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Research paper

Land-use change under different climatic conditions: Consequences for organic matter and microbial communities in Siberian steppe soils

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ABSTRACT

The Kulunda steppe is part of the greatest conversion areas of the world where 420,000 km^2 grassland have been converted into cropland between 1954 and 1963. However, little is known about the recent and future impacts of land-use change (LUC) on soil organic carbon (OC) dynamics in Siberian steppe soils under various climatic conditions. By investigating grassland *vs.* cropland soils along a climatic gradient from forest to typical to dry steppe types of the Kulunda steppe, our study aimed to (i) quantify the change of OC stocks (0–60 cm) after LUC from grassland to cropland as function of climate, (ii) elucidate the concurrent effects on aggregate stability and different functional soil organic matter (OM) fractions (particulate *vs.* mineral-bound OM), and (iii) assess climate- and LUC-induced changes in the microbial community composition and the contribution of fungi to aggregate stability based on phospholipid fatty acid (PLFA) profiles. Soil OC stocks decreased from the forest steppe (grassland: 218 ± 17 Mg ha^{-1}) over the typical steppe (153 ± 10 Mg ha^{-1}) to the dry steppe (134 ± 11 Mg ha^{-1}). Across all climatic regimes, LUC caused similar OC losses of 31% (95% confidence interval: 17–43%) in 0–25 cm depth and a concurrent decline in aggregate stability, which was not related to the amount of fungal PLFA. Density fractionation revealed that the largest part of soil OM (>90% of total OC) was associated with minerals and <10% of C existed in particulate OM. While LUC induced smaller relative losses of mineral-associated OC than particulate OC, the absolute decline in total OC stocks was largely due to losses of OM bound to minerals. This result together with the high ^{14}C ages of mineral-bound OM in croplands (500–2900 yrs B.P.) suggests that mineral-bound OM comprises, in addition to stable OC, also management-susceptible labile OC. The steppe type had a larger impact on microbial communities than LUC, with a larger relative abundance of gram-positive bacteria and less fungi under dry conditions. Our results imply that future drier climate conditions in the Siberian steppes will (i) result in smaller OC stocks on a biome scale but (ii) not alter the effect of LUC on soil OC, and (iii) change the microbial community composition more than the conversion from grassland to cropland.

1. Introduction

Global soils hold a substantial proportion of the earth‘s carbon with about 1325 Pg organic carbon (OC) being stored in the upper first meter and almost 3000 Pg OC when deeper soil layers are included (Köchy et al., 2015). Past research found soil OC to be very sensitive to land-use changes (LUC) (Guo and Gifford, 2002; Murty et al., 2002; Poeplau et al., 2011), and its role to regulate climate

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change and food security is considered to be crucial (Lal, 2004). This particularly concerns steppe soils as they are rich in organic matter (OM) and commonly under intensive agricultural use. Nowadays, about 14% of agricultural land globally consists of steppe soils, typically Chernozems and Kastanozems (FAO, 2013).

Land-use change from grassland to cropland usually involves a loss of OC due to smaller residue inputs into the soil and larger soil OM decomposition as triggered by soil tillage (Mann, 1986; Poeplau et al., 2011). Previous studies observed a break-down of soil macroaggregates due to soil tillage and a subsequent release of occluded particulate OM which is then mineralized by microorganisms (reviewed by Bronick and Lal, 2005). The formation and stabilization of macroaggregates depend on the abundancy and functioning of soil fungi, since their extensive hyphae network generally supports aggregate formation and stabilization (Guggenberger et al., 1999). Besides the stabilization of soil OM by occlusion within aggregates, soil OM can be chemically stabilized by its association with mineral surfaces. Mean residence times of mineral-associated OM are in the range of >100yr, while particulate OM has a turnover of years (Kleber et al., 2015).

