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Predicting soil respiration using carbon stock in roots, litter and soil organic matter in forests of Loess Plateau in China

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A B S T R A C T

Understanding the dominant variables driving soil respiration is critically important for predicting soil CO_2 emission and assessing the carbon balance of forest ecosystems. In a small catchment of the semiarid Loess Plateau in China, soil respiration and soil biophysical factors were studied on sites of five forest types, comprising plots established in a pure *Pinus tabulaeformis* plantation, a pure *Robinia pseudoacacia* plantation, a mixed *P. tabulaeformis* and *R. pseudoacacia* plantation, a pure *Platycladus orientalis* plantation, and a natural *Populus davidiana* stand. Soil temperature at the 10 cm depth was found to be the most predominant factor controlling the temporal pattern of soil respiration, accounting for 11–40% seasonal variation in the rate of soil CO_2 efflux across forest types. By applying an empirical model and the calculated temperature sensitivity of soil respiration (Q_{10}) and the rate of basal soil respiration (R_{10}), annual soil CO_2 emission was estimated separately for each forest type using the automatically monitored data of soil temperature at the 10 cm depth. The annual soil CO_2 emission varied greatly with forest types and ranged from 647.71 g C m^{-2} y^{-1} in the *P. orientalis* plantation to 1448.50 g C m^{-2} y^{-1} in the natural *P. davidiana* stand. Annual soil CO_2 efflux is better predicted by soil organic carbon content and the amount of carbon in roots, litter and top soil than soil temperature when data are pooled for all plots of the five forest types. A first order exponential analysis indicates that about 77% of the variation in annual soil CO_2 efflux is explained by root carbon stock, 63% by the combined carbon stock in roots, litter, and top soil, and 48% by the combined carbon stock in litter and top soil. We conclude that annual soil CO_2 efflux can be predicted by carbon pools in roots and soils rather than by soil temperature in watersheds where spatial variation in soil temperature is relatively small in the semiarid Loess Plateau of China.

1. Introduction

Soil CO_2 efflux from terrestrial ecosystems to the atmosphere has been considered as the second largest global carbon flux, and is the vital component of ecosystem respiration (Raich and Potter, 1995). Estimating the magnitude of CO_2 emitted from soil surface is of critical importance in evaluating the role of ecosystems in the context of global warming, as soil respiration determines the net ecosystem carbon balance. In order to accurately predict soil CO_2 emission in time and space, great progress has been made in identifying the driving biophysical factors of soil respiration in recent decades (Davidson et al., 1998; Buchmann, 2000; Campbell et al., 2004). Yet, as a main biome of China, the Loess Plateau has received little attention, and data on CO_2 emissions are scarce for forest ecosystems in this region (Zhou and Shuangguan, 2009). Quantifying the rate and magnitude of soil CO_2 emission and understanding the dominant environmental constraints of soil respiration are essential for improving our knowledge on the ecological role of forests in the Loess Plateau of China, where it is undergoing the rapid temperature increases in China (Wang et al., 2003).

Soil respiration is a composite process integrating two major carbon fluxes, i.e. autotrophic respiration of plant roots and heterotrophic respiration through soil microbial activities (Janssens and Pilegaard, 2003), and is influenced by multitudes of

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environmental factors during field investigation. To date, most models for predicting the rate of soil respiration has been largely based on the relationship of soil CO_2 efflux with soil temperature, especially in biomes with great fluctuations in temperature (van't Hoff, 1898; Janssens and Pilegaard, 2003; Campbell et al., 2004), as soil temperature often positively correlates with soil respiration and accounts for its temporal variation across a wide range of circumstances (Buchmann, 2000). Compared to soil temperature, soil moisture maintains a less clear relationship with soil respiration because either excess or deficit in soil water content may constrain the rate of soil respiration in a temperate region (Vincent et al., 2006). Empirical models may be modified by incorporating the parameter of soil water content when predicting soil respiration under specific conditions with optimal soil water content (Vincent et al., 2006).

The confounding effects of soil temperature and moisture prohibit the widespread use of the empirical models established for specific sites in estimating soil CO_2 emissions across different biome types (Davidson et al., 1998). Therefore, much effort has been directed at understanding the role of other biophysical factors in controlling soil respiration (Janssens et al., 2001). Vegetation type was proven a predominant factor affecting soil respiration through modification of soil chemical and physical properties (Boudot et al., 1986), control of the quantity and quality of plant litter inputs (Epron et al., 2004), and effects of plant roots and associated microbial activities (Janssens et al., 1998). Many studies have found positive relationships of soil respiration with forest floor mass, soil carbon content and fine root biomass, and the spatial variation in soil respiration across different vegetation types can be well explained by the empirical models based on these variables (Søe and Buchmann, 2005; Wang et al., 2006). It is evident that soil temperature plays a predominant role in the spatial variations of soil respiration across sites of climatically contrasting environments (Campbell et al., 2004), but on a local scale or under the same climatic conditions, other biological and biophysical factors, such as vegetation type, stand structure and development, and the size and quality of various organic carbon pools, may prevail as dominant drivers of soil respiration (Campbell et al., 2004; Epron et al., 2006). Substrate quantity and quality have been shown to affect the Q_{10} in forests and grassland ecosystems (Campbell et al., 2004; Xiao et al., 2007), greatly modifying the soil respiration–temperature relationship when substrate supply is limiting. Therefore, reassessment of controlling factors of soil respiration is necessary for biomes with highly specialized climatic and environmental conditions, such as the Loess Plateau.

