce trees indicate a development towards a mesophytic spruce forest, being the climax plant association for the loamy soils in the Taiga of European Russia, characterised by short-term stagnic conditions only in spring and high rates of carbon and nutrient turnover (Ilichev, 1982). At present, sites with this climax feature cannot be found. Consequently, the natural Albeluvisol of the chronosequence showed a birch–aspen forest with spruce trees in the underwood, also developing towards the climax stage described above. The dominance of *C. angustifolium* after 12 years of self-restoration is out of the ordinary succession, presumably caused by a short fire incident. Comparing the post-agrogenic succession of this study with that on sandy soils of the same climate (Kalinina et al., 2009) revealed that both successions developed into a climax spruce forest, however, the succession on sandy soils via a pine forest stage and the succession on loamy soils via a birch forest stage. According to Shugart (1984), Razumovsky (1999), the time scale for self-restoration of spruce forests is approximately 150–200 years.

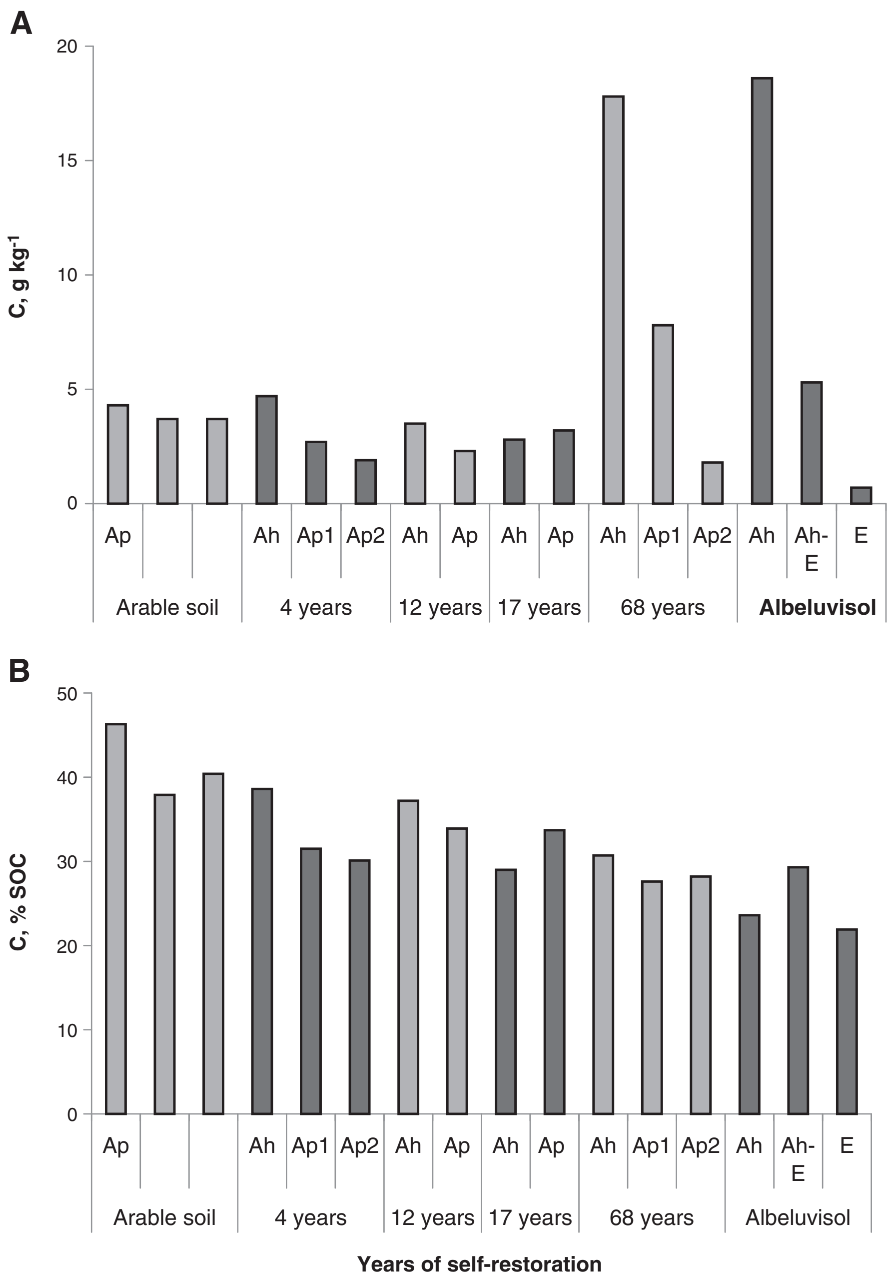

Fig. 7. Contents of total organic carbon (A: g kg^{-1}; B: % of SOC) of the fraction occluded POM in the density fraction <1.8 g cm^{-3} in the Albeluvisols under arable, after 4, 12, 17, and 68 years of former arable, and under natural forest. Standard deviations < 10%.

Hence, the first appearance of spruce trees after 68 years of self-restoration found in this study implies that the climax spruce forest stage is reached much earlier on loamy soils than on sandy soils.

