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

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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

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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