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The effects of forest thinning on soil carbon stocks and dynamics: A meta-analysis

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ABSTRACT

Forest thinning is widely used in forest management activities and has complex effects on underground carbon processes. Although many case studies have been done, how forest thinning affects soil carbon stocks and dynamics remains unclear, especially at different recovery stage. Here, we synthesized the results from 53 peer-reviewed publications and conducted a meta-analysis to evaluate the general responses of 10 variables related to forest soil carbon stocks and dynamics to forest thinning management. Overall, we did not find remarkable effects of thinning on soil moisture, fine root biomass and soil carbon stocks (including soil total carbon, soil organic carbon and microbial biomass carbon). However, thinning resulted in a significant reduction in litterfall production (−23.7%), while significantly increasing soil temperature (+8.7%) and soil respiration (+29.4%) in general. In particular, the effect of forest thinning on soil respiration was significant in light (thinning intensity < 33%) to moderate (33–67% of thinning intensity) thinning. In the early stage of recovery (≤2 yr after thinning), this effect was also significant. Thinning significantly increased soil respiration in both broadleaved (+35.6%) and mixed forests (+9.3%) but not in coniferous forest due to the difference of litterfall quality. These results provide a synthetic review of the effects of forest thinning on soil carbon stocks and dynamics and may help to improve forest management strategies.

1. Introduction

Forest soils contain a large amount of carbon and play an important role in the global carbon cycle (Dixon et al., 1994). As forest soil respiration is one of the major sources of atmospheric carbon (Davidson and Janssens, 2006), small changes of soil carbon and/or soil respiration can influence the strength of the global carbon cycle. In forest ecosystems, human disturbances, such as forest management practices, could largely affect soil carbon stocks and soil carbon emission (Foote et al., 2015; Cheng et al., 2014). Therefore, quantitative evaluation of the effects of forest management practices on soil carbon stocks and dynamics is critical for understanding the terrestrial ecosystem carbon cycle.

Forest thinning has been found to enhance wood production, regulate stand structure, decrease severe wildfire events, and increase forest resilience to environmental disturbances particularly during drought (Makinen and Isomaki, 2004; Sohn et al., 2016; Wang et al., 2017), and is thus an important silvicultural practice widely-used in forest management. In addition, thinning alters the microclimate, surface energy balance, litterfall input, fine root density, nutrient budgets, the composition of soil microbial community and their activities. For example, more litterfall, woody debris, and dead root biomass induced by forest thinning initially change substrate availability, soil enzymatic activity, carbon mineralization and nitrogen mineralization (Adamczyk et al., 2015). Because thinning opens the forest canopy, which makes it easy for the forest floor to receive more solar radiation during the daytime but loses more longwave radiation during the nighttime, daily variations of soil temperature increase, further stimulating microbial activities and litterfall decomposition (Misson et al., 2005). Therefore, forest thinning influences soil carbon stocks and dynamics in both direct and indirect ways (Ma et al., 2004; Tian et al., 2010; Olajuyigbe et al., 2012; Baena et al., 2013; Cheng et al., 2015).

A previous meta-analysis by Zhou et al. (2013) addressed the impacts of partial cutting on both aboveground and mineral soil carbon stocks but did not consider the changes in soil organic carbon (SOC), microbial biomass carbon (MBC), litterfall production, fine root

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Fig. 1. The distribution of forest thinning experiments selected in this meta-analysis.

biomass, and soil respiration after thinning. More importantly, it did not cover the evolution dynamics of carbon stocks after thinning. Generally, forest thinning significantly decreases litterfall production and fine root biomass at first, due to the removal of plant photosynthetic biomass. However, fine root biomass increases after recovery, and this negative effect is short-lived. Soil total carbon and SOC stock are determined by carbon input and decomposition, mineralization and leaching. Zhou et al. (2013) found that partial cutting did not show significant effect on mineral soil carbon stock.

