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Substrate quality and soil environmental conditions predict litter decomposition and drive soil nutrient dynamics following afforestation on the Loess Plateau of China

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ABSTRACT

To elucidate the effects of land-use types and afforestation age on litter decomposition, soil nutrient dynamics, and their relationship with substrate quality and soil environmental conditions, soil and litter samples were collected from farmland as well as four afforested land-use types (*Robinia pseudoacacia*: Rps; *Caragana korshinskii*: Cko; *Pinus tabulaeformis*: Pta; and *Armeniaca sibirica*: Asi), with each land-use type having three succession chronosequences (10, 25, and 40 a) in the Gaoxigou catchment area. These twelve afforested lands were converted from similar farmlands, and litterbag experiments were conducted in each land to determine litter decomposition rate (LDR). In addition, the carbon, nitrogen, and phosphorus contents and stoichiometry in soil and litter, soil properties, and litter biomass were determined. The results showed that soil environmental conditions such as soil water content, bulk density, pH, and temperature improved with afforestation age. Soil nutrient contents were higher in afforested lands and increased with afforestation age. The soil organic carbon (OC), total nitrogen (TN), and total phosphorus (TP) were positively correlated with the litter biomass, soil microbial carbon, and soil water content, but were negatively correlated with the soil bulk density, pH, and temperature. The litter OC, TN, and TP contents were mainly affected by the land-use types without being influenced by afforestation age. LDR is the main litter factor affecting soil nutrients, and is significantly influenced by substrate quality and environmental conditions, especially litter TN and N:P ratio, soil water content, and pH. The annual rates of increase for soil OC and TN during the initial (farmland–10a) and middle (10–25 a) periods were significantly higher than those during the later period (25–40 a) in Rps and Cko, but the Pta forest showed a completely opposite trend, which can be explained by a synchronous change in the LDR driven by the soil water content. In addition, the soil OC, TN, and TP contents were positively correlated with the litter TN, TP, and biomass, but had no correlation with the litter OC. The N:P ratio can be used as an indicator to reveal a tight coupling among soil and litter nutrients. Overall, these results provide evidence that litter decomposition in afforestation systems is linked to soil nutrient dynamics, and is mainly limited by substrate quality and environmental conditions.

1. Introduction

Afforestation on farmland with poor soil fertility and productivity is an effective approach to restore degraded environments and improve the crucial ecosystem processes (Han et al., 2017; Zhao et al., 2015a). During afforestation, the aboveground plant communities supply substrates (litter and rhizodeposition) to the soil ecosystem, whereas underground soil provides water and mineral elements for plant growth

Abbreviations: SOC and LOC, soil and litter organic carbon; STN and LTN, soil and litter total nitrogen; STP and LTP, soil and litter total phosphorus; SCN and LCN, soil and litter C:N ratio; SCP and LCP, soil and litter C:P ratio; SNP and LNP, soil and litter N:P ratio; SMC, soil microbial carbon; SBD, soil bulk density; SWC, soil water content; ST, mean temperature in the first 10 cm of soil (a horizon); pH, mean pH in the first 10 cm of soil (a horizon); LB, litter biomass; LDR, litter decomposition rate; Rps, *Robinia pseudoacacia*; Cko, *Caragana korshinskii*; Pta, *Pinus tabulaeformis*; Asi, *Armeniaca sibirica*; PCA, principal component analysis; RDA, redundancy analysis; NMDS, non-metric multidimensional scaling

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(Fan et al., 2015; C. Zhang et al., 2016a). Litter, as a link between the aboveground vegetation and the belowground soil, plays an important role in the metabolism and circulation of nutrients in the plant-soil system through enabling different nutrient return and decomposition rates (Deng et al., 2016b; X.X. Zhang et al., 2016b). Thus, assessing the substrate quality and decomposition dynamics of litter can provide a framework for expounding the nutrient feedback processes in a plant-soil system and the nutrient balance of afforestation ecosystems (García-Palacios et al., 2016; Horodecki and Jagodziński, 2017).

It is well known that changes in substrate quality are important factors that affect and change the soil carbon (C), nitrogen (N), and phosphorus (P) contents, because litter nutrients are directly and proportionally supplied to the soil (Xu et al., 2013). For instance, leguminous plants can boost soil N content faster than other plants due to their large litter nitrogen content (Horodecki and Jagodziński, 2017; Mueller et al., 2012), and soil and litter C:N:P stoichiometry are highly coupled in tropical forest plantations (Marichal et al., 2011). Delgado-Baquerizo et al. (2015) also demonstrated that litter N and P contents had significant correlations with soil N and P increments, but not with labile C variables. However, Phillips et al. (2011) found that plants had a greater effect on the availability of soil organic C relative to N and P. Thus, large uncertainties remain concerning nutrient balances in plant–soil systems, especially the C interrelationship between soil and litter, which need to be further verified in other regions. In addition to the direct return of C, N, and P to soil, the litter substrate quality can also influence the litter decomposition rate (LDR), and thus radically determine soil nutrient cycling and fluxes (Pena-Pena and Irmler, 2016). For instance, litter with a higher N content tends to contain more labile complexes (e.g., phenolic acids and flavonoids), which are usually easily accessed by decomposers, and thus can be quickly decomposed (Garcia-Palacios et al., 2016). Parsons and Congdon (2008) observed that the LDR had a significant positive correlation with the litter total nitrogen (LTN) and phosphorus (LTP) concentrations, but was negatively correlated with the cellulose and lignin contents. Previous studies have also shown that the litter N:P ratio, reflecting the N and P utilization efficiency of litter decomposers, appears to be a crucial determinant of LDR (Güsewell and Verhoeven, 2006; Gusewell and Gessner, 2009), whereas others have shown that litter with lower initial C:N ratio decays faster (Cornwell et al., 2008; Horodecki and Jagodziński, 2017; Perez-Harguindeguy et al., 2000). Although these studies provided valuable recommendations for understanding the effect of substrate quality on litter decomposition, there is still necessary to broaden detailed researches since these conclusions remain divisive, especially which C:N:P stoichiometry can indicate the decomposition dynamics of litter.

