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Responses of soil respiration and its temperature sensitivity to thinning in a pine plantation

Xueyong Pang[a,b], Weikai Bao[a,*], Biao Zhu[b], Weixin Cheng[b,c]

[a] Key Laboratory of Mountain Ecological Restoration and Bioresource Utilization, Chengdu Institute of Biology, Chinese Academy of Sciences, Chengdu 610041, China
[b] Department of Environmental Studies, University of California, Santa Cruz, CA 95064, USA
[c] State Key Laboratory of Forest and Soil Ecology, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110164, China

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ABSTRACT

Understanding the effects of forest management practice on soil respiration (R_s) and its temperature sensitivity (Q_{10}) is crucial for the accurate estimation of the global carbon budget. However, the dynamics of R_s and Q_{10} resulting from plantation thinning are not well understood. To evaluate the impacts of forest thinning on R_s and Q_{10}, we selected a pine plantation in the eastern Tibetan Plateau and applied the technique of thinning by simulating gap formation. We measured R_s monthly before (from July to November 2008) and after (from December 2008 to June 2012) thinning, combining with monthly microclimatic factors. R_s showed significant seasonal variability ($P < 0.001$) in both control (0.30 ± 0.05 to 2.94 ± 0.29 μmol C m^{-2} s^{-1}) and thinned (0.25 ± 0.04 to 2.99 ± 0.08 μmol C m^{-2} s^{-1}) stands, with higher rates from July to September and lower rates from December to February. These seasonal dynamics were primarily driven by soil temperature rather than by moisture limitation, except during an especially dry season, when soil moisture significantly affected R_s. There were significant differences in R_s during the growing season between the control and thinned sites following thinning. R_s increased at the thinned sites compared with the control sites during the summer of the first and the third year following thinning; however, R_s decreased at the thinned sites in the second summer. This suggested that climatic variability, such as change in soil moisture induced from thinning, played an important role in controlling R_s. There was no significant difference ($P = 0.083$) in R_s between control and thinned treatments after thinning (December 2008 to June 2012). For example, averages of R_s were 1.19 ± 0.34, 1.20 ± 0.36, 1.16 ± 0.38 μmol C m^{-2} s^{-1} in the control, small gap and intermediate gap treatments, respectively. In addition, the short-term Q_{10} showed a significantly seasonal variability ($P < 0.001$) and was altered by thinning ($P = 0.048$). The long-term Q_{10} also showed a significant inter-annual variability ($P < 0.001$), while thinning did not affect it. During the study period (December 2008 to June 2012), the Q_{10} values for the small and intermediate gaps significantly increased by 13.9% and 25.9% ($P < 0.05$), respectively, compared with the control. These results suggest that the forest thinning by simulating natural gap formation has a relatively small impact on soil CO_2 emission and its temperature sensitivity in comparison to the greater influence of inter-annual climatic variability.

1. Introduction

Global forest ecosystems contain about 1,146,000 Mt of carbon (C) (Dixon et al., 1994). As an important component of terrestrial ecosystems, forests are recognized as one of the most important potential carbon sinks (Pan et al., 2011). Forest soil respiration (R_s) plays an important role in regulating pools of soil carbon and carbon-cycling in terrestrial ecosystems, which directly affects the atmospheric concentration of CO_2 (Bond-Lamberty and Thomson, 2010). Therefore, forest ecosystems play an important role in the mitigation of climate change through carbon sequestration (Sullivan et al., 2008). Among variables that can substantially influence the intensity and process of R_s and thus C-cycling in forest ecosystems, management practice alone may change some forests from important carbon sinks to carbon sources or vice versa (North et al., 2009). Therefore, understanding the potential impacts of forest management practices on the intensity and processes controlling R_s is crucial for the accurate estimation of the global carbon balance (Raich et al., 2002; Schimel, 1995; Sullivan et al., 2008).

Abbreviations: R_s, soil respiration rates; C, carbon; Q_{10}, temperature sensitivity of soil respiration.

