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Sub-tropic degraded red soil restoration: Is soil organic carbon build-up limited by nutrients supply

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ABSTRACT

The long-term Forest Restoration Experimental Project (FREP) was established in 1991 on a subtropical, barren, degraded, red soil sparsely vegetated grassland in Taihe County, Jianxi province, China. The objective of the FREP was to evaluate the effects of restoration on ecological functions through afforestation by using various local species. This information will provide guidance for future restorations at severely deteriorated landscapes, which are very common in southern China. In this study, we selected five restoration forests: Chinese sweetgum (*Liquidamber formosana*), schima (*Schima superb*), masson's pine (*Pinus massoniana*), slash pine (*Pinus elliottii*), Chinese sweetgum × slash pine mixtures, and one experimental control (grassland with low coverage of annual and perennial plants). These were selected to evaluate the differences in soil organic carbon (TC), soil nitrogen including total soil nitrogen (TN) and available nitrogen (Av-N), soil phosphorus including total phosphorus (TP) and available phosphorus (Av-P), and their molar ratios (C:N, C:P, and N:P). A similar assessment was also conducted on the species functional groups (coniferous forest, broad-leaved forest, and mixed-species forest) based on groupings of studied species. Furthermore, we evaluated the relationships between TC and soil N and P, and their stoichiometry to explore the biochemical mechanisms of soil organic matter buildup. Finally, we explored the recovery trajectory of TC and TN in the FREP's evergreen broad-leaved forest by comparing it with local evergreen climax ecosystems.

Over the 19-year study period, restoration significantly improved the TC and soil N and P compared to the control sites, but there were no significant differences in the TC and soil N and P among the restoration functional groups and among forest stand types. The TN and C:P ratios were closely related to soil organic carbon contents suggesting that they were good predicator of soil organic carbon. The overall data clearly demonstrated that the restoration through local species and nutrient cycling concentrating C, N, and P in topsoil. The recover trajectory suggests that the evergreen forest (schima) in FREP is still in the early developmental stages, and its projected rate of TC and TN growth is much slower than the average growth rate in the region. This case study clearly demonstrated that although the recovery is at its early stage with a very slow process, the active restoration can enhance soil carbon sequestration, nutrients availability, and the capability of soil organic carbon sequestration is regulated by the soil nutrients supply.

1. Introduction

Red soils, generated by abundant rainfall and high temperature, cover over 204 million hectares (M ha) in tropical and subtropical regions of southern China (Xu et al., 2003), and there are about 5 M ha in Jiangxi province alone (Ye, 1982). Historically, the region was covered by evergreen broadleaved forests: local climax forest species were *Schima* spp., *Castanopsis* spp., *Quercus* spp., *Cylobalanopsis* spp., etc. The population in the region increased dramatically during the past century (Li et al., 2003), increasing demand for firewood, timber and food; intensive anthropogenic disturbances have destroyed the evergreen vegetation. As a result, the red soil's deterioration, degradation, and erosion become common phenomenon; without proper policy to guide management practices, the region turned into a bare barren grassland landscape, also called "red desert", because of the soil color and low productivity (Li et al., 2003). Fortunately, restoring the "red desert" under the new federal forestry policy, by re-establishing vegetation, improving soil quality, and establishing forests, has emerged as the region's top priority (Liu et al., 2004; Zheng et al., 2004; Yan et al., 2007). How to restore

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such a "deserted" landscape to enhance ecosystem functions (i.e., soil fertility and carbon sequestration), meet government goals, and contribute to the climate change portfolio is an imperative question. We designed a long-term Forest Restoration Experimental Project (FREP) in the "red desert" region (Taihe County, Jiangxi province) to explore the effectiveness of the restoration and the recovery of ecosystem functions.

Soil organic carbon is closely associated with a wide range of physical, chemical and biological properties of soil, and thus plays a critical role in almost all soil processes and functioning (Harris et al., 1996; Nambiar, 1997; Smith et al., 2000). The total soil organic carbon content (TC) has long been recognized as a key component of soil quality (Reeves, 1997), and thus TC maintenance in the restoration is a major determinant of the soil productivity and long-term stability of the restored ecosystem. Meanwhile, TC storage has been widely considered as a promising measure for mitigating global climate change through carbon sequestration in the soil (Lal, 2004, 2005).

Soil nutrients are indicators of ecosystem productivity (Vitousek, 1984), especially, soil nitrogen and phosphorus in the red soil region (Liu et al., 2004). Nitrogen and phosphorus are considered the most important limiting elements for vegetation in terrestrial ecosystems (Chapin et al., 1986; Vitousek and Howarth, 1991). The amount of plant available-nitrogen (Av-N) and -phosphorus (Av-P) constrains both natural and managed ecosystems, including non-fertilized agricultural land productivity (Seneviratne, 2000). At longer time scales (decadal or centurial) for typical ecosystem development, the major source of phosphorus is from rock weathering, while nitrogen is of atmospheric deposition (Manzoni et al., 2010). Thus, plants growing on young soils are often nitrogen limited, while vegetation on older, highly weathered soils (like red soils in our study region) is often phosphorus limited (Jobbagy and Jackson, 2001; Reich and Oleksyn, 2004). These broad-scale trends in soil properties, coupled with smaller scale heterogeneity in soil–vegetation interactions, produce a wider range of soil nutrient availability and patterns of nutrient limitations. This in turn provides an indication of soil biochemical coupling mechanisms between soil organic carbon and nutrients resulting from soil weathering, roots transferring, and decomposing of plant tissues and residues (Reich and Oleksyn, 2004; Townsend et al., 2007). It is important, thus, to quantify soil nitrogen, phosphorus, and their available forms during forest restoration processes to further determine their interactions with soil organic carbon in different forest restoration types.

