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Changes in above- and below-ground nitrogen stocks and allocations following the conversion of farmland to forest in rocky desertification regions

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ABSTRACT

Afforestation of degraded land is one of the principal strategies for preventing soil erosion and promoting ecosystem recovery in fragile regions, especially in rocky desertification areas. In China, millions of hectares of farmland have been converted into forest in order to arrest and reverse rocky desertification under the Grain for Green Program (GGP). This study evaluated implications of land-use change from annual maize cultivation to perennial *Zanthoxylum bungeanum* plantations (1-, 4-, 7-, and 10-year-old) in the karst region of Guizhou province, southwest China. The study analyses the variations of biomass and nitrogen (N) storages as well as N distributions in biomass components and soil depths. Results showed that the N content in components of *Z. bungeanum* ranged from 0.31% to 3.24% with a mean value of 1.75%, which was lower than that of maize (2.13%) in the same region. The biomass N storage measured for the maize cropland was 210.59 kg ha^{-1}, while this value increased linearly with stand ages for the four *Z. bungeanum* plantations (0.94, 108.31, 212.20, and 262.12 kg ha^{-1}, respectively). The average amount of soil N storage in the *Z. bungeanum* plantations (9.33 t ha^{-1}) was significantly lower than in the adjacent intensively managed maize cropland (10.04 t ha^{-1}). This is mainly due to long-term organic and inorganic fertilizer inputs in the farmland stage. Total ecosystem N storage averaged 10.25 t ha^{-1} in the maize cropland, and 9.38, 9.82, 9.05, and 9.67 t ha^{-1} in the 1-, 4-, 7- and 10-year-old *Z. bungeanum* plantations, respectively. Soils accounted for 97% of total ecosystem N storage in both land-use systems. This study suggests that the reduction of surface soil disturbance during plantation management practices plays a crucial role in improving the N storage. Data of annual plantation area and biomass N accumulation rates under the GGP indicate that Guizhou province was a net N sink with 2.35×10^8 kg N in 2010, corresponding to 41.45% of N (NO_X-N and NH_3-N) emissions in that year. Besides increasing N sequestration over time (as these forest mature), the large-scale plantations of *Z. bungeanum* have the potential to restore severely degraded soils in the karst region of SW China.

1. Introduction

Rocky desertification, a process characterized by serious soil erosion and widespread bedrock exposure, is one of the most serious land degradation issues in karst areas (Xiong et al., 2009). Rocky desertification in southern China and sandy desertification in northern China are two major environmental problems that hamper local sustainable development (Wang and Li, 2007). In response to these environmental crises, a range of policies have been developed to support forest management strategies aimed at the prevention of land degradation and the creation of new forests, mainly on barren, degraded or former agricultural land (Madsen, 2002; Smith et al., 2000). Therefore, a nationwide Grain for Green Program (GGP), also known as the Conversion of Cropland to Forest and Grassland Program (CCFGP) (Ostwald et al., 2007), was initiated by the Chinese government in 1999. The GGP is the largest ecological restoration project in China with the intention of preventing further soil erosion, controlling desertification, and improving land quality. In practice, the GGP helped to restore the ecological functionality in degraded areas by returning cultivated

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slopes and barren lands to pastures and forests. Over the past ~10 years, the replacement of annual crops by perennial plants has led to a marked improvement of the natural environment. According to the Annual Reports on the Development of Chinese Forestry, 2.34×10^7 ha of lands, including 8.27×10^6 ha of croplands and 1.51×10^7 ha of barren lands, have been planted under the GGP during the period of 1999–2010 (State Forestry Administration, 1999–2011). Therefore, the broad areal extent of GGP in the degraded region of China will lead to an increase in new forests and ultimately contribute to improvements in regional biogeochemical cycles.

The impact of afforestation and reforestation on carbon (C) and nitrogen (N) cycles, has garnered significant attention in recent years (Fortier et al., 2015; Li et al., 2012; Ritter, 2007). A shift in land-use from agriculture to forestry induces major changes in the N cycle, including inputs, internal cycling, and losses. The N cycle in agricultural soils is characterized by an open cycle. N fertilizer is supplied regularly in large amounts and approximately the same amount of N leaves the ecosystem via leaching or harvested crops. However, the soil properties of former cropland after afforestation are slowly modified towards conditions found in closed forests because of a lack of the intense cultivation (high fertilization, annual tillage, weed control, etc.) as well as due to the effect of trees themselves (Zhang et al., 2012). In the initial phase of afforestation, plantations on former cultivated land have higher N status as a legacy of former fertilization, which supports continued high mineralization and nitrification in the mineral soil (Jug et al., 1999). Even a century after afforestation, soils in plantations on former cropland have N-cycling characteristics that differ significantly from those of nearby soils with unbroken forest cover (Compton et al., 1998; Jussy et al., 2002). Mobilized N can be fixed in the biomass of above- and below-ground vegetation for a longer period of time. Namely, plant biomass after afforestation might act as an important sink for N and lead to an overall increase in N retention within the system (Heilman et al., 1995). Moreover, afforestation of agricultural land is likely to have a large effect on the N equilibrium, resulting in changing flows of N from plant biomass fractions and soil organic matter pools. Therefore, the magnitude and duration of the net gains or losses of stored N in different stand-aged forest and the effects of the change in land-use on N cycling is of particular interest (Hansen, 2002). Despite the importance of these changes in the N stocks and cycles following the conversion of agriculture to forestry, the effects of widely applied afforestation remains unclear. Furthermore, little is known about changes in N stocks and distributions in former framlands and recently converted forests under the GGP, particularly in the karst region.

