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Self-restoration of post-agrogenic soils of Calcisol–Solonetz complex: Soil development, carbon stock dynamics of carbon pools

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ABSTRACT

This chronosequential study focusses on the vegetation succession, pedogenesis, carbon stocks and different carbon pools of post-agrogenic Calcisol–Solonetz complexes in the dry steppe zone of Russia. The sites were comparable in terms of climate, soil texture and land-use history, but differed in the duration of agricultural abandonment, covering 1, 7, 12, 17 and 42 years of self-restoration. During self-restoration without direct human impact, the vegetation developed towards a steppe with dominance of *Artemisia lercheana*/*pauciflora* and *Stipa pennata*. After 17 years, the abundance of *Artemisia pauciflora* indicated again the Solonetz locations within the Calcisol–Solonetz complex, which were not visible during arable land use. Pedogenesis resulted in the recovery of the natural soil structure—fine subangular polyhedral for Calcisol and crumble fine platy for Solonetz. The recovery of soil structure of Solonetz was in accordance with a decline of water-stable aggregates from 84% to 68%. The plow features were still well visible after 42 years of self-restoration in both soil groups. Partial integration of Btn materials into the plow layer induced a pH increase during cultivation of the Solonetzes, while slight pH decreases were observed during self-restoration afterwards. Other chemical properties of both soil groups remained unchanged. Post-agrogenic Solonetzes showed an exchange sodium percentage (ESP) below 5.0% and an electrical conductivity (ECe) below 50 mS m^{-1} at the topsoil during the period of self-restoration. The development towards natural soils was observed in terms of soil organic carbon (SOC) dynamics. SOC stocks of the Calcisols increased slowly from 2.0 to 3.5 kg m^{-2} in the upper 0–0.5 m, comprising 64% of the natural soil. SOC stocks of the Solonetzes grew from 1.7 to 3.1 kg m^{-2} in the upper 0–0.5 m and almost reached the level of natural soil already after 12 years of self-restoration. The long-term modelling showed a recovery of SOC stocks almost after 100 years for the Calcisol and the Solonetz chronosequences. The nutrient dynamics traced SOC dynamics during the self-restoration. The investigation of different carbon pools showed a significant organic carbon (OC) enrichment of the density fractions <1.8 g cm^{-3} (free particulate organic material (POM) and occluded POM) and the density fractions >1.8 g cm^{-3} (sand coarse/medium silt, fine silt, clay) following an increase of total SOC during self-restoration. In the Calcisol chronosequence, the dynamics of all fractions was close to the dynamics of total SOC with the exception of free POM showing a moderate accumulation rate in relation to total SOC. Post-agrogenic Solonetzes showed a more intensive accumulation of free POM and a slower OC sequestration in aggregates compared to total SOC. Both chronosequences showed comparable recovery rates for the passive SOC pool and total SOC. Despite all these alterations the study showed no full restoration for many parameters within the chronosequential time scale of 42 years.

1. Introduction

Until recently, abandonment of arable land was a worldwide process comprising 2,197,000 km^{-2}. The reasons are different depending on the country and space of time: intensification of farming and increase of production, wars, and economic crises (Ramankutty, 2006; Lyuri et al., 2010). From 1987 to 2007, about 706,000 km^{-2} of arable land was abandoned in Russia, 562,000 km^{-2} of abandonments was found in the European part of Russia (Lyuri et al., 2010). 68% of abandonments occurred after 1990 due to the economic crises (Vuichard et al., 2008; Henebry, 2009; Lyuri et al., 2010; Kurganova et al., 2010, 2014; Schierhorn et al., 2013). Although a wide range of climatic zones of Russia were affected, most of the abandoned sites were documented in the zones with unfavourable environmental conditions for farming (Lyuri et al., 2010; Kurganova et al., 2014). Hence, most abandonments of the dry steppe have been documented on arable land without irrigation (Lyuri et al., 2010). As a consequence of abandonments, self-restoration

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set in. Self-restoration is a process without any direct human impact and describes the alteration of formerly agricultural or post-agrogenic soils (Lyuri et al., 2006). A chronosequential approach was applied to study the processes of self-restoration.