The Loess Plateau in China is characterized by arid and semiarid climate and severe aeolian erosions (Zhang et al., 2011). Plant root growth and vertical transport of organic matter are highly prohibited due to soil compaction and high clay content. On most forest sites, development of forest floor litter layer and soil organic matter are very poor because of restricted root growth and high surface runoff. It is of typical conditions of substrate limitation to soil respiration. To determine the control of biotic and environmental factors on soil respiration in forests of the Loess Plateau, we conducted an experiment within a hilly catchment in Shanxi province of China and investigated seasonal variations of soil CO_2 efflux across five forest types, i.e. a pure *Pinus tabulaeformis* plantation, a pure *Robinia pseudoacacia* plantation, a mixed *P. tabulaeformis* and *R. pseudoacacia* plantation, a pure *Platycladus orientalis* plantation, and a natural *Populus davidiana* stand. Two major objectives were addressed in this study: the first was to quantify the magnitude of annual soil CO_2 emission under different forest cover types; the second was to identify the role of selected biophysical variables, e.g. carbon pools of soil, plant roots, and litter, and soil temperature, in predicting annual soil CO_2 efflux in semiarid Loess Plateau. We predicted that, because of substrate limitation, the variation in annual soil respiration across different forest types could be well explained by the size of various carbon pools in the semiarid Loess Plateau.

2. Materials and methods

2.1. Study sites and experimental design

This study was carried out in the Caijiachuan watershed (latitude 36°14′–36°18′ N, longitude 110°40′–110°48′ E, elevation 904–1592 m a.s.l.) of Jixian in Shanxi province, China. The topography of this watershed is characterized by typical loess gullies and hills, and the soil belongs to loess-derived Cinnamon soil (Bi et al., 2008). Long-term average annual temperature is about 10 °C. Mean annual precipitation is 579.5 mm, almost 80% of which falls between June and August (Fig. 1). Potential annual evapotranspiration is 1724 mm.

Five study sites were selected based on existing natural and experimental forest types in the drainage basin, representing (1) pure *P. tabulaeformis* plantation, (2) pure *R. pseudoacacia* plantation, (3) mixed *P. tabulaeformis* and *R. pseudoacacia* plantation, (4) pure *P. orientalis* plantation, and (5) natural *P. davidiana* forest. All but the *P. davidiana* site were located in the same gully with a similar elevation above the sea (1120 m). The natural *P. davidiana* stand was located in the gully about 4 km southeast of other sites with an elevation of about 1040 m a.s.l. All of the plantations were established in 1993 on the natural slope of Loess Plateau (Zhang et al., 2008), displacing the original natural shrubs. Detailed information for these five sites is shown in Table 1. In early spring of 2008, three plots of 20 × 20 m were established for each forest type, and the plots were spaced at least 10 m apart.

2.2. Forest survey and measurements of root and litter carbon stock

In mid-August 2008, survey was carried out on tree density, height, and stem diameter at breast height (DBH; 1.37 m in height) on each plot. In order to avoid the influence of root sampling on soil respiration, root biomass was determined later in the experiment when the final measurements of soil respiration were completed. Soil cores for root biomass were collected at five locations and every 20 cm to a depth of 100 cm by a handheld cylinder auger of 8 cm in diameter and 20 cm in height on each plot. Plant roots were separated from the cores by washing off the soil within a 0.4 mm mesh bag, and oven-dried at 80 °C to constant weight. Litter

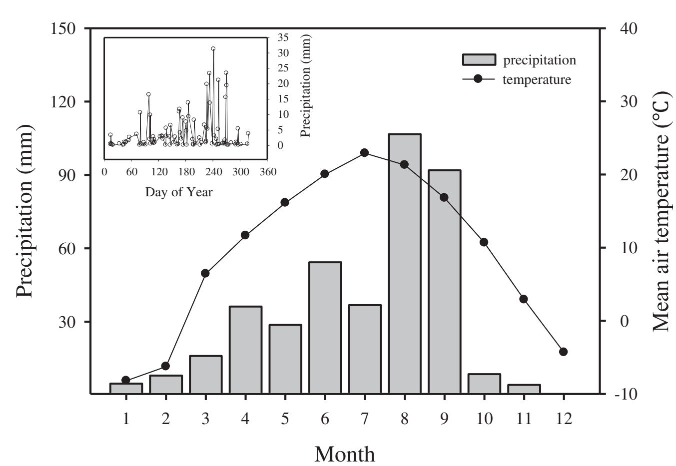

Fig. 1. The meteorological conditions of the studied region during 2008.