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Restoration of shrub communities elevates organic carbon in arid soils of northwestern China

Huang Gang [a,*], Zhao Xue-yong [b], Li Yu-qiang [b], Cui Jian-yuan [b]

[a] Fukang Desert Ecology Station, State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Beijing South Road 818, Urumq 830011, China

[b] Naiman Desertification Research Station, Cold and Arid Regions and Environmental & Engineering Research Institute, Chinese Academy of Sciences, LanZhou 730000, China

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ABSTRACT

Artificial restoration by shrub plantation in semi-arid sandy land can increase carbon sequestration. However, little information is available on the carbon flux input to soil resulted from fine roots turnover and leaf fallen during restoration. The present study relying on the ingrowth core and sequential core methods investigated the fine-root dynamics and fine-root production of three shrub stands (dominated by *Artemisia halodendron*, *Caragana microphylla* and *Salix gordejevii* respectively) which have different life-forms and root architectures. The soil carbon and nitrogen stock was also estimated in the restoration, and the relative contribution of carbon input related to fine root mortality and leaf fallen was assessed. The mean standing live and dead fine-root biomass in *A. halodendron* stand at the primary restoration were significantly less than in *C. microphylla* stand at moderate restoration and *S. gordejevii* stand in lowland. Consistent with leaf production, fine root production showed a positive correlation with soil water content and followed the order of *A. halodendron* < *C. microphylla* < *S. gordejevii.* In contrast, the fine-root turnover rate was quicker in primary restoration phase (2.12 year^{-1}) than in moderate restoration phase (1.55 year^{-1}) and lowland (1.28 year^{-1}). The annual carbon and nitrogen inputs via fine root mortality and leaf fallen increased from 74.78 g C m^{-2} year^{-1} and 1.25 g N m^{-2} year^{-1} in *A. halodendron* stand to 189.66 g C m^{-2} year^{-1} and 1.67 g N m^{-2} year^{-1} in *S. gordejevii* stand. Although the share of the fine roots of *A. halodendron* seized a relatively smaller proportion in the net primary production compared with those in *C. microphylla* and *S. gordejevii*, the relative contribution of carbon input related to fine roots mortality in primary restoration phase was higher than in the other two shrub stands. The present study proved that the carbon input to soil by fine-root mortality considerably contributed to the restoration of soil carbon and nitrogen stock in semi-arid degraded lands.

1. Introduction

Indiscriminate human activities in the past half century have resulted in the presently serious and evident problem of land degradation (IPCC, 2007). The modification of land use is a fundamental research in the global change studies. Various ecological effects related to land use have received considerable attention (Canadell and Raupach, 2008). Due to deforestation and cultivation of native tropical rainforests, restoration of degraded lands in these regions is always considered as an important method to retard the effects of climate change, particularly, those of warming gases (Canadell and Raupach, 2008; Miles and Kapos, 2008). However, several recent investigations in tropical and temperate regions have found that restoration measures by planting vegetation or farming in degraded land cannot contribute more carbon to soil compared with native forests (Cahill et al., 2009; Hertel et al., 2009; Liao et al., 2010). This conclusion is in line with a meta-analysis including 87 studies (Liao et al., 2010). Prior works have indicated the insufficiency of taking restoration measures to recover soil properties in forests (Canadell and Raupach, 2008). Mitigation of greenhouse gases requires reasonable and efficient artificial restoration measures to increase vegetation carbon fixation in low productivity regions (Lal, 2001, 2002; Boellstorff, 2009). Arid and semi-arid lands cover approximately 45% of the global terrestrial area and contain 16% of the global soil carbon pool (Nosetto et al., 2006). More importantly, over two-thirds of lands in arid and semi-arid regions have been destroyed by desertification, leading to ca. 20–30 Pg C loss (Ojima et al., 1995; Lal et al., 1999). If efficient restoration measures will be successfully applied on the degraded lands, these lands could sequester 0.9–1.9 Pg C y^{-1} during a 25–50-year restoration phase

* Corresponding author. Tel./fax: +86 0991 7885413.
E-mail addresses: hg@ms.xjb.ac.cn (H. Gang), zhaoxy@cern.ac.cn (Z. Xue-yong), gsyqli@yahoo.com.cn (L. Yu-qiang), jytsui@gmail.com (C. Jian-yuan).

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(Lal, 2001). This value accounts for 30% of the present atmospheric CO_2 level (IPCC, 2001). In sandy land, planting shrubs has been proved as an efficient restoration measure (Zhao et al., 2007b). The formation of shrub plantation in degraded sandy lands promotes species establishment, soil texture, and nutrient recovery as well as sand dune stabilization (Su and Zhao, 2003; Zhao et al., 2007b; Shrestha and Stahl, 2008; Cahill et al., 2009).