Soil complexes with Calcisols and Solonetzes in close vicinity are characteristic of the dry steppe zone. Mechanical reclamation technologies and moderate tillage destroying the Bt/Btn horizons improved water infiltration as well as soil moisture conservation (Riddell et al., 1988; Malhi et al., 1992; Lyubimova and Degtyareva, 2000; Lyubimova, 2002, 2003; Novikova et al., 2009; Kalinichenko et al., 2011; Lyubimova et al., 2012). This results in the fact that sodium is replaced by calcium in Solonetzes and the stability of soil aggregates increases within the plow layer (Lyubimova and Degtyareva, 2000; Lyubimova, 2003; Novikova et al., 2009; Kalinichenko et al., 2011; Lyubimova et al., 2012; Belic et al., 2012). Consequently, cultivation reduced the spatial variation of the hydrological regime within the soil complexes and caused a loss of spatial soil variation, particularly a loss of Solonetz properties (Lavado and Cairns, 1980/1981; Oreshkina and Zablotskii, 1983; Samra and Singh, 1990; Kalinichenko et al., 2011). It is expected that self-restoration of these levelled post-agrogenic soil complexes affects the recovery of solonetzic properties. Preliminary studies of post-agrogenic soils undergoing self-restoration indicated developments towards a natural composition in vegetation as well as in soils (e.g. Kalinina et al., 2009, 2011, 2013; Nicodemus et al., 2012; Cuesta et al., 2012; Vladychenskii et al., 2013). The dynamics of these changes depends on environmental conditions, soil genesis, previous land use history, and the existence of wild plant seeds nearby (Paul et al., 2002; Kalinina et al., 2009, 2011, 2013; Vladychenskii et al., 2013; Laganiere et al., 2010).

An increase of soil organic carbon (SOC) stocks has been documented after land use change from cropland to grassland or forest (e.g. Post and Kwon, 2000; Guo and Gifford, 2002; Lal, 2004; McLauchlan et al., 2006; Morris et al., 2007; Poeplau et al., 2011; Kurganova et al., 2014). Post-agrogenic soils under self-restoration show a high carbon sink potential (Vuichard et al., 2008; Henebry, 2009; Kurganova et al., 2010, 2014; Schierhorn et al., 2013). Recent estimations showed a net carbon sink of approximately 470 Tg C for European Russia, Belarus, and Ukraine from 1990 to 2009 (Schierhorn et al., 2013) or 870 Tg C for the entire Russian territory during the same period (Kurganova et al., 2014). Hence, a carbon sink is expected for post-agrogenic Calcisols and Solonetzes investigated in this study. However, increasing spatial variation of the hydrological regime and increasingly different inputs of plant residues during self-restoration might cause differences between Calcisols and Solonetzes. Nevertheless, the climatic conditions of the dry steppe is believed to result in an overall decreased SOC accumulation rate of the studied post-agrogenic soils compared to Chernozems of the long grass steppe of Russia, which showed a level of 50 g C m^{-2} yr^{-1} for the upper 0.2 m (Kalinina et al., 2011). An appropriate model may support a laboratory approach. Consequently, the SOC model ROMUL (Chertov et al., 2001a,b, 2007) has been implemented to understand long-term trends of SOC changes during self-restoration and the differences in SOC dynamics between Calcisols and Solonetzes. These models consider impacts of litter input, litter quality, soil temperature and moisture on the dynamics of SOC stock.

