Forest Ecology and Management 389 (2017) 46–58

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

# Comparison of nitrogen nutrition and soil carbon status of afforested stands established in degraded soil of the Loess Plateau, China

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ARTICLE INFO

*Article history:*
Received 12 September 2016
Accepted 4 December 2016

*Keywords:*
Root N uptake
Soil N availability
Monoculture
Mixed stand
Degraded soil
Afforestation

ABSTRACT

The Loess Plateau in China constitutes an area short of soil nitrogen and organic carbon due to local land degradation induced by various factors (i.e. long term changes of land use, climate conditions, and soil properties). The present study aimed to examine the effects of species and land management by afforestation on tree N acquisition capacity and soil N and C availability in degraded soils of the Loess Plateau area. We quantified root N uptake of inorganic and organic N sources as well as soil N and C availability, both at the tree species (i.e. *Robinia pseudoacacia* L., *Juglans regia* L. and *Pinus tabulaeformis* Carr.) and the land management (i.e. arable vs. monoculture vs. mixed afforested stands) levels. Our results indicated that afforestation improved soil N and organic C availabilities compared to abandoned arable land ($p < 0.05$). In particular, the presence of $N_2$-fixing *R. pseudoacacia* enhanced root N concentrations (ca. 3.0 times) and soil $NO_3^-$ (ca. 5.4 times), soil total N (ca. 1.9 times) and organic C (ca. 3.4 times) availabilities, but decreased soil $NH_4^+$ (ca. −33%), microbial biomass carbon (ca. −74%) and nitrogen (ca. −54%) in the mixed stand compared to *J. regia* monoculture. Under the experimental conditions applied, the afforested trees preferred organic over inorganic N compounds as well as $NO_3^-$ over $NH_4^+$; *J. regia* in monoculture had a highest root amino acids N uptake capacities (i.e. $76.6 \pm 7.7$ nmol N $(g\,fw)^{-1}\,h^{-1}$ for glutamine, $90.3 \pm 8.9$ nmol N $(g\,fw)^{-1}\,h^{-1}$ for arginine) compared to other tree species whereas such high uptake capacities were largely repressed in the mixed stand with *R. pseudoacacia*. Thus, in the Loess Plateau area, the inter-planting system of *J. regia* with $N_2$-fixing *R. pseudoacacia* could improve the total soil N and organic C pools as well as plant N cycling compared to traditional arable land use and *J. regia* monoculture system. This study shows that inter-planting *R. pseudoacacia* with economic fruit trees can be considered a successful strategy for soil regeneration by afforestation in future land management projects.



## 1. Introduction

Forest trees support important ecosystem functions and services such as nutrient cycling, carbon (C) sequestration, water and soil conservation (Dixon et al., 1994; Lang et al., 2014). However, land use change and deforestation by anthropogenic activities have caused climate change and an extensive decline of these ecosystem services and resulted in land degradation (Harris et al., 2012; Budiharta et al., 2014). Therefore, afforestation has been proposed as the effective practice for restoration of ecosystem services in degraded ecosystems, e.g., by improving soil conservation and carbon sequestration (Harris et al., 2012; Li et al., 2012; Hoogmoed et al., 2014).

Soil nitrogen (N) availability is a predominant nutritional factor that regulates forest growth and development and consequently, ecosystem functions and services, particularly in temperate forest ecosystems (e.g. Lovett et al., 2004; Chapman et al., 2006; Rennenberg et al., 2009; Rennenberg and Schmidt, 2010; Rennenberg and Dannenmann, 2015). In general, soil N is used

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http://dx.doi.org/10.1016/j.foreco.2016.12.011

by plants in both inorganic and organic forms (Stoelken et al., 2010). However, previous studies have shown that the preference for different N sources (e.g. inorganic vs. organic sources) differs among tree species particularly in N limited forests (Schimel and Bennett, 2004; Rennenberg et al., 2009). Recent studies have proposed that tree roots can take up all N forms available in the soil (i.e. inorganic and organic) in N limited forests, while particular N sources may be preferred in N saturated forests (Rennenberg and Dannenmann, 2015). Under N limited condition, N availability for a specific tree will be determined by climate, physical as well as chemical properties of the soil (e.g., Greaver et al., 2016), but also by competitive interactions at the forest ecosystem level. These interactions existed not only for old growth trees, its natural regeneration and other woody and herbaceous understorey species, but also for free living and symbiotic microorganisms (Rennenberg and Dannenmann, 2015). Since afforestation is predominantly carried out on degraded and marginal soil for restoration of ecosystem services, it has to be elucidated if afforestation with appropriate tree species will (1) alter strategies of plant N acquisition as adaptation to low N availability; (2) improve plant N use efficiency; and (3) increase soil N availability in order to achieve successful and sustainable afforestation.

