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Effects of revegetation and precipitation gradient on soil carbon and nitrogen variations in deep profiles on the Loess Plateau of China

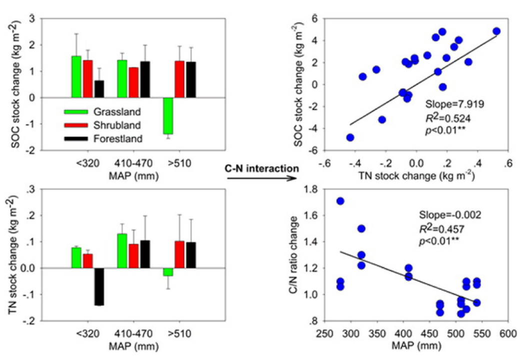
Dengfeng Tuo [a], Guangyao Gao [a,b,*], Ruiying Chang [c], Zongshan Li [a], Ying Ma [d], Shuai Wang [e], Cong Wang [a], Bojie Fu [a,b]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] Joint Center for Global Change Studies, Beijing 100875, China
[c] Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan 610041, China
[d] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 100101 Beijing, China
[e] State Key Laboratory of Earth Surface Processes and Resources Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

HIGHLIGHTS

- Variations of SOC and TN stocks among depths were strong in wetter areas.
- Grassland restoration resulted in great SOC and TN accumulations in drier areas but losses in wetter areas.
- SOC and TN changes in surface layer following revegetation significantly increased along precipitation gradient.
- C-N interaction in the shallow layer was stronger than that in the deep layer.
- N limitation occurred in drier areas during vegetation restoration.

GRAPHICAL ABSTRACT



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ABSTRACT

Precipitation is one of the most important factors affecting the variations in soil carbon (C) and nitrogen (N) following revegetation. However, the effects of revegetation and precipitation gradients on soil organic carbon (SOC), total nitrogen (TN) and C-N interactions in deep profiles over large scales are poorly understood. This study measured the SOC and TN stocks to depth of 300 cm in three revegetation types (grassland, shrubland and forestland) and paired cropland stands at seven sites along a precipitation gradient with mean annual precipitation (MAP) from 280 to 540 mm yr^{-1} in the Loess Plateau of China. The results showed that the SOC and TN stocks in the 0–300 cm profile increased along the precipitation gradient. Revegetation did not always result in accumulation of SOC and TN stocks, which depended on the precipitation condition and varied among different vegetation types. Grassland restoration resulted in more SOC and TN accumulation than shrubland and forestland in areas with MAP < 510 mm, whereas there were losses in SOC and TN following grass plantation in sites with MAP > 510 mm. The changes in SOC and TN stocks following revegetation (ΔSOC and ΔTN) were significantly correlated with MAP in only the 0–20 cm layer, whereas the changes in the C/N ratio of each depth were significantly and negatively correlated with MAP. The correlations between ΔSOC and ΔTN were stronger in the 0–60 cm layer than that in the 60–300 cm layer, and an accumulation of 1 g TN was associated with approximately 7.9 g increase of SOC in the 0–300 cm profile following revegetation. This study indicated that the changes in soil C and N stocks following revegetation had different patterns along precipitation

* Corresponding author at: Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China.
E-mail address: gygao@rcees.ac.cn (G. Gao).

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gradient and among depths, and grassland restoration and N fertilizer input benefitted soil C and N sequestration in drier areas.

1. Introduction

Global climate change, especially global warming in recent decades, is profoundly influenced by the sequestration dynamics of soil carbon (C) and nitrogen (N) (Laganière et al., 2010; Durán et al., 2017; Qiu et al., 2017). Revegetation in previously arable land is widely considered to be a major measure of soil organic carbon (SOC) and total nitrogen (TN) sequestrations, which plays an important role in reducing atmospheric CO_2 (Banning et al., 2008; Carvalhais et al., 2014). Thus, it is meaningful and necessary to investigate the processes and mechanisms of SOC and TN changes and explore their causes during revegetation, especially because revegetation has been proposed as an effective approach for climate change mitigation (IPCC, 2013; Liu et al., 2017; Pires et al., 2017).

Precipitation plays decisive roles in determining the net primary productivity and ecosystem structure in arid ecosystems (Iglesias et al., 2012), which in turn have the potential to affect soil C and N accumulation through biotic processes associated with both vegetation productivity and organic matter decomposition (Carvalhais et al., 2014; Campo and Merino, 2016). The influence of revegetation on SOC and TN is highly variable across the precipitation gradient. At the global scale, soil C has declined by 20–43% due to the conversion of forest to agricultural land (Murty et al., 2002). In contrast, Berthrong et al. (2012) noted that SOC stock increased at drier sites but decreased at wetter sites after the conversion of unforested lands to forests. In addition, the effect of precipitation on N cycling has also been found to be highly variable. Aranibar et al. (2004) reported that soil fixed more N_2 in arid than humid areas, and N sequestration was stronger during dry years than during wet years. It is essential to investigate the spatial variability of the changes in the SOC and TN stocks following revegetation across a precipitation gradient at the large spatial scale.