It is often difficult to clearly select certain chemical, physical, and biological indices to represent soil quality because of the dynamic interactive nature of these indices and involved processes and functions (Schoenholtz et al., 2000). Some researchers simply propose functioning characteristic (e.g., mineralization N) as an indicator (Doran and Parkin, 1994; Reganold and Palmer, 1995; Powers et al., 1998). The complication, exists however because there is seldom a one-to-one relationship between a function and the indicator; more likely, a given function (e.g., sustain biological productivity) is supported by a number of soil properties, while any given soil property may be relevant to several soil functions simultaneously (Burger and Kelting, 1999). For example, soil organic matter plays a role in almost every soil function (Harris et al., 1996; Nambiar, 1997). Also, many soil chemical properties directly influence microbiological processes via nutrient and carbon supply relationship, and these processes, together with soil physical–chemical processes determine (1) the capacity of soils to hold, supply and cycle carbon, and (2) the movement and availability of nutrients (Powers et al., 1998). In our study, we selected TC, nitrogen, phosphorus, and their available forms to quantify how restoration may affect their quantities, and explore their multidimensional relations of the biochemical ratios with soil organic carbon accumulations in the ecosystem restoration processes. Furthermore, arguments also have been raised about using volumetric (kg ha^{-1}) or gravimetric (g kg^{-1}) units in the soil chemical property analyses (Doran and Parkin, 1996). Reganold and Palmer (1995) confirmed that the divergent outcomes regarding the effects of various grassland management regimes on soil chemistry depended on whether gravimetric or volumetric measurements were used because of the physical property (soil bulk density) differences. We used gravimetric measurements in our nutrient analyses because of the similarities in our physical property (soil bulk density) measurements (Table 1).

It is often difficult and challenging to predict the restoration rate and trajectory of soil organic carbon accumulation and nutrients recovery, although it is essential to evaluate the effectiveness of the restoration efforts. Jackson and Hobbs (2009) suggested that active intervention may promote fast ecosystem recovery, even on severely altered sites. They further warned that estimating the trajectory of restoration is more challenging because the knowledge of the ecosystem origin and its history is often unavailable, and often spans more than the past few decades. Furthermore, the restoration pathways are often quite different depending on the type of restoration; for example, soil properties restoration (Paul et al., 2010) is different from vegetation restoration (Ashton et al., 2001). Fortunately, the local natural reserves and protected areas in our study area provide an ideal trajectory for our FREP study. The focus of this study was to assess the overall impact of forest restoration with local climax species on soil organic carbon contents, soil N, P, Av-N, and Av-P, to evaluate relationships between the TC and soil N, P, Av-N, Av-P, and their biochemical ratios, and tentatively to explore their relative recovery trajectories. The objectives of this study were to determine: (1) whether forest restoration with local climax species improves soil organic carbon contents, soil N and P, and their available forms; (2) whether soil organic carbon has a positive relationship with soil N, P, Av-N, Av-P, and/or their biochemical ratios during restoration processes; and (3) what the recovery trajectories of TC and TN may exist for the FREP restoration. Our study aimed to investigate the magnitudes of improvement in soil organic carbon content and nutrients through active forest restoration process, explore the potential recovery trajectory pathways of soil organic carbon accumulation and hence provide a scientific guidance to understand the restoration potential for the severely degraded ecosystems in Southern China.

2. Study site and methods

2.1. Study site

The FREP, 133 ha, is located in Taihe County (26°44′N, 115°04′E), Jiangxi, China (Fig. 1). It was a bare barren grassland landscape over the past several decades. In 1991, a long-term restoration experimental station was established in this grassland to examine forest restoration strategies on ecosystem functions (Liu et al., 2004). The FREP experimental design was completely random design with at least three replicates by forest types and planting densities (Liu et al., 2004). In our study, we selected five forest types with the same initial planting density: Chinese sweetgum (*Liquidamber formosana*), masson's pine (*Pinus massoniana*), schima (*Schima superb*), slash pine (*Pinus elliottii*), mixtures of Chinese sweetgum x slash pine, and experimental control. The experimental control, arid and semi-arid grasses dominated grasslands, was left to natural regeneration without human plantings, and after 19 years there were no trees established.

The FREP has a rolling topography with an elevation range from 75 to 131 m. It has the subtropical moist monsoon climate, with a