Despite efforts to investigate the ecological effects of shrub plantation, the restoration effects on soil carbon stock and carbon sequestration have been scarcely reported (Jackson et al., 2002; Cahill et al., 2009; Piao et al., 2009). Soil organic carbon dynamics (including soil organic residues) from shrub plantations have been considered primarily in terms of aboveground parts and root standing crop. The amount of soil organic carbon from fine-root mortality and decay during growing season, as reported in some ecosystems, is equal to or even higher than that from leaves (Vogt et al., 1996; Gill and Jackson, 2000; Nadelhoffer, 2000; Block et al., 2006). According to 45 case studies across a range of climates and soil types, Amos and Walters (2006) suggested that carbon inputs to soil derived from fine-roots range from 1.5 to 4.4 Mg C ha^{-1} $year^{-1}$. Fine-roots also influence the responses of the soil carbon pool to climate changes. Iversen et al. (2008) reported that root mortality results in 681 g m^{-2} of extra carbon input to the soil under elevated CO_2 over a nine-year experiment. In addition, root exudates are another ignorable component in the influx of C to soil by roots (Jones et al., 2009). Although it is difficult to determine the amount of root exudates in natural environment, some researchers showed the amount of C entering into grassland soils from root exudates is similar to that derived from root turnover (Hodge et al., 1997; Paterson and Sim, 1999; Paterson, 2003). A pot-comparing experiment also implied that the increase in soil carbon might be caused more by the activity of live fine roots than by fine root mortality (Guo et al., 2005). Recently, Hertel et al. (2009) reported that quick and continuous fine-root mortality is responsible for potential contribution of fine-root-related soil carbon flux to soil at a value ranging from 127.2 to 232.8 g C m^{-2} $year^{-1}$. Compared with species in tropical rainforests, shrubs in arid and semi-arid regions generally invest more carbon for the development of their root system (Jackson et al., 1996; Nadelhoffer, 2000). Therefore, there might be a considerable amount of C-transfers from vegetation to the soil through root turnover in shrub plantation that could play an important role in increasing soil organic carbon during restoration.

To control desertification development in northern China, a series of work has been implemented in the Horqin sandy land in eastern Inner Mongolia, China. Fencing and planting shrubs have been regarded as the successful measures for mobile sand dune restoration since 1970s. By persistently monitoring the succession of soil and vegetation during the restoration process, scientists reported that both soil available nutrients and plant community structure changed obviously. Specifically, *Artemisia halodendron* Turcz. ex Bess, as a pioneer species, has colonized and established its populations in highly unstable and nutrient-poor mobile sand dunes, while *Caragana microphylla* Lam. and *Salix gordejevii* Chang et Skv. are primarily distributed at moderate restoration phase and lowland between sand dunes which are characterized with proper soil nutrients and stable environmental condition. The orderly distribution and succession of vegetation during mobile sand dune restoration process have been ascribed to their different abilities to adapt to nutrient-poor habitats and to compete with grasses in lowland between sand dunes (Li et al., 2007; Zhao et al., 2007a). Broad studies have investigated the vegetation eco-physilological changes, including biomass distribution, plant life-form, morphological traits. However, as we know, little information is available for fine root dynamics and carbon flux to soil resulted from fine root mortality. In the present study, we took a continuous restoration gradient of habitats as a case to address the following questions:(1) whether *A. halodendron* stand has a higher fine-root production and quicker root-turnover rate than *C. microphylla* and *S. gordejevii* stands, if this is true, carbon input related to fine root mortality decreases with the improvement of habitat; (2) whether the relative contribution of carbon input to soil via fine root mortality is higher in *A. halodendron* stand than in *C. microphylla* and *S. gordejevii* stands and (3) whether there are some differences of carbon sinks derived from the fine-root mortality for the three shrub stands.

2. Materials and methods

2.1. Site description

The present study was conducted at the Naiman Station of Desertification and Farmland Research, the Chinese Academy of Sciences (42°58′N, 120°43′E; approximately 360 m a.s.l.) at the eastern part of Inner Mongolia, China. Naiman is located at the southwestern part of the Horqin Sandy Land, 400 × 400 km^2 in size, and represents the most desertification-threatened area in north China. The landscape in this area is characterized by sand dunes alternating with gently undulating lowland areas (Li et al., 2005). The soils are sandy, loose in texture, and particularly susceptible to wind erosion (Li et al., 2005). This area belongs to the continental semi-arid monsoon climate in the temperate zone.

The present study site was fenced off in the autumn of 1988 to exclude cattle and sheep grazing (Hansson et al., 1995). At present, the experimental site includes mobile, semi-fixed and semi-shifting sand dunes, as well as lowland between sandy dunes, which represent the general condition of the soil, topography, and vegetation in this region. Initially, *A. halodendron* and *C. microphylla* were planted in mobile sand dunes. Then, with the stabilization of mobile sand dunes and the recovery of soil properties and vegetation, *A. halodendron* gradually retreated from the vegetation community, and the soil became characterized by semi-fixed and fixed sand dunes (Zhang et al., 2005; Zhao et al., 2007a). *S. gordejevii* occurs in lowlands between sand dunes. The soil properties and vegetation cover in *S. gordejevii* stand are best in the three shrub types (Liu et al., 2007). To reflect the variation of fine root production and turnover among shrub types, in the present study, *A. halodendron* plantation in mobile sand dunes, *C. microphylla* plantation in semi-fixed sand dunes, and *S. gordejevii* in lowlands between sand dunes in the fenced experimental site were chosen to represent different restoration degrees, according to soil properties and vegetation composition (Zhu, 1981; Li et al., 2009a,b). The habitat for each selected shrub presented the most typical characteristics of fine root growth in their normal condition. The standing structural and edaphic characteristics of shrub stands are shown in Table 1. Three plots for each shrub stand (nine plots in total) were used to investigate root growth and standing crop conditions in different shrub stands by soil and ingrowth cores. The two independent methods were conducted using the same sampling scheme. All plots were located according to a random sampling rule.

2.2. Sequential coring method

Sequential coring method was used to investigate the seasonality of live fine-root biomass and fine-root turnover rate. Three soil core samples were taken from each of the three plots in each shrub stand on April 20, June 23, August 20, and September 22, 2007. The soil core samples were divided into two soil depths of 0–20 and 20–40 cm. The roots distributed at 0–40 cm soil depth represented c. 70% of the entire soil profile (Zhao, 1994; Huang et al., 2008). To prevent disturbance from sampling and maintain the homogeneity of samples, all investigated shrubs had similar canopy shapes and