Soil development resulted in a new morphological stratification of the topsoil (Fig. 2; Table 1). Chronosequential alterations started with the formation of a well rooted Ah horizon after 4 years of self-restoration followed by the development of an organic surface layer of moder after 17 years of self-restoration. At the end of the chronosequence, the bottom of the well visible former ploughing horizon clearly showed some bleaching, although not underlined by decreasing contents of dithionite-soluble Fe. During self-restoration the soil structure of the topsoil changed from clod subangular blocky to fine granular elements in the newly built Ah horizons and to platy subangular blocky structures in the former ploughing horizons below. After 12 years of self-restoration, a downsizing of the soil structure elements took place, accompanied by a decreasing bulk density. These changes are in accordance with findings of other studies (e.g. Olszewska and Smal, 2008; Kalinina et al., 2011) and are expected to result from the gradual input of new organic residues as well as from an increasing soil biological activity in terms of increasing rooting and soil fauna populating (Jug et al., 1999). Changes in soil structure are accompanied first by increasing, then by decreasing proportions of large water-stable macroaggregates (>2000 μm) and mean weight diameters of water-stable aggregates (Fig. 3). The turning point after 12 years is related to the change in vegetation from meadow to forest. The same trend was observed in other soils during self-restoration (Jastrow, 1996; Kalinina et al., 2011). It is assumed to be caused by the introduction of fresh organic residues acting as binding agents for the macroaggregates formation in association with hyphae (Jastrow, 1996; Tisdall and Oades, 1982).

At the beginning of self-restoration, the mineral topsoil showed a homogenous vertical SOC distribution. At the end, we found a vertical

Table 2
Contents of hot water extractable carbon (Chwe) and contents of organic carbon in the grain size fractions of the density fraction > 1.8 g cm^{-3} of the Albeluvisols under arable, after 4, 12, 17, and 68 years of former arable, and under natural forest.

