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Effects of sandy desertified land rehabilitation on soil carbon sequestration and aggregation in an arid region in China

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ABSTRACT

The rehabilitation of sandy desertified land in semi-arid and arid regions has a great potential to increase carbon sequestration and improve soil quality. Our objective was to investigate the changes in the soil carbon pool and soil properties of surface soil (0–15 cm) under different types of rehabilitation management. Our study was done in the short-term (7 years) and long-term (32 years) desertification control sites in a marginal oasis of northwest China. The different management treatments were: (1) untreated shifting sand land as control; (2) sand-fixing shrubs with straw checkerboards; (3) poplar (*Populus gansuensis*) shelter forest; and (4) irrigated cropland after leveling sand dune. The results showed that the rehabilitation of severe sandy desertified land resulted in significant increases in soil organic C (SOC), inorganic C, and total N concentrations, as well as enhanced soil aggregation. Over a 7-year period of revegetation and cultivation, SOC concentration in the recovered shrub land, forest land and irrigated cropland increased by 4.1, 14.6 and 11.9 times compared to the control site (shifting sand land), and increased by 11.2, 17.0 and 23.0 times over the 32-year recovery period. Total N, labile C ($KMnO_4$–oxidation C), C management index (CMI) and inorganic C ($CaCO_3$–C) showed a similar increasing trend as SOC. The increased soil C and N was positively related to the accumulation of fine particle fractions. The accumulation of silt and clay, soil C and $CaCO_3$ enhanced the formation of aggregates, which was beneficial to mitigate wind erosion. The percentage of >0.25 mm dry aggregates increased from 18.0% in the control site to 20.0–87.2% in the recovery sites, and the mean weight diameter (MWD) of water-stable aggregates significantly increased, with a range of 0.09–0.30 mm at the recovery sites. Long-term irrigation and fertilization led to a greater soil C and N accumulation in cropland than in shrub and forest lands. The amount of soil C sequestration reached up to 1.8–9.4 and 7.5–17.3 Mg ha^{-1} at the 0–15 cm layer over a 7- and 32-year rehabilitation period compared to the control site, suggesting that desertification control has a great potential for sequestering soil C and improving soil quality in northwest China.

1. Introduction

Desertification is defined as land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors including climatic variations and human activities (UNEP, 1990). Land desertification leads to decline in soil structure and reduction in aggregation, and in turn, leads to reduction in the total soil carbon pool and emission of CO_2 from soil and vegetation to the atmosphere, and therefore, impacted the global C cycle (Lal, 2001; Jabro et al., 2008; Yu et al., 2007). It is estimated that desertification affects about 1.137 Bha of soils and an additional 2.576 Bha of rangeland vegetation in drylands around world and the total historic loss of C due to desertification may be 18–28 Pg (Lal, 2001), indicating that land desertification characterized by soil degradation and diminution or destruction of biological potential of ecosystems have played an important role in atmospheric enrichment of CO_2. Restoring these systems through the adoption of appropriate land use practices such as revegetation would increase the pool of C in soil and biomass and yield significant ecosystem carbon gains (Nosetto et al., 2006).

Sandy desertification under the wind and sand activities is one of the main forms of land desertification (Wang et al., 2004). China is one of the most severe sandy desertification countries. The

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results of monitoring, based on remote sensing, showed that the total area of sandy desertified land in north China was 38.57 Mha in 2000 (Wang et al., 2004). Feng et al. (2001) estimated that desert lands in north China caused a net emission of 2.17 Pg of C over the past 40-year period during the 1950s–1990s. In the semi-arid Horqin sandy land of northeast China, Zhou et al. (2008) estimated the total loss of soil organic carbon resulting from desertification was 107.53 Mt on land area of 26,393 ha during the last century.

Desertification control has been considered as a principal strategy to maintain ecological security in north China. In the past several decades, some effective measures of desertification control have been widely applied in desertified zone from northeast to northwest China. Successful measures included the establishment of protective forest belts and sand-fixing shrub forest, the retirement of degraded marginal cropland into forest or grassland, the prohibition of livestock grazing to recover vegetation in desertified grassland (Research Group of Study on Combating Desertification/Land Degradation in China, 1998). Desertification control in desertified lands of north China were also reported to enhance soil C sequestration (Feng et al., 2001; Lal, 2002; Wang et al., 2008) because desertification control could effectively decrease wind erosion and improve soil development, and in turn, enhance soil C content through increase in net primary productivity and biomass returned to the soil (Su and Zhao, 2003; Duan et al., 2004; Li et al., 2007; Su et al., 2007a). The increased soil C content can enhance the formation of soil aggregates (Bronick and Lal, 2005), and therefore to stabilize shifting sand.

Accurate estimate for soil carbon sequestration potential through rehabilitation of desertified lands need to be supported by a series of researches in various regions in north China. Especially, researches from long-term observation sites in typical areas of desertification control are very important for evaluating soil carbon sequestration effect of desertified land rehabilitation. The objective of this study was to evaluate the short- and long-term effects of the establishment of vegetation and desertified land rehabilitation on soil carbon sequestration and aggregation in the extremely arid region in northwest China.