* Corresponding author at: Chengdu Institute of Biology, Chinese Academy of Sciences, PO Box 416, Chengdu 610041, PR China. Tel.: +86 28 82890528; fax: +86 28 82880288.
E-mail addresses: pangxy@cib.ac.cn (X.Y. Pang), baowk@cib.ac.cn (W.K. Bao).

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Thinning, the cutting down and removal of a proportion of trees in a forest, has been a common management practice in China and other regions (Martin-Benito et al., 2010; Tian et al., 2009). Many studies have shown that thinning provides many benefits to forest stands, including the short-term enhancement of tree growth and forest productivity by reducing the competition for resources (Martin-Benito et al., 2010); the acceleration of nitrogen mineralization rate by increasing the temperature of the surface soil layers (Thibodeau et al., 2000); and a decrease in the vulnerability of trees to insect attack (Coyea and Margolis, 1994). Thinning is expected to change soil environments, the allocation of aboveground and belowground productivity, and root density and turnover (Bowden et al., 2004; Keith et al., 1997). The majority of soil studies relating to forest thinning management focus on the impacts on carbon stocks and pools (inventory data), while information on the physiological response of soil processes such as R_s and Q_{10} is still limited and requires greater investigation.

The low and mid-altitude forests of the eastern Tibetan Plateau have experienced a shift in vegetation cover in the last century, from a native broad-leaved forest (dominated by *Quercus liaotungensis*) mixed with Chinese pine (*Pinus tabuliformis*) and with large grass openings, to high density Chinese pine monoculture stands with little herbaceous cover, less herbaceous diversity, and a thick litter layer (Bao et al., 2007; Li et al., 2009; Pang and Bao, 2011; Wu et al., 2006). These dense plantation forests are carbon sinks (73.2–111.6 gC m^{-2} $year^{-1}$) (Huang et al., 2007), but they are more susceptible to intense stand-replacing fires than the forests with naturally regenerated structures. To reduce fuels and fire hazard, improve the nutrient conversion from the thick litter layers to the soil and recreate the multi-layered forest stand structure by simulating natural regeneration, thinning treatments for stand structural adjustment are being implemented in the Chinese pine forests of the eastern Tibetan Plateau (Jiang et al., 2011).

Conventional thinning treatments often use intensive mechanical harvesting to reduce tree density, for example, by removing lines of trees. These practices may not be suitable for the complex mountainous conditions in our research areas and could result in soil and water loss and soil degradation. In this study, we applied a thinning technique by simulating natural gap formation, i.e., selective cutting groups of trees within a small area to create a forest gap. The advantages of this technique are that it reduces disturbance, improves the microenvironments of the understory layer, and accelerates the cycling and turnover of organic matter (Wang et al., 2010). However, it remains largely unknown how thinning by simulating gap formation may change soil carbon fluxes, even though it is necessary to understand the potential feedbacks between forest management activities and climate warming (Sullivan et al., 2008; Tang et al., 2005b).

In the literature, the reported response of R_s to the removal of trees from ecosystems is inconsistent. R_s has been reported to increase (Kaye and Hart, 1998; Selig and Seiler, 2004; Selmants et al., 2008), decrease (Kaye and Hart, 1998; Tang et al., 2005b), or remain unchanged (Toland and Zak, 1994) in response to overstory harvesting. The inconsistency in the response of R_s to thinning may stem from the uneven balancing between the autotrophic and heterotrophic components of soil respiration (Yuste et al., 2007). For instance, R_s may be reduced by thinning due to the death of respiring tree roots (Pypker and Fredeen, 2003; Tang et al., 2005b; Wiseman and Seiler, 2004); but R_s could also increase after thinning due to the rapid decomposition of dead roots by soil microbes (Yuste et al., 2007), or the respiration of fine roots from the rapid growth of new plants in the thinned stands (Campbell et al., 2009). Forest thinning can influence the decomposition rate of soil organic matter and plant litter by altering the understory microclimate (Zhang and Zak, 1995, 1998), thus adjusting the soil R_s response.