Horizon	Depth	Chwe		Sand		Silt				Clay	
				2000–63 μm		63–6.3 μm		6.3–2 μm		<2 μm	
		C in fractions									
	(cm)	(g kg^{-1})	% SOC	(g kg^{-1})	% SOC	(g kg^{-1})	% SOC	(g kg^{-1})	% SOC	(g kg^{-1})	% SOC
Arable soil											
Ap	12	3.0	28.6	0.3	3.2	0.4	4.4	0.6	7.0	2.9	31.3
	21	1.9	18.5	0.4	4.6	0.6	6.0	0.7	7.1	3.7	38.1
	29	1.4	13.2	0.4	4.5	0.5	5.6	0.7	7.2	3.1	34.5
4 years											
Ah	8	3.3	25.9	0.4	3.2	0.5	4.1	0.9	7.0	4.1	33.7
Ap1	15	1.2	13.6	0.2	2.1	0.5	5.6	1.0	11.7	3.6	41.7
Ap2	35	0.9	12.9	0.1	1.1	0.5	7.7	0.6	9.8	2.8	43.4
12 years											
Ah	10	3.1	29.9	0.3	3.0	0.4	4.8	0.9	9.0	3.3	34.5
Ap	27	1.8	22.6	0.2	2.6	0.4	5.3	0.7	9.6	2.9	42.1
17 years											
O	2+	151.2	38.1	nd	nd	nd	nd	nd	nd	nd	nd
Ah	8	2.9	28.3	0.4	3.6	1.0	9.8	0.3	3.3	3.6	36.7
Ap	21 (28)	2.3	21.4	0.3	3.0	0.8	8.9	0.4	4.2	3.6	37.9
68 years											
O	3+	163.7	40.8	nd	nd	nd	nd	nd	nd	nd	nd
Ah	2 (4)	17.0	29.6	0.7	1.2	2.0	6.2	3.4	6.2	11.2	20.0
Ap_1	8 (11)	7.8	20.9	0.7	2.8	2.2	10.5	3.1	10.7	9.3	32.7
Ap_2	21	1.5	21.3	0.2	3.8	0.3	5.3	0.5	7.4	2.5	38.4
Natural Albeluvisol											
O	3+	158.0	37.5	nd	nd	nd	nd	nd	nd	nd	nd
Ah	2 (4)	22.4	25.9	0.5	0.6	1.5	1.9	1.9	2.4	8.4	10.6
Ah–E	10	5.2	23.6	0.4	2.0	1.2	6.7	1.9	10.8	5.9	32.7
E	16	0.9	20.2	0.1	3.1	nf	nf	0.2	8.4	1.7	51.9

nf — not found.
nd — not determined.
Standard deviations < 10%.

Table 3
C/N ratios in the fine silt and clay fractions of the density fraction > 1.8 g cm^{-3} and in the fractions of free POM and occluded POM of the density fraction < 1.8 g cm^{-3} of the Albeluvisols under arable, after 4, 12, 17, and 68 years of former arable, and under natural forest.

Horizon	Depth (cm)	> 1.8 g cm^{-3}		< 1.8 g cm^{-3}	
		Silt 6.3–2 μm	Clay <2 μm	Free POM	Occluded POM
Arable soil					
Ap	12	nf	8.7	23.5	19.6
	21	nf	9.3	29.5	20.8
	29	nf	9.3	36.0	21.0
4 years					
Ah	8	nf	7.9	25.4	23.6
Ap_1	15	nf	9.0	31.1	24.0
Ap_2	35	nf	7.8	44.7	25.4
12 years					
Ah	10	nf	7.9	21.6	22.2
Ap	27	nf	8.1	55.9	29.5
17 years					
Ah	8	nf	8.7	29.0	23.4
Ap	21 (28)	nf	9.9	34.7	25.0
68 years					
Ah	2 (4)	20.2	9.9	23.0	22.4
Ap_1	8 (11)	15.0	9.5	35.0	31.4
Ap_2	21	nf	14.3	45.1	59.8
Natural Albeluvisol					
Ah	2 (4)	13.9	10.6	22.7	20.9
Ah–E	10	12.5	10.9	22.9	25.3
E	16	nf	13.8	31.4	28.5

nf — not found.
Standard deviations < 10%.

differentiation and a redistribution of SOC in the mineral topsoil with increasing C contents in the newly built Ah horizon and decreasing C contents in the lower part of the former ploughing horizon, thus reflecting the morphological alterations and approaching the feature of the natural Albeluvisol (Table 1). In accordance with findings of other studies (Alriksson and Olsson, 1995; Jug et al., 1999; Richter et al., 1999; Smal and Olszewska, 2008; Vesterdal et al., 2002), the effect of C redistribution in the topsoil is expected to result from the formation of the organic moder surface layer. Although the lower part of the former ploughing horizon was impoverished in SOC, the ploughing border was clearly apparent after 68 years of self-restoration. The presence of the former ploughing horizons after a long time (e.g. 170 years) of self-restoration is also documented in other studies performed in the boreal Taiga zone (Kalinina et al., 2009; Vladychensky et al., 2009). As opposed to this, disappearance of the ploughing border was shown for post-agrogenic Chernozems in the forest steppe zone after 37 years of self-restoration (Kalinina et al., 2011). Thus, the permanence of these features differs widely depending on pedogenic conditions.

