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The response of carbon storage to the age of three forest plantations in the Loess Hilly Regions of China

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ABSTRACT

The Grain for Green Project (GGP) has increased the area of forest plantations on the Loess plateau region of China, which has created a need to understand the potential for long-term carbon (C) sequestration. The objectives of this work were to investigate the response of biomass C and soil organic carbon (SOC) densities to the age of these forest plantations and to determine their contribution to the C sources/sink within these regional forest ecosystems. In this project three different species of plants, *Caragana korshinskii* Kom., *Hippophae rhamnoides* and *Prunus davidiana* (Carr.) Franch, were studied by selecting 3 plantation areas where each plant had grown for 9-years and 3 separate plantation areas where each plant had grown for 26-years. All three of these species were widely planted in the case study area. A total of 54 quadrants (2 m × 2 m) were randomly selected in 18 plots (3 plots for each species × 3 species × 2 stand ages) from these plantations for measuring the above- and below-ground biomass as well as the biomass C concentration and density of the three species. A bucket auger was used to collect soil samples from 0 to 100 cm soil depth to determine the SOC concentration and density in each plot. Biomass density, biomass C and SOC increased with growth between 9 and 26 years for all three plant species. The biomass densities for *P. davidiana*, *C. korshinskii* and *H. rhamnoides* increased from 27.3 ± 7.5 to 49.9 ± 11.9 Mg ha^{-1}, 16.6 ± 3.8 to 39.0 ± 18.2 MgC ha^{-1}, and 14.4 ± 4.4 to 23.7 ± 5.7 Mg ha^{-1}, respectively. The biomass C for *P. davidiana*, *C. korshinskii* and *H. rhamnoides* also increased during this time from 9.5 ± 2.6 to 18.7 ± 4.1 Mg ha^{-1}, 6.2 ± 1.1 to 14.6 ± 6.6 Mg ha^{-1}, and 6.2 ± 1.9 to 8.5 ± 2.0 Mg ha^{-1}, respectively. Similarly, the SOC for *P. davidiana*, *C. korshinskii* and *H. rhamnoides* during this time increased from 114.1 ± 13.9 to 185.4 ± 21.2 Mg ha^{-1}, 80.0 ± 9.0 to 93.3 ± 10.7 Mg ha^{-1}, and 62.4 ± 3.5 to 81.6 ± 15.4 Mg ha^{-1}, respectively. Significant differences ($P < 0.05$) were found for the biomass C and SOC densities between the 9- and 26-year old plantations, demonstrating that biomass production continued to significantly impact the SOC storage with increasing age of the forest plantations investigated. This work suggested that both the stored biomass C and SOC in these plantations did not decrease during the growth period from 9- to 26-years. The results of this study highlighted the importance of forest age in understanding the C storage of these forest plantations.

1. Introduction

In recent years, forest plantations have been established on many marginal croplands, wasteland and deserts nationwide to prevent ecosystems from degrading and to improve environmental quality (Fang et al., 2001; Zeng et al., 2014). Given the increasing area of forest plantations in China (Chen et al., 2007; Zhou et al., 2009), an understanding of the changes in carbon (C) storage among various forest plantations at different growth stages can aid in managing C sequestration of these forest plantations and contribute to knowledge on the dynamics of the C sources/sink of local forest ecosystems.

Since 1999, the Grain for Green Project (GGP), the largest cropland retirement program worldwide, has been implemented on the Loess plateau, and thus the area of forest plantations has rapidly increased in this region (Chen et al., 2007; Zhou et al., 2009). During this period, three highly drought-resisting species *Caragana korshinskii* Kom., *Hippophae rhamnoides* and *Prunus davidiana* (Carr.) Franch, have been widely planted in the loess hilly regions. This raised two questions; 1) how does variation in the biomass of the three tree species impact the stored soil organic carbon (SOC) after the conversion of croplands to plantations? and 2) how does the biomass C and SOC storage respond to forest age?

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Several ecologists have studied how growing conditions, including resource availability, determine the growth and C storage of vegetation (Winjum and Schroeder, 1997; Wei et al., 2004; Lutz et al., 2013; Gao et al., 2015). Net Primary productivity (NPP) was highly correlated with the C stored in above-ground biomass (excluding herbaceous plants) of forests in China (Fang et al., 2001). However, it was unclear if such a trend would be also true for SOC under forest plantations, i.e., whether SOC storage would increase with increased forest biomass. Afforestation and reforestation/revegetation may present considerable opportunities for C storage in soil, e.g. land conversion from crop to vegetation, while afforestation of grazing land can lead to relatively smaller increase or decrease in soil C (Guo and Gifford, 2002; Metz et al., 2007). Afforestation typically resulted in increases in biomass and dead organic matter C pools, and to a lesser extent, in soil C pools (Paul et al., 2003). On sites with initial low soil C (e.g., long-term cultivated cropland), afforestation can yield soil C accumulation (Post and Kwon, 2000). Conversely, on sites with initial high soil C (e.g., some grassland ecosystems) the soil C can decline following afforestation (Guo and Gifford, 2002; Tate et al., 2005). Accumulation of biomass C after afforestation varies greatly by tree species and site (Richards and Stokes, 2004).

Shoot/root allocations combined with vertical root distributions, affected the distribution of SOC with depth, thus the most important changes in SOC occurred in the topsoil and SOC storage at deeper depths was more stable (Jobbágy and Jackson, 2000). Stored SOC decreased with soil depth, with an average 59% of the total stored SOC in the topsoil (S1), and more interestingly stored SOC is reportedly higher in reforested areas compared to native forests (Lozano-García et al., 2016).

