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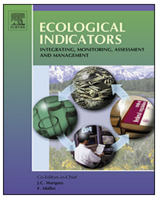

Original Articles

Changes of soil properties regulate the soil organic carbon loss with grassland degradation on the Qinghai-Tibet Plateau

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ABSTRACT

Grassland in the Qinghai-Tibet Plateau (QTP) provides tremendous carbon (C) sinks and is the important ground for grazing. Grassland degradation, the loss of plant coverage and the emergence of sand activities, results in substantial reduction in soil organic carbon (SOC). To demonstrate the pattern of SOC loss and to elucidate underlying mechanisms, vegetation, soil microclimate, soil properties and respiration of grasslands with different degradation severity over the QTP were investigated. The survey and laboratory data were analyzed by three structural equation modeling (SEM) analyses, which based on three conceptual understandings. The black box model (M1) directly related the abiotic and biotic factors to SOC without consideration of any mechanisms. The biological understanding model (M2) developed the structure of SEM mainly considering ecological processes that regulate the soil SOC. The overall model (M3) developed the SEM structure with the inclusion of both physical and biological processes. Soil moisture (θ), the above and the below-ground plant productivity, and SOC significantly decreased while soil temperature (T_{soil}) maintained with the development of land degradation. All the three models successfully fitted the data with R^2 about 0.50. Significant pathways from latent variables to SOC were only observed from soil microclimate and soil properties in the M1. In the M2, three mechanisms can explain the SOC change. The decrease in θ and the consequent adverse effect on soil respiration suggest suppressed C output through microbial decomposition, thus lead to the less SOC loss. The decline in aboveground net primary productivity (ANPP) resulted from a decrease in coverage or due to the change in relative abundance of sedge, forbs, and grass directly or indirectly reduced the C input, and finally lead to the 40–50% loss in SOC. In the M3, only the change in soil properties can explain the SOC reduction. Our results suggest that changes in soil abiotic factors like soil bulk density and pH are the primary factors control the SOC change with land degradation.

1. Introduction

Grassland takes up about 40% of the global surface (Suttie et al., 2005), and 23.5% of it has been degraded or is currently undergoing degradation (UNEP, 2007; FAO, 2010). Human-induced disturbances like overgrazing and livestock trampling are considered as the major causes of grassland degradation (Steffens et al., 2008; Martinsen et al., 2011; Dong et al., 2012; Dlamini et al., 2014) as they both can cause plant dying and plant cover reduction (Klein et al., 2007; Harris, 2010; Chen et al., 2015; Kuzyakov et al., 2016). The grassland degradation can lead to the soil organic carbon (SOC) depletion with the magnitude ranging 33%–90% (Xie et al., 2007; Zuo et al., 2009; Harris, 2010; Martinsen et al., 2011; Dong et al., 2012; Wen et al., 2013; Dlamini et al., 2014). Changes in soil microclimate, soil properties, and plant production, and interaction between soil and plant have been proposed to explain the SOC depletion with land degradation (Baldock and Skjemstad, 2000; Mills and Fey, 2004; Podwojewski et al., 2011; Hiltbrunner et al., 2012; McHunu and Chaplot, 2012).

SOC loss could be the result of the plant cover reduction because the lower plant cover might result in a decrease in either aboveground or below-ground production and consequently, reduces the C input into the soil (Dlamini et al., 2014; Kuzyakov et al., 2016). The shifting dominance of the plant community composition from more to less productive species (e.g., perennial graminoids to annual forbs,

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graminoids to shrubs, Huenneke et al., 2002; Wang et al., 2014) not only reduces the C quantity into soil but also alters the C quality, and consequently affects C output via microbial decomposition of SOC (soil respiration, Rs). Degradation-induced changes in soil properties could accelerate the SOC depletion, which restrains the C input but stimulates the Rs and erosion. For example, an increase in the bulk density (BD) and a decrease in the water holding capacity will slow down the retention and mobility of available nutrients (Dong et al., 2012) and eventually lead to a limitation on plant productivity. The change in the BD and soil porosity tend to reduce the infiltration but intensify the runoff, thus enlarge the potential of SOC loss by water erosion (Hiltbrunner et al., 2012). The disaggregation of soil aggregates makes the SOC become unprotected and be readily available to decomposition and erosion, therefore result in more C output (McHunu and Chaplot, 2012; Dlamini et al., 2014). Another potential mechanism of SOC stock depletion associated with land degradation lies in the alteration of the soil temperature (T_{soil}) and moisture due to degradation (Hoshino, 2010). An increase in T_{soil} will stimulate the rate of SOC decomposition, while the associated decline in soil moisture (θ, v/v%) might reduce it as θ might be the constraint on SOC decomposition in dryland biomes (Risch et al., 2007; Liu et al., 2016).

Most studies focus on the direct effect of one or several typical factors, few studies have quantitatively assessed the potential interactions among factors that may directly and/or indirectly contribute to the SOC depletion, which is critical for understanding the mechanisms of SOC depletion with land degradation. Structural equation modeling (SEM) is a powerful approach designed for the study of multivariate hypotheses and understanding interacting systems (Grace and Kelley, 2006; Eisenhauer et al., 2015; Chen et al., 2016a,b). The SEM analysis has been widely used in ecological studies to develop causal understandings from observational data, which can provide quite different perspectives by partitioning direct and indirect effects and thereby revealing a variety of mechanisms behind the overall patterns (Luo et al., 2017).

