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Nutrient removal under different harvesting scenarios for larch plantations in northeast China: Implications for nutrient conservation and management

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ABSTRACT

Larch (*Larix* spp.) is a dominant timber species in northeast China. However, compared with the adjacent secondary forests, the soil nutrient conditions in the 40-year-old larch plantations have significantly deteriorated. Moreover, large quantities of nutrients are removed from sites when larch plantations are harvested, leading to further depletion of soil nutrients. Therefore, it is essential to assess nutrient removal under different harvesting scenarios to improve nutrient management. In this study, we quantified biomass and nutrient (including macro-nutrients: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg), and micro-nutrients: iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn)) accumulation in above- and below-ground components along a chronosequence (10-, 21-, 34- and 55-year-old, respectively) of larch plantations in northeast China. Our results showed that the root/shoot ratio was 0.23, 0.12, 0.18 and 0.24 in the 10-, 21-, 34- and 55-year-old stands, respectively, with an average of 0.19. For each larch tree thinned in the 10- and 21-year-old stands or harvested in the 34- and 55-year-old stands, 173.6, 1197.3, 1878.1 and 4230.7 g of nutrient elements were removed from the sites, respectively. If the leaves, branches, bark and roots remained at the sites, nutrient removal was reduced by 89, 69, 59 and 44% in the 10-, 21-, 34-, and 55-year-old stands, respectively. Branches and leaves contained the largest proportion of nutrients in the 10- and 21-year-old stands, and should thus remain at the sites to avoid further nutrient removal during early thinning. In contrast, debarking stems was a feasible practice when clear-cutting the 34- and 55-year-old stands because bark contained large amounts of nutrients (especially N, P and K). Substantial proportions of the macro-nutrient N and the micro-nutrient Zn were accumulated in the stems, and thus, these two elements would become depleted after harvesting. Except for the stems, macro-nutrients (N, P and K) were mainly stored in the leaves of the 10- and 21-year-old stands and the bark and roots of the 34- and 55-year-old stands, By contrast, macro-nutrients (Ca and Mg) and micro-nutrients (Fe, Mn, Cu and Zn) were primarily concentrated in the branches and roots of all tested stands. Therefore, nutrient loss may be avoided by leaving the harvested components containing specific nutrients at the sites.

1. Introduction

Plantation forests are increasing worldwide (FAO, 2010). In China, the current area occupied by plantation forests has reached 6.9×10^7 ha and accounts for 36% of the total national forest area (Chinese Ministry of Forestry, 2014). Larch (*Larix* spp., mainly including *L. olgensis*, *L. principis-rupprechtii*, and *L. kaempferi*) is the dominant timber species of plantation forests in northeast China (Zhu et al., 2008, 2010; Mason and Zhu, 2014) and has been planted because secondary forests cannot meet increasing timber demands (Yang et al., 2013). The area of larch plantations in northeast China has reached 2.61×10^6 ha and accounts for 85% of the total area of larch plantations in China (Chinese Ministry of Forestry, 2014). Larch plantations provide a large proportion of the timber supply and carbon (C) sequestration (Yan et al., 2014; Gao et al., 2016). However, compared with adjacent secondary forests, the soil nutrients of ca. 40-year-old larch plantations have dramatically declined (e.g., ~30% of soil available nutrients) due to the

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single species composition and mono-silviculture systems used in these plantations (Yang et al., 2013). Wang et al. (2014) found evidence of nutrient depletion in the deep-layer soils of larch plantations in northeast China. Larch plantations are frequently subjected to different harvesting types (e.g., thinning and clear-cutting) and scenarios (e.g., stem-only harvesting and whole-tree harvesting), which can remove large quantities of nutrients with biomass from the sites and thus lead to further depletion of soil nutrients and greater negative effects on long-term productivity (Yan et al., 2014; Gómez-García et al., 2016). Therefore, it is imperative to maintain the soil nutrients of the larch plantations to meet the growing demands for timber supply, bio-energy production and C sequestration.

The biomass of plantations has been of critical importance for economic and ecological requirements (e.g., Egnell, 2011), and the pattern of biomass allocation between above- and below-ground plant components affects plant growth, biogeochemical cycling and ecosystem function (Peichl and Arain, 2006; Peri et al., 2010; Uri et al., 2014). Although root biomass accounts for a substantial proportion of the total forest biomass, the below-ground components (i.e., entire root systems) are rarely evaluated due to the great complexity of extracting roots (Augusto et al., 2015; Addo-Danso et al., 2016). Therefore, biomass and/or nutrient accumulation in roots have often been neglected or roughly estimated from root/shoot (R/S) ratios (Mokany et al., 2006; Uri et al., 2014). Such neglect or rough estimation of root systems may lead to considerable uncertainties in determining biomass and nutrient accumulations (Peichl and Arain, 2006; Luo et al., 2012).