Research on LUC effects in steppe soils predominantly focused on American prairie soils. For this region the OC stock decline after conversion from grassland to cropland was estimated to be 24–32% for conventional soil tillage practices (Beniston et al., 2014; Doran et al., 1998; VandenBygaart et al., 2003). Some studies were conducted in steppe soils of the European part of Russia where the decrease of OC stocks after conversion from grassland to cropland ranged from 27% to more than 40% (Mikhailova et al., 2000; Rodionov et al., 1998). Apart from that, there is no study dealing with the effects of LUC on soil OC in steppe soils of Siberia, despite the region belongs to the greatest agricultural production areas in the world and occupies an area greater than that in the Great Plains (Frühauf, 2011). Moreover, little is known about the effects of LUC on soil OM under different climatic conditions, which is particularly important in the course of climate change. For south-western Siberia, Hijoka et al. (2014) predicted a temperature increase of 2–6 °C until the late 21st century coming along with more frequent drought events, which translates into a higher degree of aridity. As this will change the environmental conditions there is an increasing demand for understanding how LUC impacts are affected by climate change. Studies on the climate-dependent effect of LUC on soil OM have not come to a clear conclusion yet. Burke et al. (1989) and Guo and Gifford (2002) found a positive relationship between relative OC loss and precipitation (until a mean annual precipitation of ca. 600 mm), but did not have an explanation for this finding. Poeplau et al. (2011) identified temperature being positively correlated to the relative soil OC loss due to LUC, but not the mean annual precipitation (MAP). Considering processes of carbon stabilization in soil, we believe that soil OC losses should be larger under dry conditions, as the formation of OM-protecting mineral-organic associations is reduced under dry conditions (Kleber et al., 2015). Thus, larger proportions of readily decomposable particulate OM are expected in arid regions, as evidenced by Amelung et al. (1998), which would lead to larger losses of soil OC upon LUC. To elucidate the effects of LUC on soil OM in Siberian steppe soils under different climatic conditions we investigated the effect of LUC from grassland to cropland in soils of the south-western Siberian Kulunda steppe along a climatic gradient. The region is part of the greatest conversion area of the world, where 420,000 km^2 of grassland were converted into cropland between 1954 and 1963 as part of the so-called “Virgin Lands Campaign” (Russian: “zelina”). The main objectives of our study were to (i) investigate the climate-dependent effect of LUC from grassland to cropland on soil OC stocks, (ii) account for the concurrent effects on aggregate stability and different functional soil OM fractions (particulate *vs.* mineral-bound OM), and (iii) determine changes in the microbial community composition along the climatic gradient and the two land use types and the contribution of fungi to aggregate stability. We approached this by quantifying soil OC stocks under different land use (grassland *vs.* cropland) in a paired plot design along a climatic gradient with sites in the forest, typical and dry steppe types and assessing the concurrent changes in aggregate stability and density-separated soil OM fractions. The apparent stability of particulate and mineral-bound OM was estimated based on ^{14}C measurements. Based on phospholipid fatty acid (PLFA) profiles we elucidated the amount of bacterial and fungal PLFA and separated the microbial community into six microbial groups. We hypothesize that the response of soils to LUC depends on the climatic conditions with larger OC losses in arid regions. Moreover, we expect that the loss of OC relates to a decrease in aggregate stability which itself is associated to a reduction in the amount of fungal PLFA.

2. Material and methods

2.1. Study sites and soil sampling

The Kulunda steppe is situated in the Altai Krai region of the Russian Federation, between 51°N and 54°N and 78°E and 84°E, and belongs to the Eurasian loess belt (Fig. 1). The area is separated into three distinct steppe types: the forest steppe (FS) with a MAP of 350–450 mm, the typical steppe (TS) with a MAP of 300–350 mm and the dry steppe (DS) with a MAP of 250–300 mm. The mean annual temperature (MAT) increases from FS (MAT 1 °C)to DS (MAT 2 °C) by around 1 °C (climate data from “WorldClim” data base; Hijmans et al., 2005). As a result, aridity increases in the order FS < TS < DS and the vegetation cover changes from partially forested areas in FS to mostly grassland areas in DS with the largest biomass production in FS and the smallest one in DS. Dominant plant species in the grasslands of FS were *Bromopsis inermis* and *Stipa capilata*, while *Festuca valesiaca* and *Bromopsis inermis* dominated in grasslands of TS. Grasslands of DS were characterized by *Festuca valesiaca* and *Artemisia frigida*. The agricultural production in the entire area focuses mainly on wheat and sunflower, but also rape seed and peas are common. In FS and TS, soils were mostly classified as Chernozems, reflecting the wetter climate as compared to DS, where Kastanozems are more frequent.

For assessing the impact of LUC on soil, we used a paired plot design (Poeplau and Don, 2013). Nine sites were selected, three sites in FS, two sites in TS and four sites in DS, with a total of 21 plots (Table S1). Each site consisted of at least two plots, one reference plot, representing the soil conditions before LUC and one or more conversion plots, representing the soil conditions at a certain time after LUC. Seven sites consisted of one reference and one conversion plot, while two sites (in DS) consisted of one reference and two conversion plots (triple plot), giving a total of eleven pairs (reference and conversion plot). The grasslands chosen as reference plots were either in pristine state or in use as extensive pastures. As further criteria, soils had to be unaffected by erosion and LUC should have occurred at least 20 years ago, as several studies showed most soils establish a new equilibrium approximately after that time (e.g. Murty et al., 2002; Poeplau et al., 2011). For a LUC chronosequence in FS, we also included one plot with <20 yrs since LUC. Per plot one key profile was established for soil description and sampled according to generic horizons down to a depth of ca. 160 cm. Subhorizons (e.g. A1, A2) were treated separately in the laboratory, but the measurements were bulked according to the proportion of a subhorizon in the main horizon to obtain one value per horizon (A, AC, C). Additionally, per plot three randomly chosen soil profiles were excavated around the key profile and sampled in 0–10, 10–25 and