Alpine grassland on the Qinghai-Tibetan Plateau (QTP), 60% of the total plateau area, accounts for 54.5% of the SOC stock in grasslands in China (Ni, 2002). However, approximately 90% of the alpine grassland on the QTP has been degraded due to climate change, overgrazing and rodent damage since the 1990s (Zhou et al., 2005; Harris 2010; Dong and Sherman, 2015). The degradation of alpine grassland has led to the 1.01 Pg C (1Pg = 10^{12}g) loss since the 1980s, which is more than twice of potential C accumulation due to climate change and elevated CO_2 concentration (Xie et al., 2007). But, the mechanisms that control the SOC loss with land degradation remain unclear. A field survey across the grassland ecosystem on the QTP was carried out. Three hypothesis-oriented path modelings were employed to answer: 1) how grassland productivity of the different vegetation types, soil properties, and soil microclimate respond to grassland degradation? 2) what are the directly and indirectly control over SOC dynamics? 3) which biological processes or the physical processes determine the SOC change with land degradation?

2. Materials and methods

2.1. Environmental settings of the field surveys

Three fifteen-days campaigns were carried out from July to September in 2014 on the QTP (Fig. 1). The surveys are along a transect of 1 200 km in length and 900 km in width in central and northeast QTP. The surveys are situated 90.36°–102.23°E and 9.41°–38.42°N with a northeastern section from Lanzhou to Qilian, and an eastern section from Xining to Golmud and a southern section from Golmud to Lhasa.

Our survey mainly focused on the grassland ecosystem with an elevation ranging from about 3300–4700 m. The moist Indian monsoon and Tibetan Plateau summer monsoon come from the south resulting in a precipitation gradient from southeast to northwest (Ge et al., 2017). The annual mean temperature varies from −5.75 to 2.57 °C, and mean annual precipitation from 218 to 600 mm (Baumann et al. 2009). More than 80% the annual rainfall occurs during the summer (June to August).

The northeast of the QTP is the discontinuous and sporadic permafrost region, and also there is the seasonally frozen soil or non-frozen soil regions, while in the central and eastern of the QTP, it is mainly the continuous permafrost (Lu et al., 2017). Detailed information of permafrost classification and distribution can be seen in Cheng and Wu (2007). Permafrost in the QTP has a higher temperature than in the circumpolar region, and diurnal temperature fluctuation in the QTP may reach 25–40 °C.

Alpine meadow and alpine steppe are the most widely distributed grasslands on the QTP. The major species are *Kobresia humilis* and *Kobresia pygmaea* in the intact alpine meadow, and grass species in the alpine steppe.

2.2. Identification of land degradation

Before each campaign, the sampling sites were pre-selected based on remote sensing images. In practice, the pre-chosen sites would be adjusted when misinterpretation of remote-sensing images happened. There were 22 sampling sites in total. The survey routes mainly follow the provincial or local roads, and the sampling sites are at least 1 km far away from the road. In each site, a sequence of 3–5 degradation levels including intact, slightly degraded (SLD), moderately degraded (MD), severely degraded (SD) and very severely degraded (VSD) alpine grassland were identified based on plant coverage, aeolian activities and plant community composition. The criteria for grassland condition classification refer to a previous study in the source region of Yangtze and Yellow river (Xue et al. 2009).

The sedge species gradually decreased and the forbs species, like species from *Compositae*, increased with grassland degradation. From the severely degraded grassland, sedge species are hardly seen, and forbs species from *Compositae* and *Polygonaceae* dominate the community composition. The presence of some poisonous species like *Stellera chamaejasme Linn.* and *Ligularia rumicifolia (Drumm.)* could indicate land degradation (Li et al. 2014). Following plant turf degradation, the bare ground will gradually be visible and mainly covered by sand. Thus, the coverage of bare ground might represent the aeolian activities. The definition of different levels of land degradation was in Table A.1.

In each degraded level, three quadrats were randomly selected (30 × 30 cm) for plant coverage, community composition, soil microclimate, and soil respiration (*Rs*) measurement, and for aboveground biomass and soil samples collection.

2.3. Soil temperature, moisture and bulk density

T_{soil} was measured at the depth of 0, 5, 15, 30 and 60 cm with thermistor sensors (State Key Laboratory of Frozen Soil Engineering, Lanzhou, China). Soil samples for θ and bulk density measurement were collected at depths of 0–10, 10–20, 20–30 and 30–50 cm. In each quadrat, three replicates for each layer were collected by a soil sampler (volume, 100 cm^3), and then was put in aluminum boxes. The weight of boxes + wet soil was measured *in situ*. The weight of the box was measured before field sampling in the laboratory. After the *in situ* measurement of weight, the samples were then transported to the laboratory in Lanzhou. The samples were dried at 105 °C for 48 h to get the θ and bulk density (BD). The gravimetric θ was when converted to volumetric θ by multiplying the BD. The θ and BD were calculated as:

$$\theta = \frac{(Weight_{box+wetsoil} - Weight_{box+drysoil})/\rho}{V_{soilsampler}}$$

$$BD = \frac{Weight_{box+drysoil} - Weight_{box}}{V_{soilsampler}}$$