After 4 years of self-restoration, first changes in chemical properties were observed, indicating leaching of bases from the topsoil and increasing soil acidification (Table 1). After 17 years of self-restoration, the former ploughing horizon showed a pH decrease of about 1.8 units, loss of exchangeable cations, and depletion of the base saturation from 100 to 6.0%. Soil acidification is a common process after afforestation of abandoned agricultural sites as shown in many studies (Alriksson and Olsson, 1995; Berthrong et al., 2009; Jug et al., 1999; Ritter et al., 2003; Smal and Olszewska, 2008). It is caused by fertilisation stop and changes in both the quality of litter fall and decomposer composition towards more poorly decomposable organic debris and a fungal dominated community (Susyan et al., 2011; Thuille and Schulze, 2006). Consequently, the lower transformation rate of soil organic matter resulted in the formation of an organic surface layer and increased production of organic acids. Emmer (1995) and Nicodemus et al. (2012) found a temporary relation between the formation of a closed canopy during afforestation, increasing fulvic acid rates, and developing albic features. Susyan et al. (2011) reported an accelerated soil basal respiration within the chronosequence from arable land to forest, which is an important agent of the soil acidity (Jobbagy and Jackson, 2003). The increased soil acidity after afforestation may also be caused by an increased uptake of cations by trees and accelerated leaching of bases to deep groundwater (Jobbagy and Jackson, 2003). An inverse development towards the cation distribution in the natural Albeluvisol started after 68 years of self-restoration in the mineral topsoil through increasing SOM accumulation and mineralisation in the newly built O and Ah horizons.

During self-restoration, a depletion of plant available phosphorus and potassium contents was observed in the former ploughing horizon (Table 1). As documented in several other studies (Chen et al., 2000; Jug et al., 1999; Smal and Olszewska, 2008), a loss of nutrients in terms of afforestation on former arable soils is a result of two opposite processes — accelerated eluvial leaching of nutrients from the former ploughing horizon and nutrient uptake by plants following their accumulation within an organic surface layer and the first horizons of the mineral topsoil (Chertov et al., 2001a; Jobbagy and Jackson, 2003). These processes are also true for the self-restoration investigated in this study. The nutrient redistribution in the topsoil during the self-restoration process resulted in a loss of nutrients in the former ploughing horizon and in a supply of nutrients in the organic surface layer and in the newly built Ah horizon (Table 1).

Afforestation or self-restoration of the former arable land resulted in N accumulation in the organic surface layer and plant biomass (Ritter et al., 2003; Smal and Olszewska, 2008), while contradictory data were reported for mineral soil horizons (e.g. Berthrong et al., 2009; Poulton et al., 2003; Ritter et al., 2003). As N is always positively correlated with SOC, these different findings are discussed within the SOM chapter below. In our study, total N was mostly found to be below the detection limit and increasing N contents with the development of Ah horizons and of organic surface layers (Table 1). At the end of the studied chronosequence, the topsoil showed a vertically stratified N distribution, similar to the natural Albeluvisol and slightly increased nitrogen stocks (0.18 kg m^{-2}) in the upper 0.1 m in comparison to the natural Albeluvisol (0.12 kg m^{-2}). The low N contents are assumed to result from an agricultural land use management with no or very little N fertilisation. In contrast to the post-agrogenic Podzols with C/N ratios of 30–40 (Kalinina et al., 2009), the lower C/N ratios of restored Albeluvisol indicate a higher SOM quality also expressed by the development of moder humus.