Additionally, forest thinning can potentially affect the Q_{10} of R_s by changing substrate availability and photosynthetic activity (Gershenson et al., 2009; Högberg, 2010), root activity and inputs of labile organic carbon (Kuzyakov, 2002; Zhu and Cheng, 2011), and temperature and moisture (Davidson and Janssens, 2006). Although many studies have examined the factors influencing the Q_{10} of soil respiration, little is known regarding the response of Q_{10} to forest management practices, such as thinning.

In this study, we selected a typical pine plantation in the eastern Tibetan Plateau and artificially created gaps to simulate natural forest gaps. We investigate (i) how R_s and its temperature sensitivity change after the thinning by simulating gap formation, and (ii) how the temperature and moisture of soil surface change to modify the R_s process. Our main objectives were to explore the dynamics of R_s and Q_{10} following thinning and to elucidate the factors influencing soil respiration and Q_{10}.

2. Materials and methods

2.1. Study site

This study was conducted at Maoxian mountain Ecosystem Research Station, Chinese Academy of Sciences in Sichuan, China, located in the eastern Tibetan Plateau (31° 37′ N and 103° 54′ E). It has a montane temperate climate with mean annual precipitation of 900 mm falling mainly from May to September. October to April is the dry season. The mean annual temperature is 8.9 °C with the mean maximum monthly temperature of 18.8 °C in July and the mean minimum monthly temperature of −1.1 °C in January (Pang and Bao, 2011).

The pine plantations were established mostly in the 1980s, and comprise of 67% of the forested area in the region (Pang et al., 2011). Two pine species [*P. tabuliformis* and *Pinus armandi*] are the most widely planted in the region. The experimental site was a 26-year-old pine plantation on a 14° slope, planted in 1985. The site had not received any management since planting, but it had often been disturbed by litter collection (16.8–20.2 gC m^{-2} $year^{-1}$ being removed from the forest) in the fall and the gathering of wild mushrooms and Chinese medicinal plants in the spring of each year. The mean diameter at breast height (DHB) of the trees was 15.4 cm, with a mean height of 11.2 m and a density of 2321 stems ha^{-1} in 2008 for individuals with DHB >3 cm. The canopy leaf area index (LAI) was approximately 3.5, and the tree canopy coverage was 92% at the end of the 2008 growing season. The understory coverage was approximately 8%, with *Youngia* sp., *Viola grypoceras*, *Aruncus sylvester*, *Pyrola szechuanica* and *Rosa willmottiae* representing the major understory shrubs and herbs (Jiang et al., 2011).

The soil type at the experimental site was characterized as a Calcic Luvisol according to IUSS Working Group WRB (2007). It is a silt loam with a textural composition of 28% sand, 45% silt and 27% clay. Average litter cover was 82%, and average litter thickness was 6 cm. The litter mainly consisted of pine needles and small branches. As measured in 2008, the soil at the 0–10 cm depth had a pH of 5.27, mean organic carbon content of 3.0%, and total nitrogen content of 0.27%. A more detailed site description is given by Jiang et al. (2011).

2.2. Thinning treatments

We implemented a thinning experiment by simulating natural gap formation for the pine plantation forest within an area of about 5 ha. We randomly selected and felled some trees to form forest gaps of different sizes. We calculated the gap area by the vertical projection of the edge of forest gap. The three thinning treatments were the control (zero thinning), small creation (approximately

30 m^2) and intermediate gap (approximately 80 m^2) and were designed according to a survey of the naturally occurring forest gaps of 80–100 m^2 in size in this region. We applied a randomized block design with three blocks and 100 m spacing between each of the three blocks. In each block, we randomly arranged the three treatment plots with 30 m spacing between plots. Before the thinning in July 2008, we fenced the experimental area. In ten quadrats within each plot, we then measured the DBH, height and canopy area of each tree and the understory species composition and cover. We also measured the physical and chemical properties of the soil in each plot. The thinning treatments were implemented on 27 November 2008. We removed all marked trees within the chosen gaps, but retained the stumps at 50 cm above the ground. After thinning, we immediately removed all stems, branches and leaves of the cut trees from the plots. The understory shrub and herbaceous species were left in the plots.