The semi-arid Loess Plateau is one of the regions in China with the highest population density. The relatively long history of change of land use types, for instance, converting forests to arable land, largescale mono-cropping and over-grazing (Fu et al., 2000) has resulted in an overexploitation of forests and degradation of soil quality. Forested areas decreased by over 53% between 1949 and 2000 in this region (Jiang, 1997; Wang et al., 2006). During the past decades, studies showed that land use change induced changes of local climate conditions, intensified soil erosion and modified soil properties. Together these changes significantly affect soil organic carbon (SOC) and total nitrogen (TN) in terrestrial ecosystems (Russell et al., 2005; Qiu et al., 2010). To control soil erosion, increase storage of SOC and TN, and prevent the occurrence of soil desiccation on the Loess Plateau, revegetation by afforestation through restoration of degraded land has been proposed. To increase forest coverage is a key task of the national "Grain for Green" project of China in this region (Fu et al., 2010). The monoculture stands of exotic and indigenous tree species, such as black locust (*Robinia pseudoacacia* L.), Chinese pine (*Pinus tabulaeformis* Carr.) and the Persian walnut (*Juglans regia* L.), have been widely established during the past decades because of their high growth rates and/or great economic importance in this semi-arid environment (Zheng, 1985; Shan et al., 2003). However, monocultures of these fast growing and/or economically important tree species on marginal soils have been found to decrease soil C and N stocks, thereby impairing sustainable forest development (Hoogmoed et al., 2014; Lang et al., 2014).

In this context, reforestation with mixed species including $N_2$-fixing plants seems to constitute a strategy to promote soil C and N storage (Gamfeldt et al., 2013; Hoogmoed et al., 2014). $N_2$-fixing species are able to not only enhance soil N stocks but also increase soil $NH_4^+$ and $NO_3^-$ availabilities (Hoogmoed et al., 2014), N forms which can directly be used by other plant species. For instance, Persian walnut is considered a non $N_2$-fixing species that exhibits weak root nitrogen uptake capability and high susceptibility to water stress when growing in monoculture stand, although it has great economic benefit for the local farmers (Ellenberg et al., 1991; Loewenstein and Pallardy, 2002; Chifflot et al., 2006). However, previous studies found that N nutrition and development of Persian walnut can be greatly improved if inter-planted with suitable $N_2$-fixing nurse tree species such as black locust (Schlesinger and Williams, 1984; Bohanek and Groninger, 2005; Jose et al., 2006; Clark et al., 2008). If such a nursing effect of black locust on co-cultivated plants is also achieved under extremely low water and nutrient availability, abundant at the Leoss Plateau in China, has so far not been elucidated. It is also unclear if such a nursing effect coincides with, or precedes improved nutrient availability in the soil. Previous studies under less harsh conditions showed that different tree species may affect soil N availability and N stocks differently due to different traits of litter quantity, quality and root exudates (Rennenberg et al., 2001; Harrison et al., 2007; Hoogmoed et al., 2014; Lang et al., 2014). Thus, it is essential to improve our understanding of the linkage between plant N acquisition and soil N dynamics both at the forest management (i.e. monoculture vs. mixed stand) and the tree species (i.e. *R. pseudoacacia*, *J. regia* and *P. tabulaeformis*) levels for the establishment of future afforestation strategies in degraded areas of the Loess Plateau. Such attempts will significantly contribute to understand how the N demand of different forest types can be met on degraded N-poor soils with low atmospheric N input (Rennenberg and Dannenmann, 2015).

In the present study, we simultaneously examined soil N and organic C stocks, bioavailability of C and N compounds, as well as N acquisition preferences and capacities of plants in five afforestation stands in the southern Loess Plateau region. The objectives of this study were to demonstrate: (1) which cultivation form of *R. pseudoacacia* can improve soil properties and plant nutrition status, and (2) if differences of soil C and N availabilities are related to N acquisition processes of different tree species (i.e. *R. pseudoacacia*, *J. regia* and. *P. tabulaeformis*) and afforestation approaches (i.e. monoculture vs. mixed stand; mature forest vs. young coppice growth). In this context, we hypothesized that: (1) soils cultivated with $N_2$-fixing tree species such as *R. pseudoacacia* possess high plant available N concentrations and root acquisition capacities, (2) N nutrition of *J. regia* could benefit in N acquisition by inter-planting with $N_2$-fixing *R. pseudoacacia* even under the extreme conditions of the Loess Plateau, and (3) root N uptake preference, for inorganic and organic N sources, differ between the investigated tree species.

## 2. Materials and methods

### 2.1. Site characteristics and experimental design

The experimental field sites were located in the Huaiping National Forest farm at an altitude of 1300 m to 1400 m a.s.l., Yongshou County (34°83′N, 108°08′E), the northern slope of the Wei River of Loess Plateau, Shaanxi Province, China. The study area exhibits a monsoon climate in the warm temperate zone with an annual average air temperature of 10.8 °C, a mean annual precipitation of 610 mm and 210 frost free days per year (Ni et al., 2010). The soil type at the experimental field sites is a loessal soil developed from loess materials. The topography and soil textural class include sand (30–55%), silt (20–45%) and clay (15–25%) (Liu et al., 2014).

Field experiments were conducted in early September 2012, before any visible signs of leaf senescence, at five afforestation sites: (1) mature *Robinia pseudoacacia*, (2) mature *Robinia pseudoacacia* mixed with mature *Juglans regia*, (3) mature *Juglans regia*, (4) young *Robinia pseudoacacia* coppice, and (5) mature *Pinus tabulaeformis* and an additional fallow arable land site, which was abandoned for over 10 years, as the control site (no tree stand). The dominant understory herbaceous species are *Stipa breviflora* Griseb., *Leymus secalinus* (Georgi) Tzvelev, *Heteropappus hispidus* (Thunb.) Less., *Artemisia mongolica* (Fisch. ex Besser) Fisch. ex Nakai, *Bothriochloa ischaemum* (L.) Keng, *Potentilla chinensis* Ser. and *Carpesium divaricatum* Siebold & Zucc. (You et al., 2010). The study sites are relatively flat with slopes less than 4° in the sampling area and all experimental sites are located in close vicinity