Science of the Total Environment 651 (2019) 2068–2079

Contents lists available at ScienceDirect

Science of the Total Environment

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

Microbial biomass and enzymatic responses to temperate oak and larch forest thinning: Influential factors for the site-specific changes

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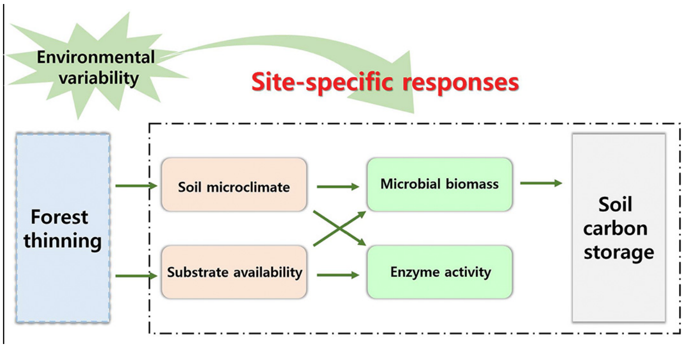
HIGHLIGHTS

- Microbial biomass and enzyme activity respond to thinning differently across sites.
- Thinning effects on soil properties lead to the site-specific microbial responses.
- Shifts in soil carbon storage depend on the microbial biomass response to thinning.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 September 2018
Received in revised form 10 October 2018
Accepted 11 October 2018
Available online 11 October 2018

Editor: Elena Paoletti

Keywords:
Enzyme activity
Forest management
Response ratio
Soil carbon storage
Thinning intensity

ABSTRACT

Microbial biomass and enzyme activity are essential for ecosystem function in managed forests; however, uncertainty remains because microbial biomass and enzymatic responses to thinning highly differ with case studies. This study addressed the drivers for the site-specific responses of microbial biomass and enzyme activity to thinning. Study sites included two oak and three larch forests; each had un-thinned control, intermediate thinning (15–23% basal area reduction), and heavy thinning treatments (30–44% basal area reduction). Soil properties (temperature, water content, pH, total and inorganic nitrogen, and total carbon/nitrogen ratio), microbial biomass, enzyme (β-glucosidase, *N*-acetylglucosaminidase, leucyl aminopeptidase, acid phosphatase, and phenol oxidase) activity, and soil carbon storage were determined 6 years after thinning. Compared to the control, microbial biomass carbon and nitrogen were higher under the intermediate and the heavy thinning by 13.9 and 24.4% and 11.5 and 29.9% at one oak forests, respectively, and higher under the intermediate thinning by 53.7 and 70.7% at one larch forests. There were the post-thinning changes in leucyl aminopeptidase activity by −46.9% and by 150.0–210.0% at an oak and larch forest, respectively, acid phosphatase activity by 60.0% at one oak forest, and phenol oxidase activity by 355.0% at one oak forest. The effect sizes of thinning for soil properties explained 94% and 77% of variance of the effect sizes for microbial biomass and enzyme activity. Especially, the effect sizes for soil water content, NH_4^+, total carbon/nitrogen ratio, and temperature were the most influential. Furthermore, the effect size for soil carbon storage was parabolically related to the effect size for microbial biomass carbon ($R^2 = 0.66$). These findings highlight that inconsistent thinning effects on soil properties varied microbial biomass and enzymatic responses to thinning, which differentiated the change in

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https://doi.org/10.1016/j.scitotenv.2018.10.153

soil carbon storage across sites. Future studies should consider such inconsistencies when examining the effects of forest management.

1. Introduction

Thinning is a common forest management practice around the world to remove suppressed trees and sustain forest structure. The consequences of thinning have been a primary interest in forest ecology dating back to when the consideration of forest management first became active (Fernow, 1911). The majority of traditional forest thinning researches has sought optimal practices to increase tree crop yield, and has focused on tree growth response to thinning (Zeide, 2001). However, other topics, such as carbon and nutrient cycles, have been combined with the current forest thinning researches to consider climate change and carbon sequestration (Bastida et al., 2017; Zhang et al., 2018).

Microbes are the principal components of carbon and nutrient dynamics in the soil. Microbial biomass can potentially act as available carbon and nutrient sources in the soil due to fast turnover (Bonde et al., 1988). The accumulation of microbial biomass includes the synthesis of recalcitrant by-products using labile carbon sources, and it can enhance the stabilization of soil organic matter (Sollins et al., 1996). Meanwhile, enzymes secreted by soil microbes catalyze the degradation of soil organic matter and depolymerize carbon and nutrient sources (Deng and Popova, 2011; Sinsabaugh, 2010). Enzyme activity in the soil is an early indicator of soil fertility because enzymatic depolymerization is the major process that results in plant-available nutrients from soil organic matter (Schimel and Bennett, 2004; Sinsabaugh et al., 2008). Studying microbial biomass and enzyme activity is important for elucidating the management impacts on forest carbon storage, given the close interaction among the enzymatic degradation of soil organic matter, the accumulation of microbial biomass, and soil carbon content (Lange et al., 2015; Moorhead et al., 2013).