2. Methods

2.1. Site description

The study site, covering Pingchuan marginal oasis, Linze county in the middle of Hexi Corridor region of Gansu province, is located between 39°09′–39°19′N and 100°02′–100°21′E at the southern edge of Badan Jaran Desert, with an altitude ranging from 1368 to 1380 m (Fig. 1). The marginal oasis is connected with dense moving and denudation residual dunes as well as Gobi. The region has a typical temperate desert climate: dry and hot in summer, cold in winter, plenty of sunshine, very little precipitation, strong winds, and frequent drifting sands. The mean annual precipitation within the region encompassing the study sites was 117 mm. And the mean annual air temperature is 7.6 °C, with an absolute maximum of 39.1 °C and an absolute minimum of −27 °C. Mean annual pan-evaporation is around 2390 mm. Mean annual wind velocity is 3.2 m s^{-1}, and prevailing wind direction is northwest. Gales with wind velocity >17 m s^{-1} occur 15 or more days per year (Su et al., 2007a). The depth of groundwater level ranges from 4 to 10 m. The main soil types are Aripsamment and Calciorthids with loose structure and very low organic matter, and are very susceptible to wind erosion (Chen et al., 1998). The natural vegetation at the edge of oasis composed of some desert shrubs including *Calligonum mongolicum* Turcz., *Calligonum gobicum* A.Los., *Haloxylon ammodendron* Bge., *Caragana korshinskii* Kom., *Hedysarum scoparium* Fisch. et Mey., and *Tamarix chinensis* Lour., and some small subshrubs such as *Nitraria sphaerocarpa* Maxim. and *Reaumuria soongorica* Maxim. The staple crops are spring wheat (*Triticum aestivum*), maize (*Zea mays*) and cotton (*Gossypium hirsutum*) in the oasis.

In 1975, Lanzhou Institute of Desert Research, Chinese Academy of Sciences established the Linze Station of Desertification Research in Pingchuan and conducted a desertification control project to monitor desertification processes and develop effective techniques to restore vegetation and rehabilitate desertified land. The rehabilitation techniques applied included establishing straw checkerboards as sand barrier and planting drought-tolerant indigenous desert shrubs within checkerboards on mobile sand dunes, planting fast-growing trees at the fringe of oasis as protecting forest belts, and reclaiming sandy land as irrigated cropland (Su et al., 2007a). After the project was finished, the rate of shifting sand area in the restoration site declined from 54.6% in pre-treatment to 9.4% (Research Group of Study on Combating Desertification/Land Degradation in China, 1998). In 2000, a similar project was conducted in adjacent rehabilitated area and the same rehabilitation techniques were applied. The recovery observation sites established in different periods provided us sufficient information to evaluate the ecological effect of desertified land rehabilitation.

2.2. Field and laboratory measurements

2.2.1. Experiment design and soil sampling

In 2007, we selected two study sites adjacent rehabilitation areas about 2 km away from the recovery sites established in 1975 and 2000. Before the rehabilitation, the landscape of the two areas was denudation and shifting sand dunes. Previous analysis of soil properties in different periods showed that soil texture and organic carbon concentration in soil profile were not significantly different on the shifting sand dunes over time (Chen et al., 1998; Su et al., 2007a). This suggested that the soils have relatively similar characteristics before the rehabilitation. The recovery treatments applied in the two periods (7- and 32-year-old) included establishing straw checkerboards as sand barrier and planting *Haloxylon ammodendron*, establishing poplar (*Populus gansuensis*) shelter forest belts, and leveling sand dunes as irrigated cropland. Therefore, our treatments included: (1) control (untreated shifting sand land); (2) 7-year-old *H. ammodendron* shrub land; (3) 32-year-old *H. ammodendron* shrub land; (4) 7-year-old poplar shelter forest land; (5) 32-year-old poplar shelter forest land; (6) 7-year-old reclaimed irrigated cropland; and (7) 32-year-old reclaimed irrigated cropland. Table 1 shows the characteristics and management of the different land cover types.

Within each treatment recovery site, we selected three 20 × 20 m quadrats as soil sampling sites. Within each quadrat, five soil samples at 0–15 cm layer with uniform distribution separated by 5 m each were taken and bulked to obtain a composite sample. On the *H. ammodendron* shrub lands, ten samples (five were distributed under canopy and others outside canopy) were taken and mixed in each sampling quadrat. Soil bulk density was determined using a soil core (100 cm^3) taken in each sampling location. After air drying, each composite sample was split into two subsamples. One subsample was sieved to <2 mm for the analysis of soil particle distribution and to <0.1 mm for the determination of soil organic C, total N, $CaCO_3$, and labile C ($KMnO_4$ oxidation C). The other subsample of soil was sieved to <8 mm sieve for aggregate stability determination.

2.2.2. Soil analyses

Soil dry aggregate size distribution was determined by manual dry sieving method (Institute of Soil Sciences, Chinese Academy of