2.3. Field measurements of soil respiration

We established a 1 m × 1 m subplot in the center of each forest gap (or plot in the control treatment). In each subplot we inserted into the soil four polyvinyl chloride collars of 10.4 cm in diameter and 5 cm in height for the respiration measurements. The collars were inserted into soil to a depth of 2 cm. To minimize any disturbance effect on CO_2 efflux, the collars were installed at least 24 h before the first measurement. We left the collars at the same location to facilitate the next measurement. The plants inside the collars were clipped at ground level, and the litter within the collars was removed before measurements. R_s was measured from the collars in the four corners of the subplot using a Licor 6400 portable photosynthesis system equipped with a Licor 6400-09 soil respiration chamber (Licor Inc., Lincoln, NE, USA). We also monitored soil temperature (a probe connected to the Licor 6400) and the volumetric soil moisture content (WET-2-K4, Delta-T Devices Ltd, UK) at a depth of 10-cm near each of the soil respiration measurement collars in each plot. This study included data from July 2008 to June 2012, but soil moisture was not measured from July to December 2008, and April and May 2010 due to the probe failure. The R_s rate was measured once (from 10:00 to 13:00 h) on the first day of every month, except during rain or when snow covered the ground in winter. We took 2–3 measurements at each location during each measurement period. We divided all data into two groups: before thinning (from July to November 2008), and after thinning (from December 2008 to June 2012).

2.4. Data analyses and statistics

2.4.1. Analysis of soil CO_2 efflux, temperature and moisture

We firstly averaged soil CO_2 efflux, temperature and volumetric moisture from the four collars in each subplot, and used the mean to represent each subplot. Then we further analyzed the effect of thinning and seasonality on R_s, soil temperature and soil moisture by two-way ANOVA. For each time period, we then analyzed the effect of the thinning treatments on R_s, soil temperature and soil moisture with one-way ANOVA. The significance level was set at $P < 0.05$. An exponential equation (Eq. (1)) was selected to determine the relationships between R_s and soil temperature and soil moisture. To explore the effect of seasonal drought on R_s, a linear regression was used to fit the relationship of soil moisture and R_s during the growing season (June to September) of each year after thinning, because seasonal drought often occurred during that period.

2.4.2. Q_{10} calculation

The Q_{10} value, defined as the increment in R_s occurring when the temperature is increased by 10 °C, was used to describe the sensitivity of R_s to temperature. For each thinning treatment, a Q_{10} value for the post-thinning measurement period (December 2008 to June 2012) was computed based on the monthly measurements of R_s and soil temperature. The Q_{10} values used in this study were calculated according to the following equations (Lloyd and Taylor, 1994):

$$R_s = \alpha e^{\beta T} \tag{1}$$

$$Q_{10} = e^{10\beta} \tag{2}$$

where R_s is measured soil CO_2 efflux, T is measured soil temperature at a depth of 10 cm, and α and β are regression coefficients.

2.4.3. Comparisons of Q_{10}s and Q_{10}y

Both short-term (Q_{10}s) and long-term (Q_{10}y) Q_{10} values were estimated using the seasonal and annual data sets for each thinning treatment, respectively. For example, growing season (May to October) and non-growing season (November to April) represent the two main seasons defining plant growth within a year. We calculated Q_{10}s based on the data for each season before and after thinning. We also calculated Q_{10}y based on data from a whole year. We tested for significant differences between Q_{10}s and Q_{10}y among the various treatments and different seasons or year-to-year variability using two-way ANOVA with SPSS v11.5. A linear regression was used to model the relationship between Q_{10}s and soil temperature and volumetric moisture in the corresponding periods. The significance level was set at $P < 0.05$.

3. Results

3.1. Seasonal and annual variation of R_s

Fig. 1 showed the seasonal variation in soil temperature (a), volumetric soil moisture content (b) and R_s (c) from July 2008 to June 2012. Each value represented the mean of the daytime measurements (10:00–13:00 h) for 12 collars.