Thinning potentially shifts microbial biomass and enzyme activity. Thinning creates canopy openings that allow additional light and precipitation to arrive on the forest floor (Pang et al., 2016; Trentini et al., 2017), and reduces the loss of soil water through transpiration at a stand-scale (Gebhardt et al., 2014). Thinning can also accelerate the turnover of fine roots (Asaye and Zewdie, 2013; Shen et al., 2017), produce unharvested residues (Kim et al., 2018a; Smolander et al., 2015), and decrease litterfall under the canopy opening (Schliemann and Bockheim, 2014). These changes in microclimate and substrate availability affect microbial biomass and enzyme activity, which can, in turn, cause alterations in the soil carbon balance and storage after thinning. For example, the growth of microbial biomass after thinning can encourage both the retention of soil carbon by converting labile organic compounds to recalcitrant metabolites (Settineri et al., 2018) and the loss of soil carbon through the heterotrophic soil respiration (Pang et al., 2016). Moreover, stimulated soil enzymes in thinned forests catalyze the biodegradation of litters and slashes that can be further humidified into the stable soil organic carbon pool (Waldrop et al., 2003; Xiao et al., 2018).

Despite the numerous investigations on soil microbes in thinned forests, there is an uncertainty regarding microbial biomass and enzymatic responses to thinning. Previous studies have reported either increase (Chen et al., 2015; Dannenmann et al., 2006; Ma et al., 2018; Pang et al., 2016; Settineri et al., 2018; Shen et al., 2018), decrease (Boerner et al., 2006; Geng et al., 2012; Schilling et al., 1999) or no change in microbial biomass and enzyme activity as a result of thinning (Giai and Boerner, 2007; Maassen and Wirth, 2004; Overby and Hart, 2016; Tan et al., 2008). The inconsistency associated with thinning has been detected not only within a single stand (Chen et al., 2016; Ma et al., 2018), but also over a couple of sites (Dannenmann et al., 2006; Giai and Boerner, 2007; Kim et al., 2018a). Although several studies have attempted to address pre-treatment stand productivity, topography, and thinning intensity as possible drivers for such inconsistencies (Dannenmann et al., 2006; Kim et al., 2018a), little evidence is available to interpret the inconsistent responses of microbial biomass and enzyme activity to thinning across multiple study sites.

The present study tracked microbial biomass and enzymatic responses to the thinning of temperate oak and larch forests, which are important for timber production and mushroom cultivation in this climatic zone (Kim et al., 2015, 2016; H.S. Lee et al., 2018). Our primary hypothesis was that thinning would have the site-specific effects on microbial biomass and enzyme activity due to differing microclimate and substrate availability. The present study contained two oak and three larch forests that received three levels of thinning intensities to identify the factors that influence microbial biomass and enzymatic responses to thinning throughout these forest ecosystems. Especially, our experimental design considered variation in the location and topography, which are regarded to control the magnitude and direction of the thinning effects as well as soil and climatic conditions (Dannenmann et al., 2006; Kim et al., 2018a, 2018b). We also assessed whether the microbial biomass and enzymatic responses to thinning contributed to the site-specific alteration in soil carbon storage after thinning, which has been observed in a previous study (Kim et al., 2018b).

2. Materials and methods

2.1. Studied forests

The present study utilized two oak (HCO and YYO) and three larch (GNL, IJL, and MFL) forests in South Korea. The forests were under a temperate climate with hot, humid summers and cold, dry winters. The overstory of the two oak forests were dominated by naturally regenerated oak (*Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.), while that of the three larch forests were governed by artificially planted Japanese larch (*Larix kaempferi* Lamb.) (Table 1). The understory contained *Q. mongolica*, *Lindera obtusiloba* Blume, *Pteridium aquilinum* (L.) Kuhn, *Zanthoxylum schinifolium* Sieb. et Zucc., *Ulmus laciniata* (Trautv.) Mayr, and *Lespedeza bicolor* Turcz. at HCO (Kim et al., 2015), *Q. mongolica*, *Rhus trichocarpa* Miq., *Pinus koraiensis* Sieb. et Zucc., and *L. obtusiloba*, at YYO, *Cornus controversa* Hemsl., *Styrax obassia* Sieb. et Zucc., *L. obtusiloba*, and *Carpinus laxiflora* Sieb. et Zucc. at GNL, *L. obtusiloba*, *Lespedeza bicolor* Turcz., *Kalopanax septemlobus* (Thunb.) Nakai, *P. koraiensis*, and *Quercus serrata* Murray at IJL, and *Acer pseudosieboldianum* (Pax) komarov, *C. controversa*, *L. obtusiloba*, *S. obassia*, *Q. mongolica*, and *Q. serrata* at MFL (Kim et al., 2016). The soil at the studied forests was typically a dry brown forest soil type (B1) in accordance with the forest soil nomenclature of South Korea (Kim et al., 2018b). This forest soil type generally occurs on well drained mountainsides and features acidic and dry soil conditions. The forests under each forest type principally varied in topography (altitude and slope), which potentially affects soil properties and microclimate (Table 1). While HCO, YYO, GNL, and IJL were established in the central area of the Korean peninsula, MFL was located in the southern area (Fig. 1).

The forests consisted of three stands; each had three circular plots that had 9–12 m radius to account for differences in the forest area (YYO and MFL: 6 ha GNL and IJL: 5 ha; HCO: 1.5 ha). Plots were installed