Located in the central karst regions of southwest China, Guizhou province is subject to severe rocky desertification. In 2000, approximately 3.25×10^4 km^2 of the province had outcrops of carbonate rocks, making up 17.10% of its total land area (Jiang et al., 2014). To prevent soil erosion and restore ecosystem functionality, Guizhou is high on the list of provinces for implementation of the GGP and provides a particularly good context for evaluating the influence of land-use change on the dynamics of biomass and N stocks in this area. By the end of 2011, 1.20×10^6 ha of land in Guizhou province, including 4.39×10^5 ha of steep cropland and 7.60×10^5 ha of barren land has been planted with trees under the GGP, accounting for 4.97% of the national GGP-lands (including 5.31% of total steep croplands and 4.80% of total barren lands, respectively) (State Forestry Administration, 1999–2011). It is expected that 7.03×10^5 ha of steep croplands (>25°) will be converted to forests during the period from 2014 to 2020 (Guizhou Provincial Forestry Department, 2014). Therefore, the large-scale of actual and potential implementation of the GGP in the karst region of Guizhou province involves a shift from this high level of human interference in the annual cycle of cultivating and harvesting crops to a lower level interference in a much longer forest cycle (Hansen, 2002). This process will lead to an expansion of new forests and will ultimately change regional N cycle as well as reduce of N leaching over the long term. An improved quantification of the change in biomass and N pool allocation is fundamental to the understanding of the effect of land-use and land cover change on ecosystem function at a regional and national scale. This understanding is required for scientists, managers, and policy makers to play their roles in the implementation of the GGP.

In this study, we examined the changes of vegetation biomass, ecosystem (plant and soil) N storages, and allocations following the conversion of farmland (*Zea mays* L.) to forestland (1-, 4-, 7-, and 10-years old *Z. bungeanum*) under the GGP in the Hua Jiang Karst Canyon of Guizhou province. The focus of this study was to: 1) compare the changes of above- and below-ground biomass between cropland and forest; 2) quantify the N stocks in plant and soil in both before and after land-use changes; and 3) implicate the N pools by restoring the degraded karst regions under the GGP in Guizhou province.

2. Materials and methods

2.1. Site description

The study site is situated on the Hua Jiang Karst Canyon (HJKC) of Guizhou province, southwest China, located in the range of 25°39.2′–41′N latitude and 105°36.5′–46.5′E latitude. The total area of HJKC is 51.62 km^2, of which 87.92% is karst. This area has been considered as a typical representative of karst region in SW China. The terrain, soil type, and climatic condition in this region are described in more detail by Cheng et al. (2015).

The landscape in the HJKC is characterized by cultivated land and recently converted forest land. The cultivated land is mainly upland maize (No. 778 Andan) field, and the area of cultivated land is about 1051.0 ha (Gao and Xiong, 2015). In the process of maize cultivation, the field will receives significant amounts of farmyard manure (15,000 kg ha^{-1}) and multi-element compound fertilizer (750 kg ha^{-1}), which were used as base fertilizers. Additionally, urea is applied to the field as topdressing fertilizers during seedling and huge bellbottom periods at 150 kg ha^{-1} and 225 kg ha^{-1} levels, respectively. However, the use of nitrogen fertilizer is markedly reduced and sometimes ceased altogether following the conversion of cropland to forest under the GGP. The recently converted forest is mainly consist of *Z. bungeanum* with an area of 1786.9 ha (Li et al., 2010). *Z. bungeanum* is a suitable species for plantation/afforestation to restore the rocky desertification, due to its fast growth and adaptability to poor habitat, drought tolerance, and calcareous soil. Furthermore, the fruit of the *Z. bungeanum* tree can be sold to supplement the income of farmers in poor karst areas of Guizhou. Indeed, the HJKC has become a demonstration of how rocky desertification may be arrested under the GGP in Guizhou province and all over China, because ecological restoration under the GGP in this region increased vegetation coverage from 21.4% in 2001 to 53.2% in 2005 (Chen et al., 2007).

2.2. Biomass estimation

Because most of the land was discontinuous in rocky desertification regions, the area of the sampled fields was relatively small. It was about 0.10 ha for the maize field and approximately 0.25 ha for the *Z. bungeanum* plantation. Biomass of the maize was measured by placing three random one-meter-square (1 m × 1 m) quadrats (blocks) in the fields, and the height (H) and circumference at the base of the stem (CBS) of each plant were measured in the quadrats (Table 1). Total biomass of maize was measured by cutting,