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A meta-analysis of soil microbial biomass levels from established tree plantations over various land uses, climates and plant communities

Qian Zhang [a,b], Junjie Yang [c], Roger T. Koide [d], Tao Li [e], Haishui Yang [f,*], Jianmin Chu [a,b,**]

[a] Research Institute of Forestry, Chinese Academy of Forestry, Beijing 100091, China
[b] Key Laboratory of Tree Breeding and Cultivation, State Forestry Administration, Beijing 100091, China
[c] State Key Laboratory of Forest and Soil Ecology, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[d] Department of Biology, Brigham Young University, Provo, UT 84602, USA
[e] Terrestrial Ecology Section, Department of Biology, University of Copenhagen, Universitetsparken 15, DK-2100 Copenhagen, Denmark
[f] Key Laboratory of Crop Physiology, Ecology and Production Management, Ministry of Agriculture/College of Agriculture, Nanjing Agricultural University, Nanjing 210095, China

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ABSTRACT

Uncertainties remain as to the potential for tree plantations to affect soil microbial biomass. Our aim was to determine the factors accountable for the maintenance and the increase of soil microbial biomass following tree plantation. Based on mixed effect models, we conducted a meta-analysis with three fixed and two random factors to test the impact of tree plantation on soil microbial biomass. Previous land use was more important than climate or plant species in its effect on soil microbial biomass after tree plantation. There was a positive impact on soil microbial biomass for tree plantations on bare land but a negative impact for which on previously forested land. Climate and plant species were found to be not as important in their effects on soil microbial biomass. Our meta-analysis gives a general pattern that previous land use type is the major controlling factor of soil microbial biomass following tree plantations and promotes our understanding of the effects of rehabilitation of degraded sites on vegetation recruitment.

1. Introduction

Forest ecosystems cover approximately 40% of Earth's ice-free, terrestrial surface (Waring and Running, 2007) and tree plantations comprise approximately 5% of this area (FAO, 2002; Häggman et al., 2013). Deforestation, the removal of forest cover as a result of human activities, has resulted in many serious environmental problems, e.g., flooding and soil erosion, loss in soil carbon storage and habitat destruction for wildlife, etc. (Bhagwat et al., 2008; Godar et al., 2015; Jandl et al., 2007; Lindenmayer and Hobbs, 2004). Such degraded lands need proper ecological rehabilitation through which soils can be managed to support biological productivity. Plantation forestry is a method by which degraded sites can be rehabilitated to previous levels of productivity. There is a global trend of an increasing tree plantation surface throughout the world from 140 million hectares in 2005 to over 180 million hectares by 2020 (FAO, 2006). Tree plantations showed much positive effects on provision of ecosystem services (Ray et al., 2015), e.g., providing refuge for wildlife (Bhagwat et al., 2008; Lindenmayer and Hobbs, 2004), increasing carbon sequestration (Livesley et al., 2009), reducing natural disasters, such as flooding and soil erosions (Chirino et al., 2006), and producing woods for industry. As the support of forest ecosystem, soils are sensitive and vulnerable to forest degradation and deforestation. The most obvious forms of soil degradation in forest areas include nutrient depletion, soil erosion, etc. As soils are vulnerable to loss in aboveground biomass and diversity (e.g. de-forestation), it is important to elucidate factors affecting soil microbial biomass, a small but sensitive component of soil, following variations in aboveground biomass and diversity.

Soil organic matter has an important impact on all soil functions and plays a central role in the global carbon cycle (Blume et al., 2016; Karmakar et al., 2016). Microbial biomass is the most active fraction of soil organic matter (Cuevas et al., 2013; Jenkinson and Ladd, 1981; Singh et al., 1989). In nearly all ecosystems, microorganisms are responsible for most of the respiration and a large portion of the nutrient cycling. Microorganisms are generally considered the driving force behind litter decomposition processes (DeAngelis et al., 2013a; Smith and Paul, 1990). They act as both a source and a sink for available nutrients (Diaz-Ravina et al., 1993; Smith and Paul, 1990) and play a major role in numerous ecosystem functions, such as organic matter turnover, nitrogen cycling, nutrient mobilization/immobilization, humification, degradation of pollutants and maintenance of the soil structure (DeAngelis et al., 2013b; Lejon et al., 2005; Moller et al., 1999; Preston et al., 2001; Stevenson, 1982). Measurement of soil microbial biomass can give an early indication of changes in total soil organic matter long

* Correspondence to: H. Yang, College of Agriculture, Nanjing Agricultural University, No.1, Weigang Road, Xuanwu District, Nanjing 210095, China.
** Correspondence to: J. Chu, Research Institute of Forestry, Chinese Academy of Forestry, Beijing 100091, China.
E-mail addresses: yanghaishui@njau.edu.cn (H. Yang), cjmcaf@163.com (J. Chu).

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before changes in total soil C or N can be reliably detected (Powlson et al., 1987).

The effect of tree plantations on soil microbial biomass carbon (MBC) has previously been documented (Jesus et al., 2009; Smith et al., 2015), but the process remains poorly understood. Tree plantations have been found to have positive (Yao et al., 2006), negative (Cao et al., 2008) or no effects on soil MBC (Sparling et al., 1994). The inconsistent results from individual studies likely arise because the magnitude and direction of the change in soil microbial biomass are affected by multiple factors including climate, previous land use and tree species, etc. In order to better understand how and why tree plantation affects soil microbial biomass, it is undoubtedly necessary to determine the general patterns and the major controlling factors of soil microbial biomass.