The changes of SOC and TN vary along a soil profile as a result of the combined effects of underground (soil properties) and aboveground (climate and vegetation) factors (Stone et al., 2015; Ye et al., 2015; Lozano-García et al., 2017). The "nutrient pumping" effect following revegetation resulted in decreases in soil nutrient concentrations in deep layers and increases in shallow layers (Chen et al., 2016). However, a considerable amount of SOC and TN stocks are still stored in deep soil. Deep soil is generally the layer below 100 cm because the infiltration of rainwater is mostly limited to the 0–100 cm soil layer in many areas. Jobbágy and Jackson (2000) reported that the global SOC contents of forest, shrubland and grassland at depths of 200–300 cm accounted for 56%, 77% and 43% of the contents at depths of 0–100 cm, respectively. Zhang et al. (2013) reported that there was a strong linear function between SOC (or TN) storage in the surface (0–20 cm) and deep layers (100–300 cm). These studies suggested that SOC and TN in deep layers should be included when estimating the total soil C and N pools. However, because the distribution and magnitude of SOC and TN in deep layers are the result of multiple physical, chemical, and biological processes (Stone et al., 2015; Wang et al., 2015), most of the previous studies usually focused on the comparison of SOC and TN stocks between shallow and deep layers. The dynamics about the changes of SOC and TN stocks in deep layers following revegetation were limited understood.

Soil C and N cycles interact with each other in a terrestrial ecosystem (Ye et al., 2015; Field et al., 2017). C-N interactions should be considered when determining whether C accumulation in terrestrial ecosystems can be sustainable over a long period (Luo et al., 2004, 2006; Thornton et al., 2009; Tian et al., 2017). In general, N input is positively related to C accumulation. However, during the vegetation restoration process, accumulation of soil C may not be accompanied by increase in N (Giardina et al., 2003). For example, Deng et al. (2016) and Deng and Shangguan (2017) reported that grassland restoration had more effects on soil C accumulation than soil N, and the accretion of N could not meet the demands of C increases during long-term restoration. In addition, precipitation variability has a strong effect on C and N cycling and further affects C-N interactions. Aranibar et al. (2004) noted that N fixation associated with trees and shrubs was almost absent in arid areas, and insufficient soil N supply was expected to limit ecosystem-level uptake and C storage. The limiting effects of soil N on soil C gains in drier areas were greater than those in wetter areas (Chang et al., 2014). Therefore, analysing the C-N coupled relationship following revegetation across a precipitation gradient is necessary, and the results could have important implications for ecosystem management, especially in arid and semi-arid regions such as the Loess Plateau of China (Deng and Shangguan, 2017).

A large-scale eco-restoration project called "Grain for Green" was launched in 1999 to control severe soil erosion and restore the degraded ecosystems in the Loess Plateau. This project involved reconverting croplands into grasslands, shrublands and forestlands. From 2000 to 2010, the area of revegetation and reforestation was approximately 4.9×10^6 ha (Chang et al., 2014). Numerous studies have investigated the storage and distribution of SOC and TN after revegetation in the Loess Plateau (Zhang et al., 2013; Wang et al., 2015; Deng and Shangguan, 2017; Jia et al., 2017a). Chang et al. (2014) studied the changes in SOC and TN stocks following afforestation and the C-N relationship along a precipitation gradient, but the results were limited to the depths of 0–20 cm. To the best of our knowledge, few studies have focused on the variations of SOC and TN stocks and C-N interactions in deep soil layers following ecological restoration along a precipitation gradient, and the interaction effects of revegetation and precipitation gradients on changes in SOC and TN at the regional scale need further study.

To fill the existing research gaps, this study analysed the variations in SOC, TN and the C/N ratio at depths to 300 cm among cropland, grassland, shrubland and forestland sites along a precipitation gradient (ranging from 280 to 540 mm) in the Loess Plateau of China. The objectives of this study were to (1) compare the variations of SOC and TN stocks throughout the profile under different land use types and precipitation conditions, (2) investigate the changes in SOC and TN stocks following revegetation at various soil depths along the precipitation gradient, and (3) detect the interaction between SOC and TN changes and quantify the relative influence of environmental factors on SOC, TN and the C/N ratio in different soil depths at the transect scale.

2. Materials and methods

2.1. Study area and field investigation

This study was conducted in the Loess Plateau of China (33.72°–41.27°N, 100.90°–114.55°E) (Fig. 1). The Loess Plateau has a semi-arid continental climate with a mean annual precipitation (MAP) ranging from 150 mm in the northwest to 800 mm in the southeast. The mean annual temperature (MAT) is 5 °C in the northwest, and it increases to 13 °C in the southeast. The elevation on the Loess Plateau ranges from 200 m to 3000 m above mean sea level. Most of the native vegetation has been cleared due to the long history of crop production, resulting in severe soil erosion and infertile soil. Since the 1950s, the Chinese