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# Stand ages regulate the response of soil respiration to temperature in a *Larix principis-rupprechtii* plantation

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ABSTRACT

Understanding the linkage of soil respiration and its sensitivity to temperature with forest structure including stand age is critical for accurately assessing the impact of afforestation on global carbon balance. In this study, we investigated the changes of soil respiration ($R_S$) and its components (soil heterotrophic ($R_H$) and autotrophic ($R_A$) respiration) in response to seasonal temperature change over three *Larix principis-rupprechtii* plantation stands (10-year-old sapling stand, 20-year-old young stand and 45-year-old mature stand) in North China. We found a significant seasonal variation of $R_S$, $R_H$ and $R_A$ ($P < 0.001$), and significant stand age effect on $R_H$ ($P = 0.004$). Among the three age stands, sapling stand has the lowest $R_H$ during the snow-free season, possibly due to the lowest soil organic carbon. All three stands show that $R_S$ exponentially increases with increasing temperature, and the $Q_{10}$ of $R_H$ (from 2.69 to 3.03) is significantly lower than that of $R_A$ (from 3.06 to 4.39). Furthermore, the $Q_{10}$ of $R_H$ is significantly dependent on stand age. The $Q_{10}$ of $R_H$ at mature stand (3.03 ± 0.09) was substantially higher than that at sapling stand (2.69 ± 0.08), highlighting the importance of stand age in regulating the response of soil respiration to temperature change. We also found that the transient turnover rate of soil organic carbon in sapling stand is significantly faster than those in young and mature stands ($P < 0.001$) due to the highest soil temperature at sapling stand. Such regulations of stand age on soil carbon cycling through abiotic factors must also be taken into account when investigating the effect of plantation on the global carbon cycle.



## 1. Introduction

Soil respiration ($R_S$) is the second largest carbon flux in most terrestrial ecosystems, approximately 50–90% of total ecosystem respiration (Longdoz et al., 2000; Schlesinger and Andrews, 2000). Globally, $R_S$ is estimated to be 80–98 Pg C $yr^{-1}$ (Raich et al., 2002; Bond-Lamberty and Thomson, 2010), which is even higher than the cumulated industrial $CO_2$ emissions by fossil-fuel combustion over the last 10 years (Le Quéré et al., 2009). Furthermore, it has been estimated that global $R_S$ has significantly increased by 0.1 Pg C $yr^{-1}$ over the last two decades (Bond-Lamberty and Thomson, 2010), and will continue to increase in the future and eventually induce an important positive feedback to climate change (Friedlingstein et al., 2006). Thus, understanding the mechanisms that determine changes in $R_S$ is important in global change research, and subsequently the center-piece of many studies (Reichstein et al., 2003; Davidson and Janssens, 2006; Sampson et al., 2007; Peng et al., 2009; Wang et al., 2010a).

Forests compose a major part of terrestrial ecosystems, occupying about 30% of the world's land area. The important role of forest in the global carbon cycle has motivated ecologists to investigate change in $R_S$ and its driving factors. However, most previous studies focused on the effect of climate factors, such as temperature and precipitation, on $R_S$ (e.g. Sampson et al., 2007; Bronson et al., 2008; Maseyk et al., 2008; Laganière et al., 2012; Schindlbacher et al., 2012), and less attention has been paid to examine the linkage of $R_S$ and its components (soil heterotrophic ($R_H$) and autotrophic ($R_A$) respiration) with forest structure, particularly stand age. Accordingly, the effect of stand age on $R_S$ is not parameterized in the most current carbon cycle models (e.g. LPJ, Sitch et al., 2003; ORCHIDEE, Krinner et al., 2005), which

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further limits the capacity to evaluate the role of plantations in the current global carbon balance. Based on a recent global forest resources assessment, the area of global plantation forest is about $1.408 \times 10^8$ ha, and about 30% is distributed in China (FAO, 2006).

Temperature exerts the dominant control over $R_S$ in most forest ecosystems (Hanson et al., 2000). The $Q_{10}$ value, the factor by which $R_S$ is multiplied when temperature increases by 10 degrees, has been estimated to range from 1.81–3.05 (Wang et al., 2010a), depending on the environmental variables. In general, the $Q_{10}$ spatially increases with the decrease in temperature, and with the increase in moisture across large spatial scales (Raich and Schlesinger, 1992; Bahn et al., 2008). A number of recent studies have revealed that the temperature sensitivity of $R_S$ (particularly $R_H$) is also dependent on the substrate quality and availability (Curiel Yuste et al., 2004; Knorr et al., 2005; Conant et al., 2008; Gershenson et al., 2009; Wetterstedt et al., 2010; Subke and Bahn, 2010; Zhu and Cheng, 2011). Moreover, the quantity and quality of the aboveground and belowground detritus, as well as root activity can change with stand age (Bond-Lamberty et al., 2004; Salz et al., 2006). The findings of these studies beg the question: how temperature sensitivities of $R_S$ vary with the forest age. Answering this question is critical to more accurately assessing the impacts of afforestation on global carbon balance.