4.2. Dynamics of soil organic matter

4.2.1. Carbon stocks

Afforestation of former arable sites resulted in a net sink for atmospheric CO_2 with C sequestration mainly in the growing trees and in the surface organic layer (Morris et al., 2007; Post and Known, 2000; Poulton et al., 2003; Richter et al., 1999; Thuille and Schulze, 2006; Vesterdal et al., 2002). Relating to carbon sequestration within the mineral topsoil, either a decrease (Berthrong et al., 2009; Guo et al., 2007; John et al., 2005; Kalinina et al., 2009; Thuille and Schulze, 2006; Vesterdal et al., 2002), or an increase (Del Galdo et al., 2003; Kurganova et al., 2007; Morris et al., 2007; Poulton et al., 2003; Vladychensky et al., 2009), or no notable changes were found (Czimczik et al., 2005; Huang et al., 2011; Richter et al., 1999). These contradictory findings are due to varying interrelations between initial SOC pools and SOC dynamic trends in respect to environmental conditions (Jug et al., 1999; Laganiere et al., 2010; Paul et al., 2002; Vesterdal et al., 2002; Wilde et al., 1965). SOC contents usually increase on humus-poor former arable or devastated soils, while it can be stable or even decrease on humus-rich former agricultural soils (Paul et al., 2002; Vesterdal et al., 2002).

The results of this study showed minor alterations regarding the carbon pools of the calculated depths of 0.50 m during the chronosequence. Considering different soil compartments, C accumulation took place within the organic surface layers and the mineral topsoil of 0–0.10 m with simultaneous C loss below (Fig. 4). The results of the simulation exercise on the SOM dynamics correspond to these trends (Fig. 5). Considering the whole carbon pool, the modelling results showed also minor alterations for the time interval of the chronosequence, followed by an increasing SOM sink functioning at a long term of 200 years. According to the simulation, the chronosequence thus covers only a part of the carbon sequestration process during self-restoration. Furthermore, the natural Albeluvisol seems to be out of the line of the chronosequence, showing carbon stocks lower than those of the modelled soils. We assume that the carbon dynamics of the natural Albeluvisol is not yet balanced because of sporadic cutting. Consequently, a new equilibrium between input of the plant residues and SOM decomposition may be reached in the studied chronosequence approximately after 150 years of self-restoration according to the modelling and according to the literature (Razumovsky, 1999; Shugart, 1984). It should be pointed out that modelled data demonstrate a theoretical pattern of development, while the observed data reflect soil changes under the impact of both vegetation and various damages, including irregular thinning and probably others like deceases and fires.

4.2.2. Dynamics of different SOC pools

All functionally different SOC pools of post-agrogenic Albeluvisols showed a significant positive correlation with total SOC related to the soil mass during self-restoration (Table 2, Figs. 6 and 7). Thus, the OC accumulation of all fractions reflected the total SOC dynamics during self-restoration. The same trend was observed for the post-agrogenic Chernozems of Russia (Kalinina et al., 2011), for post-agrogenic Podzols of the Russian Taiga (Kalinina et al., 2010), for loamy alluvial soils of northeastern Italy converted from arable land to mixed deciduous woodland (Del Galdo et al., 2003), for afforested post-agrogenic soils of the USA (Degryze et al., 2004; Six et al., 2002), for soils of eucalyptus plantations established on degraded pastures in southeastern Brazil (Lima et al., 2006), and for soils of eucalyptus plantations on the former grassland in New Zealand (Huang et al., 2011).