In stem-only harvesting (SOH), only the stems are harvested, and the logging residues (leaves, branches and treetops) remain on-site. By contrast, whole-tree harvesting (WTH) removes both stems and logging residues from a site (Palviainen and Finér, 2012; Merilä et al., 2014; Nieminen et al., 2016). Moreover, root removal is becoming increasingly prevalent because of the growing demands for biomass as a renewable energy source (Augusto et al., 2015; Uri et al., 2015). Obviously, different harvest scenarios (e.g., SOH, WTH, and WTH + root harvesting) remove different amounts of nutrients along with biomass harvesting (Merilä et al., 2014; Nieminen et al., 2016). For example, Strömgren et al. (2013) reported that the combined harvesting of stems and slash would cause 2–4 times more N removal than conventional SOH. Therefore, the knowledge of nutrient accumulation and allocation to different components is essential for nutrient management and for the optimization of harvesting. Consequently, appropriate tree harvest management is of great importance for the sustainability of site productivity in plantations (Merilä et al., 2014; Achat et al., 2015).

Biomass allocation and nutrient concentrations of different components exhibit age-related changes (Peri et al., 2006, 2010). Thus, knowledge of the development of both above- and below-ground biomass over the life cycle of larch plantations is imperative for the accurate quantification of biomass and nutrient accumulation, which will allow for more reasonable decisions in terms of forest management. Although a few studies have reported the biomass and nutrient accumulation patterns in larch plantations, these studies were not based on a destructive sampling methodology, especially including the below-ground components, along a chronosequence.

In this study, we quantified the accumulation and distribution patterns of biomass and nutrients (i.e., macro-nutrients: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg); micro-nutrients: iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn)) in both above- and below-ground components of larch plantations along a chronosequence (10-, 21-, 34- and 55-year-old) in northeast China. The objectives of the present study were as follows: (i) to assess the nutrient removal coupled with biomass under seven harvesting scenarios (stem-only harvesting, stem-wood without bark harvesting, stem + branch harvesting, stem + root harvesting, stem + branch + root harvesting, WTH, and WTH + root harvesting); and (ii) to determine the optimum harvesting rotation for larch plantations to guide the nutrient conservation and management of larch plantations.

2. Materials and methods

2.1. Study site

This study was conducted at the Qingyuan Forest CERN (Chinese Ecosystem Research Network), Chinese Academy of Sciences, in the mountainous region of Liaoning Province, China (latitude 41°51′N, longitude 124°54′E, elevation 500–1100 m above sea level). The region has a continental monsoon climate, with a humid and rainy summer and a cold and dry winter. The mean annual air temperature varies from 3.9 to 5.4 °C and the minimum and maximum air temperatures are −7.6 and 36.5 °C in January and July, respectively. The annual precipitation ranges from 700 to 850 mm, of which 80% occurs from June to August. The mean annual frost-free period is 130 days, with an early frost in October and late frost in April (Zhu et al., 2007).

Since the 1960s, patches of secondary forests have been cleared and replaced with larch plantations, thereby forming a mosaiked larch plantation-secondary forest landscape (Yang et al., 2013; Mason and Zhu, 2014). *Larix* spp. (mainly including *L. olgensis*, *L. principis-rupprechtii*, and *L. kaempferi*) have been widely planted since then and have become the most important commercial timber species in northeast China (Mason and Zhu, 2014), representing 65% of the conifer plantations in these areas (Wang et al., 2006). Larch plantations mainly consist of *Euonymus alatus*, *Acanthopanax senticosus*, *Ribes mandshuricum* and *Rhamnus davurica* in the shrub layer and *Paris verticillata*, *Carex siderosticta* and *C. callitrichos* in the herbaceous layer.

2.2. Sampling and measurements

Four stands of larch plantations in a chronosequence (10-, 21-, 34- and 55-year-old) were randomly selected within the Qingyuan Forest CERN. Each stand was monospecific and even-aged. The average tree heights were 7.2, 18.2, 21.3 and 23.8 m, the average diameters at breast height (DBHs) were 6.3, 15.3, 17.3 and 25.6 cm, and the average tree densities were 4725, 1967, 1292 and 500 trees ha^{-1} for the 10-, 21-, 34- and 55-year-old stands, respectively. All four stands shared similar environmental conditions, soil types and previous land uses, varying only in the age of the plantations. Specifically, the distance between any two stands was less than 2.3 km to reduce the influences from site conditions (Sun et al., 2016). Thus, all the four stands had similar climate and micro-environmental conditions. Besides, all the four stands were located at the well-drained middle slope position, with slopes ranging from 13 to 17° and elevations ranging from 462 to 615 m above sea level, and thus similar topographical conditions. The soils of the four stands were typical brown forest soils, which were classified as Udalfs according to the United States Department of Agriculture soil taxonomy (second edition), with 25.6% sand, 51.2% silt, and 23.2% clay on average (Yang et al., 2013), and soil depth was 50–60 cm. Additionally, all the four aged larch plantations were in their first rotation, and were developed by replacing the secondary forests. Therefore, the conditions were appropriate for our chronosequence study. Three plots (20 m × 20 m) were randomly established within each stand. The DBH and tree height of all individual trees in each plot were