Furthermore, no consensus has emerged in regard to the influence of forest thinning on soil CO_2 flux (Laporte et al., 2003; Cheng et al., 2014). Some studies reported positive effects (Londo et al., 1999; Cheng et al., 2015; Shabaga et al., 2015), while others found no influence (Ma et al., 2004; Vesala et al., 2005; Kobziar, 2007; Campbell et al., 2009) or even negative ones (Son et al., 2004; Tang et al., 2005; Sullivan et al., 2008). These effects are also found to be of different magnitudes and even directions, while the level of thinning intensity is found to be highly related (Cheng et al., 2015; Baena et al., 2013).

Finally, how soil carbon stocks and dynamics respond to forest thinning at different recovery stages is still unclear, due to the lack of synthetic analysis on the experimental data. In addition to thinning intensity and recovery time, forest types (broadleaved, coniferous and mixed forest) was also found to play an important role in soil carbon stocks and dynamics due to the differences in litter quality and soil physical and chemical properties among different forest types (Nave et al., 2010; Zhou et al., 2013). Therefore, a comprehensive evaluation of soil carbon stocks and dynamics response to forest thinning among different thinning intensities, recovery stages and forest types is needed to improve understanding of underground carbon stocks and dynamics in forest management.

In this paper, we conducted a meta-analysis to reveal the general responses of soil carbon stocks and dynamics to forest thinning. This study is aimed to: (1) identify the general responses of soil carbon stocks (total carbon, SOC, MBC) and dynamics (litterfall production, fine root biomass, soil respiration) after forest thinning; (2) explore the responses of soil carbon stocks to different forest thinning intensities (light, moderate, and heavy), for different forest types (broadleaved, coniferous, and mixed forest) and different recovery stages (early, medium, and late). Given that soil substrate availability increases immediately after forest thinning, we hypothesize that forest thinning increases soil respiration and soil total carbon or SOC in general, and the increase of soil respiration mainly occurs at the early stage of recovery.

2. Materials and methods

2.1. Data collection

We searched the Web of Science before March 2018 using the following key words: “selective cutting” or “thinning” or “partial thinning” or “harvesting” or “silvicultural treatment” or “management treatment” and “forest carbon stock”. The selection criteria were as follows: (1) only field experimental data were selected; (2) the thinning treatment and control plots were established in the same abiotic and biotic conditions; (3) the means, plot replicates, stand deviations or stand errors of control and treatment are clearly reported; (4) only the control and thinning treatment data were used in multifactorial studies.

Four groups of selected variables related to soil carbon stocks, dynamics, and other associated parameters were extracted from publications of forest thinning experiments: (1) soil microclimate (soil temperature and soil moisture at the depth of 5–10 cm); (2) soil carbon stocks properties (SOC, soil total carbon, soil total nitrogen, soil C: N ratio, MBC); (3) soil carbon dynamics (litter production, fine root biomass, soil respiration).

GetData Graph Digitizer 2.24 (http://getdata-graph-digitizer.com) was used if the data were presented as figures in the publication. Thinning intensity was grouped according to the removed fraction of stand basal area, stems or volume. If the original paper used another definition, we converted it to our definition. To analyze the effects of thinning intensities, recovery stages, and forest types on soil carbon stocks and dynamics, each record includes information about location (longitude and latitude), thinning intensities, recovery stages, and forest types (broadleaved, coniferous, and mixed forest). To explore the effects of thinning intensity on soil carbon stocks and dynamics, all thinning intensity data were grouped into three categories: light thinning (< 33% volume, stand basal area or stems were removed), moderate thinning (33–67% volume, stand basal area or stems were removed), and heavy thinning (≥67% volume, stand basal area or stems were removed). We further divided recovery time into three stages: early stage (≤2 yr after thinning), medium stage (> 2 and ≤5 yr) and late stage (> 5 yr after thinning).

A total of 404 observations from 53 peer-reviewed publications were compiled. This compiled dataset covers a latitude from 27.23°S to 56.77°N, mean annual temperature from -3°C to 24.2 °C, mean annual precipitation from 282 mm to 2507 mm and recovery time from 0 to 40 years. Study sites included in this meta-analysis are shown in Fig. 1.