Environmental conditions such as climatic factors (i.e., moisture and temperature) and soil characteristics (i.e., pH, soil bulk density [SBD], and soil texture) have been found to be closely related to litter decomposition, and thus affect soil nutrient contents (Delgado-Baquerizo et al., 2015; Pena-Pena and Irmler, 2016; Pii et al., 2015), because they can modify the reproduction and growth of decomposers (microorganisms) (Fanin and Bertrand, 2016; Mueller et al., 2012). For instance, Serna-Chavez et al. (2013) reported that the soil temperature (ST) and moisture level influenced changes in the soil microbial biomass and diversity, affecting litter decomposition. Other studies showed that soil pH and SBD not affect only microbial community dynamics and respiratory characteristics, but also soil enzyme activities; thus, they also affect the litter decomposition process (Batty and Younger, 2007; Zhang et al., 2018). Furthermore, changes in environmental factors may affect the substrate quality of litter, such as the LTN and LTP concentrations, and fundamentally influence the nutrient return between plants and soil (Pena-Pena and Irmler, 2016; Zhong et al., 2017). In summary, these studies provided valuable knowledge of the response of litter decomposition to environmental factors, but there is no unanimous conclusion as to which environmental factors better reflect the LDR (Zhong et al., 2017); therefore, this topic needs further analysis.

The Loess Plateau of China, characterized by severe soil erosion and desertification, is the most degraded and fragmented ecosystem in the world (Shi and Shao, 2000). To control soil erosion and rehabilitate the degraded ecosystem, the Chinese government has launched the Grain to Green Program to transform croplands (with slopes > 25°) into woodlands or grasslands (Deng et al., 2016a; Zhao et al., 2015b). Through decades of effort, a variety of vegetation types with different afforestation ages have been formed here (Zhang et al., 2011). The restoration of vegetation has effectively promoted net primary productivity, and reduced the disturbance caused by anthropogenic activities, which have enabled the improvement of aboveground and belowground ecosystems (C. Zhang et al., 2016a). During the shift in land-use types and afforestation age, the environmental factors and substrate quality must be modified (Ren et al., 2016a), leading to differences in the speed and quantity of nutrient return (Zhang et al., 2010; Zhang et al., 2018; X.X. Zhang et al., 2016b). Variations in the soil physical and chemical characteristics, enzymatic activities, microbial biomass and diversity, and C:N:P stoichiometry during afforestation have been estimated by previous studies (An et al., 2013; Fu et al., 2000; Ren et al., 2017; Zhao et al., 2015a), but information about the effects of land-use types and afforestation age on litter decomposition and soil nutrient dynamics, and their relationship with substrate quality and soil environmental conditions, is still scarce. Such knowledge is important for understanding the essence of nutrient recycling, and for the suitable management and protection of restored ecosystems.

In this study, we hypothesized that the soil nutrient status and litter characteristics change synchronously during afforestation, and that both processes vary with land-use type and afforestation age. In addition, we assumed that litter decomposition is influenced by litter substrate quality and environmental factors, especially the LTN, litter N:P ratio, soil water content (SWC), and soil pH. Moreover, we predicted that C:N:P stoichiometry can be used to evaluate the relationship between soil nutrients and litter properties, especially the N:P ratio. Therefore, the objectives of this study were to (i) evaluate the effects of land-use type and afforestation age on the dynamics of soil and litter characteristics, (ii) determine the responses of litter decomposition to substrate quality and soil environmental factors following vegetation restoration, and (iii) evaluate the relationships between soil nutrient dynamics and litter nutrient and decomposition characteristics during afforestation.

2. Materials and methods

2.1. Study area description

The study area is located in the Gaoxigou catchment of Mizhi County, northern Shaanxi, China (37°39.53′–38°05.51′ N, 109°29.85′–109°49.85′ E), which is in the central area of the Loess Plateau (Fig. 1). The landform of the catchment is characterized by a loess hilly and gully landscape with altitudes ranging from 900 to 1100 m. The soil in this area is extremely erodible Calcaric Cambisol (FAO) that developed from wind-blown loess deposits. This region has a typical temperate semi-arid climate, with an average annual precipitation of 451.6 mm. Over 65% of the precipitation falls from July to September. The average temperature in this area is 8.4 °C, with a mean maximum temperature of 36.6 °C in August and a mean minimum temperature of −26 °C in January. The Gaoxigou catchment, as the earliest pilot project of ecological restoration and management projects in China, began to control soil and water losses to improve the environment by means of building terraced fields, afforestation, artificial grasslands, and other measures since the 1960s. After decades of artificial vegetation restoration, 80% of the basin area has been restored and the catchment environment has improved significantly. Currently, the forestland area has increased significantly, with the main afforestation species being *Robinia pseudoacacia* (Rps), *Caragana korshinskii* (Cko), *Pinus tabulaeformis* (Pta), and *Armeniaca sibirica* (Asi). Certainly,