An enrichment of active and passive carbon pools in accordance with an increase of the total SOC has been reported after conversion of cropland to grassland or forest (e.g. Del Galdo et al., 2003; McLauchlan et al., 2006; Lima et al., 2006; Lopes de Gerenyu et al., 2008; Kalinina et al., 2009, 2011, 2013). Nevertheless, the SOC sequestration pattern applying the active and passive pools is believed to shift after land use change due to the alterations in decomposability of plant residues, above/below-grand inputs, composition of destructors, and soil aggregation (Six et al., 2002; Kalinina et al., 2009; Susyan et al., 2011; Poeplau and Don, 2013). A preferential SOC sequestration within the fraction of free particulate organic matter (POM) as a result of increasing input of plant residues after grassland establishment is likely. Quantitative alterations are also expected for the fraction of occluded POM due to the fact that changes of the occluded POM contribution reflected a regeneration of the soil structure (Jastrow et al., 1998; Six et al., 1998; Kalinina et al., 2011).

To gain an insight into self-restoration without direct human impact processes of post-agrogenic soils of Calcisol–Solonetz complexes in the dry steppe, the objective of this study was first to determine the temporal development of the vegetation and the soil properties of post-agrogenic Calcisols and Solonetzes under self-restoration in the dry steppe 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 active and passive carbon pools.

2. Materials and methods

2.1. Site of investigation

The study was conducted in the dry steppe close to the small town Cherny Yar located on the elevated right bank of the Volga River about 270 km north of the city Astrakhan' (Fig. 1).

The climate of the studied region is temperate semi-arid with a mean annual precipitation of 250–260 mm, a mean annual evaporation of 1026 mm, and a mean annual air temperature of 7.8 °C. The amplitude between mean air temperatures in January and July is 29–34 °C (Lyubimova, 2003; Novikova et al., 2011). Geologically, the studied area consists of silty loam deposits from the late Khvalyn transgression of the Caspian Sea (Nature and history of Astrakhan region, 1996; Veliyev et al., 2006; Novikova et al., 2011). At a depth of more than 10 m these deposits are underlain by saline clays (Novikova et al., 2011). The Cl–Na and Cl–SO_4–Na groundwater is deeper than 7 m (Lyubimova, 2003; Novikova et al., 2011). The recent geomorphology shows a flat surface with shallow depressions produced by suffosion processes (Nature and history of Astrakhan region, 1996). This surface micromorphology exerts a considerable effect on the snow and rainwater redistribution. The area consists of a soil complex of 75% Calcisol and 25% Solonetz, the latter as patches situated within the depressions (Lyubimova, 2003; Novikova et al., 2011).

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

At suitable locations, five sites of different self-restoration ages were sampled in May 2011. The positions of soil profiles were chosen randomly and then recorded using a Garmin Etrex GPS Navigator. Frequent Purckhauer drilling (ca. 20 drillings) indicated uniform soil conditions at the different sites. Uniform grain-sized sediments confirmed the pedological affinity of the sampling sites (data not shown). The chronosequential Calcisol catena included soils of 1, 7, 12, 17 and 42 years of self-restoration and the Solonetz catena included soils of 1, 7, 12, and 42 years of self-restoration. Additionally, each catena comprised one native soil. Although this chronosequential approach is based on soil differences among locations and not on the direct changes over time, a time-shifting development or space-for-time substitution was hypothetically assumed (Walker et al., 2010), resulting in the use of time-shifting terms, although soil differences among locations were made.

We studied self-restoration of post-agrogenic soils under arable land use without irrigation for at least 50–100 years (Lyuri et al., 2010). At present, all sites, including the site with natural soils, are used as extensively grazed grassland. The distance between Calcisol and Solonetz on each site was about 10 m. The site with natural soils (48°05′00.2″N, 45°55′58.4″E for Calcisol and 48°05′05.3″N, 45°55′52.8″E for Solonetz) has never been used as arable land. The abandonment of the soil with 42 years of self-restoration (48°07′05.4″N, 45°45′15.6″E for Calcisol and 48°07′04.8″N, 45°45′15.7″E for Solonetz) occurred in 1969 due to the fusion of two collective farms ("kolkhoz"). Since 1990, the economic