In this study, we measured $R_S$ and partitioned $R_S$ into heterotrophic ($R_H$) and autotrophic respiration ($R_A$) from *Larix principis-rupprechtii* plantation in Northern China. We selected three age stands (10-, 20- and 45-year old) and measured $R_S$, $R_H$ and $R_A$ two times each month during the snow-free season in 2010, 2011 and 2012. The main objectives were to address (1) how do total soil respiration ($R_S$), heterotrophic respiration ($R_H$), and autotrophic respiration ($R_A$) change with stand age since the forest structure is significantly different, (2) how does the turnover rate of soil organic carbon vary with stand age and (3) does the temperature dependency of $R_S$, $R_H$, and $R_A$ change with stand age?

## 2. Materials and methods

### 2.1. Site description

The study was performed at Saihanba ecological station (42°24.723′ N, 117°14.844′ E, 1505 m a.s.l.) of Peking University, situated in Saihanba National Forest Park, Hebei Province. The climate is semi-humid, with a long, cold winter (November–March), and a short spring and summer. According to the long-term observation from Saihanba meteorological station during the period 1971–2010, the mean annual temperature was −1.4 °C (−21.8 °C in January and 16.2 °C in July), the mean annual precipitation was 450 mm, and the frost-free duration was 81 d. The well drained soils are predominantly sandy. Seasonal snowpack begins to appear in November, and snowmelt occurs in early April. In winter, snow accumulation is typically less than 30 cm in depth (Wang et al., 2010b). The topography is relatively flat.

### 2.2. Experimental design

In this study, we selected three different age stands, including a 10-year-old stand (Sapling stand), a 20-year-old stand (Young stand) and a 40-year-old stand (Mature stand) in August 2009. All three stands were dominated by *Larix principis-rupprechtii*, which was previously occupied by a stretch of primary forests that were harvested in large-scale industrial logging in the last century. The dominant species in the understory layer of each age stand are shown in Table 1. The distance between any two stands was not beyond 2 km, which avoided the differences in climate and soil type. Therefore, the differences in $R_S$ and its components between stands are predominantly caused by stand age. The basic characteristics of the three age stands are summarized in Table 1. All three age stands with the area of 100 m × 100 m were fenced to minimize anthropogenic disturbance. In each age stand, 20 m × 20 m plots were arranged with 3 replicates. There was more than 10 m buffer strip between the plots.

### 2.3. Soil carbon flux measurement

Soil respiration was measured using a Li-8100 soil $CO_2$ Flux system (LI-COR Inc., Lincoln, NE, USA) during the snow-free season from early May to late October in 2010, 2011 and 2012. The soil $CO_2$ efflux was calculated based on a linear increase in chamber $CO_2$ concentrations over time. Four polyvinyl chloride (PVC) collars (20 cm inside diameter, 11 cm height), determining $R_S$, were randomly placed and inserted 8 cm into the soil in each plot. Note that the litter layer depth can reach ~5 cm at the three age stands, which indicated that only the roots in the top 3 cm of soil were presumably injured (cut off) by mechanical insertion of 8 cm PVC soil collar. This was supposed not to have significant impacts on $R_S$. Four PVC deep collars (20 cm inside diameter, 50 cm height), determining $R_H$, were inserted 47 cm into the soil to cut the roots in each plot. Soil sampling by a hand auger (with a diameter of 4 cm) to 45-cm depth early in the experiment indicated that nearly no roots were present in soils deeper than 35 cm and the soil underneath it is predominantly sandy. We thus expected that soil insertion of 47 cm PVC soil collar severed nearly all the roots. In order to exclude respiration from the aboveground parts of plants, living plants inside the collars were eradicated by hand once a week and the removed plant material was left inside the collars. Soil collars were placed in the soil at least 24 h before measurements to avoid influence of soil disturbance and root injury on the measurements. Note that all PVC collars were left in the same locations throughout the snow-free period. Soil $CO_2$ effluxes were measured twice a month and five times during each measurement day (twice during night and three times during day). Respiration rates were calculated as means of three plots for each age stand. $R_A$ was calculated as the difference between $R_S$ and $R_H$.

### 2.4. Soil temperature and moisture

When respiration measurement was performed, soil temperature and moisture at the depth of 5 cm, were recorded automatically by LI-COR 8100 temperature (8100-201) and moisture (8100-204) probes near each collar. Furthermore, soil temperature and moisture at 5 cm depth was continuously recorded by EM50 (Decagon, USA) every 30 min during the snow-free period.

### 2.5. Net primary productivity

NPP was obtained as the annual increase in total woody biomass plus litter fall. The total woody biomass was estimated from the following equation:

$$\text{Ln(Total Biomass)} = 0.8016\,\text{Ln}(D^2H) + 4.8423 \quad (1)$$

where $D$ and $H$ were mean diameter at breast height and tree height. Tree height was measured with hypsometer.

### 2.6. Measurements of soil properties

In order to measure soil properties (total organic C, total N and pH values), soil was firstly air-dried and ground to pass through a 2-mm sieve. The concentration of total organic C and total N in the 0.5 M $K_2SO_4$ extracts was determined with an auto-analyzer