To our knowledge, there has been no meta-synthesis exploring the effects of tree plantations on soil MBC. In this study, field trials with a paired-site design were analyzed using a meta-analytical approach to quantitatively synthesize the soil MBC patterns in response to afforestation. Our objective was to explore whether there is a general pattern of soil MBC response to tree plantations. We hypothesized that the response of SMB to tree plantations depends on previous land use type, climate and the identity of trees planted. In order to test this hypothesis, we performed a meta-analysis with multi-factor statistical models which simultaneously estimate the relative magnitude of the effects of multiple predictor variables.

2. Materials and methods

2.1. Study selection

The literature available on changes in soil microbial biomass following tree plantations was compiled. In this study, tree plantation includes both afforestation and reforestation, in which 'afforestation' refers to the establishment of a plantation (from seedlings or seeds) on treeless land, and reforestation is the intentional restocking of existing forests and woodlands that have been depleted. Natural regeneration without human intervention was excluded. The term 'treeless land' includes croplands used for food or fibre production, permanent pasture, natural grassland, and shrub and barren land. We only included studies which reported soil microbial biomass before and after tree plantations. Only studies including first-rotation plantations after the change in land-use were utilized.

Databases from Blackwell, CNKI, Elsevier, Kluwer, JSTOR, Springer and Web of Science were searched for source data from January 1990 to August 2011 with the terms (afforestation OR reforestation OR plantation) AND microb*. In total, the dataset included 199 trials reported by 31 publications (see Appendix S1 and S2). Data presented in tables were directly extracted; graphed data was digitized with GetData software (http://getdata-graph-digitizer.com/). For each paper, the following information was compiled: sources of data, climate zone, previous land use, tree species, plantation age and soil sampling depth. When more than one depth was sampled in one specific study, soil microbial biomass at each depth was considered to be nested within the study, and treated as a random factor in the meta-analysis. When a particular chronosequence or retrospective study had observations at a number of plantation ages, each age was regarded as being nested within the study, and treated as a random factor in the meta-analysis.

2.2. Data category

We selected the following potential variables which might affect soil microbial biomass after tree plantations: (1) previous land use; (2) climatic zone; (3) tree species planted; (4) sampling depth and (5) plantation age. Previous land use type was grouped into barren land, natural forest, shrubland, pasture, grassland and cropland. Barren land is defined when the publication recorded it as "barren land", an area with little or no vegetation due to high winds, harsh climate, salt spray, infertility or toxic soil, or overexploitation by human. Climatic zones were classified into tropical, subtropical, temperate monsoon, temperate marine, temperate continental, Mediterranean and plateau (Laganiere et al., 2010). Tree species planted were categorized into pine, *Eucalyptus*, coniferous excluding pine and broadleaf excluding *Eucalyptus*. Tree species were selected according to the methods described by Laganiere et al. (2010).

2.3. Data analysis

Soil microbial biomass carbon (MBC) was the most commonly reported measure of soil microbial biomass response to tree plantation in our analyses. Therefore, we used soil MBC to represent soil microbial biomass. For each experimental comparison between tree plantation and control, we calculated an effect size for soil microbial biomass carbon based on mean values. Especially, the effect size was calculated as the log response ratio of soil MBC in the tree plantation and control: ln (Xi/Xn), where Xi is the mean soil microbial biomass carbon in the plantation treatment and Xn is the mean biomass in the corresponding control. This metric is positive if tree plantation increased soil microbial biomass carbon, and negative if it decreased soil microbial biomass carbon.

The MIXED procedure was used with restricted maximum likelihood estimation of parameters in SAS (SAS v. 9.1; SAS Institute, Inc., Cary, NC, USA). The overall weighted mean effect size (i.e. the log response ratio of soil microbial biomass carbon to tree plantation) and random between-studies variance component (sensu van Houwelingen et al., 2002) were estimated with a pure random-effects model. Each effect size estimate was weighted by the reciprocal of the within-study variance (which was estimated as the summed number of replicates in control and tree plantation) plus the maximum likelihood estimate of the residual between-studies variance component. This weighting method was used in lieu of the actual estimated effect size variance from each study, because most studies reported the levels of replication rather than the actual measures of variance (SD, SE or confidence intervals) which could be used to calculate variance (Hoeksema et al., 2010). Thus, we assumed higher levels of replication could provide more precise estimates of effect size and those studies were given higher weight in the meta-analysis. Since this variable can now be compared between different sites and different studies, a mixed linear model (PROC MIXED) was developed, including three factors as fixed explanatory variables (previous land use, climatic zone, species planted; MODEL statement) and two factors as random variables (sampling depth, plantation age; RANDOM statement). By adding these random variables to the model, we can control their effects on the dependent variable.

3. Results

3.1. Previous land use

The land use history before tree plantation significantly affected soil microbial biomass ($F = 27.62$, $P < 0.01$; Table 1; Fig.1). Tree plantations significantly increased soil microbial biomass in barren land ($t = 3.57$, $P < 0.01$), but significantly decreased soil microbial biomass beneath the forest ($t = -2.44$, $P < 0.01$). However, no significant effects were found in pasture, woodland, grassland or cropland ($P > 0.05$).

3.2. Climate zone

Soil MBC in tree plantations was found not to vary with climate zone ($F = 1.19$, $P = 0.31$, Table 1, Fig. 2). There was a significant effect of tree plantation on soil microbial biomass in the subtropical climate ($t = 2.17$, $P = 0.03$). However, no significant effects were found in temperate monsoon climate, temperate marine climate, plateau climate zone, tropical climate, temperate continental climate and Mediterranean climate zones ($P > 0.05$).