The type of land use affects the distribution pattern of carbon to functionally different SOM pools (John et al., 2005). The OC of the density fraction <1.8 g cm^{-3} (free POM and occluded POM) and the OC of sand and coarse-silt size fractions represent the active and intermediate pools with short turnover times (von Lützow et al., 2008), consisting of macro-organic matter of plant and animal origin and charcoal (Christensen, 1992). It is well known that these SOC pools are more present in forest soils than in arable soils due to increasing amounts of poorly degradable litter from the forest development (Degryze et al., 2004; John et al., 2005; Kalinina et al., 2010; Six et al., 2002). In the present study, the free POM fraction (% of total SOC) increased on an average of 14% during the time of self-restoration but did not reach the level of the natural Albeluvisol (Fig. 6). This indicates that the SOC development was not yet balanced within the 68 years of self-restoration. Our data showed an average 12% depletion of occluded POM to total SOC during self-restoration (Fig. 7), however, a recovery of the soil structure was observed. This is inconsistent with John et al. (2005) who observed higher contributions of occluded POM in loamy soils under spruce forest as compared to soils with tillage. Six et al. (2002) reported a greater aggregation in afforested ecosystems as compared to arable sites, resulting in higher intra-aggregate carbon concentrations. The same is true for restored grassland systems, where an accrual of the occluded POM contribution was coupled with a regenerating soil structure that had been destroyed during previous cultivation (Jastrow, 1996; Kalinina et al., 2011; Six et al., 1999). Our findings are assumed to be caused by an accelerating aggregate turnover (i.e. rate of formation and degradation of aggregates) due to imbalances between input of fresh organic residues and rising biological activity (Six et al., 2002) in the meadow phase. In the forest stage, the distinct gradual input of forest litter into the mineral topsoil and increasing amounts of free POM led to a relative decrease of the occluded POM.

Chwe has been used as a measure for easily decomposable OC (Körschens et al., 1998). Ghani et al. (2003), Spohn and Giani (2011) found a linear positive relationship between total SOC and Chwe. The same was supposed in the present study. Hence, Chwe reflected the total SOC dynamics during the self-restoration. This means that Chwe is not a relevant measure for detecting long-term SOM changes during self-restoration, as also argued by Spohn and Giani (2011) for soils converted from pasture to cropland.

OC in the fine-silt and clay fractions includes organo-clay complexes and mineral grains coated with OM (Christensen, 1992) and represents passive SOC (von Lützow et al., 2008). The OC of this pool (% of total SOC) showed the same recovery as that of total SOC within self-restoration. The same was observed for restored post-agrogenic Chernozems (Kalinina et al., 2011). As opposed to this, an increase of mineral-associated organic matter from 72.5 to 80% of total SOC was reported by Jastrow (1996) in a ten-year chronosequence of restored tallgrass prairie.

During self-restoration, the vertical distribution of the different SOC pools in the topsoil showed a recovery towards the natural Albeluvisol. Related to the soil mass, this process reflected the redistribution of total SOC in the topsoil. Related to total SOC, changes of the vertical OC distribution are predominantly caused by sequestration of the active SOC pool within the newly built Ah horizons and by an increased portion of the passive SOC pool in the deeper parts of the former ploughing horizon. This vertical distribution is also shown by the C/N ratios of different SOC fractions, simultaneously indicating the different recalcitrance of these various fractions. The active SOC pool represented by the free POM fraction showed lower C/N ratios at the top that increased with depth from the very beginning, whereas vertical stratification was not observed before 12 years for occluded POM and not before 68 years of self-restoration for the clay fraction (Table 3).

5. Conclusion

Sixty-eight years of self-restoration of post-agrogenic loamy soils in the Taiga zone of Russia were characterised by a vegetation succession towards a mesophytic spruce forest. Simultaneously, soils developed towards natural Albeluvisols, comprising a vertically stratified recovery of morphological and chemical features as well as C contents. The measured carbon stocks did not change substantially during self-restoration, but showed a distinct redistribution within different soil layers. The modelled carbon stocks showed also minor alterations for the chronosequence time interval, followed by an increasing SOM sink functioning in the long term, indicating that the chronosequence did not cover the full duration of self-restoration. During self-restoration, the dynamics of all C fractions followed that of total SOC. Nevertheless, the fractions showed temporally different reactions to chronosequential alterations and, as expected for a development into a forest, SOC sequestration occurred predominantly within the free POM fraction.

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