Some works explored how croplands converted to vegetated/revegetated areas contributed to above- and below-ground biomass C storage (Wu et al., 2006; Tang et al., 2014) and SOC sequestration in the Loess plateau of China (Chen et al., 2007; Wang et al., 2011; Deng et al., 2014). By investigating the vertical distribution and transformation of SOC and soil inorganic carbon (SIC) under shrubs, forests and grasslands in the Loess plateau, Zhao et al. (2016) found that the distribution of SOC within the 0–200 cm soil depth could be described by an exponential model. It was also found that within the 0–50 cm depth the initial accumulation of SOC for shady slopes was higher than for sunny slopes, and that the opposite was true for SIC. Jobbágy and Jackson (2000) found significant differences in North American SOC profiles among shrub land, grassland, and forest vegetation types with the top 20 cm of the 0–100 cm depth having SOC of 33%, 42%, and 50%, respectively. In a global perspective of root distributions, however, grasses had the shallowest root profiles, trees were intermediate, and shrubs had the deepest profiles (Jackson et al., 1996). Some differences in SOC profiles obviously cannot be explained by only considering root distributions.

On the other hand, the stand age was an important factor influencing the C accumulation and storage in soils, living biomass and fallen wood of the forest, which is referred to as the C sequestration of the forest. Some studies showed a significant increase in the C density by forest age from the initial planting to the mature stage (Harmon et al., 1990; Mao et al., 2007; Wang et al., 2012; Wei et al., 2013; Li and Liu, 2014; Xin et al., 2016). Vesterdal et al. (2002) conducted a long-term study in Denmark on changes in soil C stores following afforestation of former arable land with Oak (*Quercus robur* L.) and Norway spruce (*Picea abies* (L.)), which were compared to an adjacent ~200-year-old mixed deciduous plantations. It was found that over the short time span from 1 to 29 years C sequestration was mainly occurring in the biomass of trees while in the ~200-year-old plantation the soil C stores were clearly higher (81 Mg C ha^{-1}). They concluded that soil C appeared to be redistributed following afforestation and that nutrient-rich afforestation soils may become greater sinks for C in the long term. Western European forests were found to store increasing amounts of SOC with expanding tree biomass and to produce more litter throughout the period studied (Liskia et al., 2002).

According to the work by Fang et al. (2012) in southern Ningxia Hui Autonomous Region, the SOC content for the shrub land (including *C. korshinskii* Kom. and *H. rhamnoides*) and grassland was significantly higher than for other land uses, with cropland having the lowest SOC content and thus demonstrating that increased C sequestration could occur in this area for land conversions from cropland to either shrub land or grassland. By the time field work was conducted in 2012, the age of most plantations was > 9 years after the GGP was implemented in this study area. However, uncertainty remained about the variations in biomass C and SOC of the plantations with the above-mentioned three species and plantation ages.

In local management practices, the aboveground portion of *C. korshinskii* and *H. rhamnoides* plantations have generally been cut for renewal at the age of 8- to 10-years, while *P. davidiana* has rarely been cut because farmers have picked the fruits from these plantations. Cheng et al. (2009) suggested 11- to 15-years as the best cutting age for *C. korshinskii* in the loess hilly regions. The question was whether these plantations continued to increase the stored C when they reached 26-years-old, a declining stage in their life cycle. If so, then would early cutting cause C emissions from these forest plantations? Li et al. (2014) argued that *C. korshinskii* would reach peak biomass at the age of 16-years, while Liu (2001) stated that the growth of *H. rhamnoides* would begin to decline at the age of 25- to 30-years. In this region, few studies have documented the biomass and the C dynamics of *P. davidiana*. The focus of the present work was on whether the three plantations in the case study area enhanced or maintained retained storage between the tree ages of 9- and 26-years.

After investigating changes in soil C storage following afforestation of former arable land with oak (*Quercus robur* L.) and Norway spruce (*Picea abies* (L.) Karst.) from 1 to 29 years old, Vesterdal et al. (2002) concluded that soil C appeared to undergo redistribution following afforestation, and that mineral C stores in the top 0–25 cm of soil tended to decrease over the 29-year period. Wang et al. (2012) confirmed the effects of revegetation over time for the SOC distribution but found that the quantity variation for SOC in the 0–30 cm soil depth tended to increase following the revegetation after 10 to 35 years. The SOC also was found to show a slight increase within the 10–15 year period followed by a significant rate of increase within the 15–35 year period in the loess hilly regions of China (Wang et al., 2012). The above-mentioned works highlight the complexity and uncertainty causing variations in the C storage found in forest plantations of different ages.

Because of the variations demonstrated by the above studies, whether the C sequestration would decline or increase during the later stage of a forest plantation's life cycle could not be known. The objectives of this work were to reveal the change in the C pool in forest plantations between 9- and 26-years for the above-mentioned three species and to understand their potential for C sequestration over the long term in the semi-arid loess hilly regions of China.

2. Materials and methods

2.1. Study area

The case study area was located in Longde County (35°21′-35°47′N; 105°48′-06°15′E) in southern Ningxia Hui Autonomous Region of China (Fig. 1). The area of this county is 985 km^2 with altitudes ranging from 1720 m.a.s.l. to 2942 m.a.s.l. According to the Ecological Environment Database of the Loess Plateau (http://159.226.153.52/pdmp/index.action), the study area has a temperate continental climate, with a mean annual precipitation of 442.7 mm (2000–2005). The distribution of the precipitation is very uneven throughout the year, with > 60% of the annual precipitation falling from July to September. The mean annual evaporation is > 1360.0 mm, which is three times the precipitation level. The annual average temperature is 7.5 °C, and the accumulated temperature ≥ 10 °C is between 2500 °C and 2800 °C. The