Soil respiration (R_s) showed significant seasonal variability ($P < 0.001$) in both control (0.30 ± 0.05 to 2.94 ± 0.29 μmol C m^{-2} s^{-1}) and thinned (0.25 ± 0.04 to 2.99 ± 0.08 μmol C m^{-2} s^{-1}) stands (Fig. 1c). Soil temperature ($P < 0.001$) and moisture ($P < 0.001$) also varied significantly among different seasons (Fig. 1a and b). It appears that R_s co-varies with soil temperature (Fig. 1a and c). R_s peaked during July to September within a year and bottomed during December to February during the experimental period. Soil moisture was relatively low from June to September 2009 and from May to September 2011 in control plots (Fig. 1b). During the experimental period (July 2008 to June 2012), R_s was strongly correlated with soil temperature ($r^2 = 0.90$, $r^2 = 0.85$ and $r^2 = 0.95$ for control, small and intermediate gaps, respectively) (Fig. 2a), but not correlated with soil moisture (Fig. 2b). However, the low soil moisture significantly affected R_s during June to September of 2009 and 2011 (Fig. 3a and c), with the result that significant relationships between R_s and soil moisture were found in the relatively dry growing seasons of 2009 ($P = 0.037$) and 2011 ($P = 0.028$) (Fig. 3a and c), but not in the relatively wet growing season of 2010 ($P = 0.947$) (Fig. 3b). Soil temperature and water content were not significantly correlated with each other (data not shown).

3.2. The effect of thinning on R_s

Rates of R_s showed large variation among the different treatments before thinning (July–November 2008) (Fig. 1c), averaging at 2.66 ± 0.17, 2.19 ± 0.34, 1.71 ± 0.30 μmol C m^{-2} s^{-1} in the control, small gap and intermediate gap treatments, respectively (Fig. 1c). Although the simulated thinning treatments did not significantly ($P = 0.083$) alter soil CO_2 efflux rates during the period (December

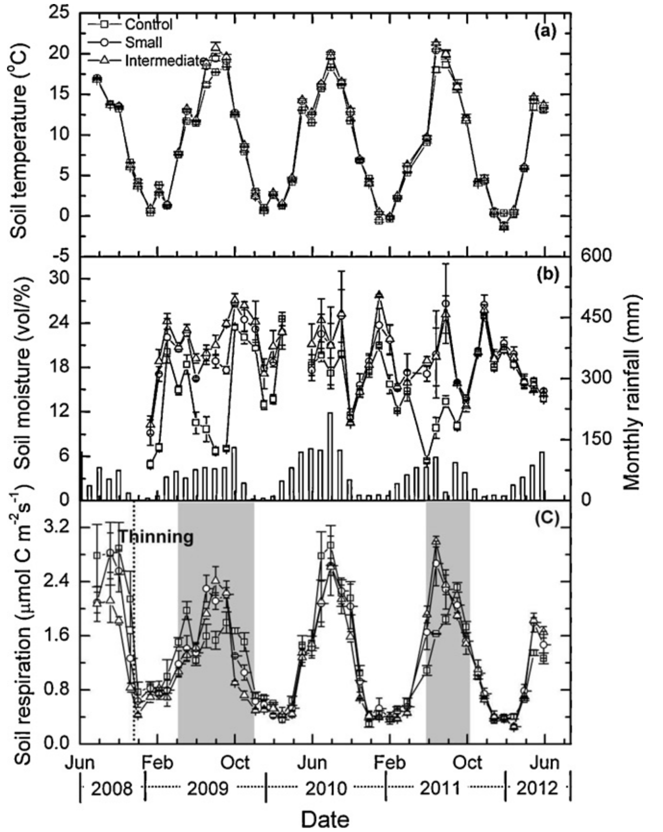

Fig. 1. Seasonal variations in soil temperature (a), and soil volumetric moisture (b), and soil CO_2 efflux rate (c) measured in the control and two treatments of thinning by simulating gap formation in a pine plantation in the eastern Tibetan Plateau. The measuring period was from July 2008 to June 2012. The thinning treatments were conducted on 27 November 2008. Blank columns indicate monthly rainfall. Each data point for R_s, soil temperature and soil volumetric moisture is a mean of twelve measurements.
The error bars indicate standard error. The data gaps are due to rain events or instrument failure. Periods with a light gray background indicate a soil CO_2 efflux rate that is significantly different among three treatments.

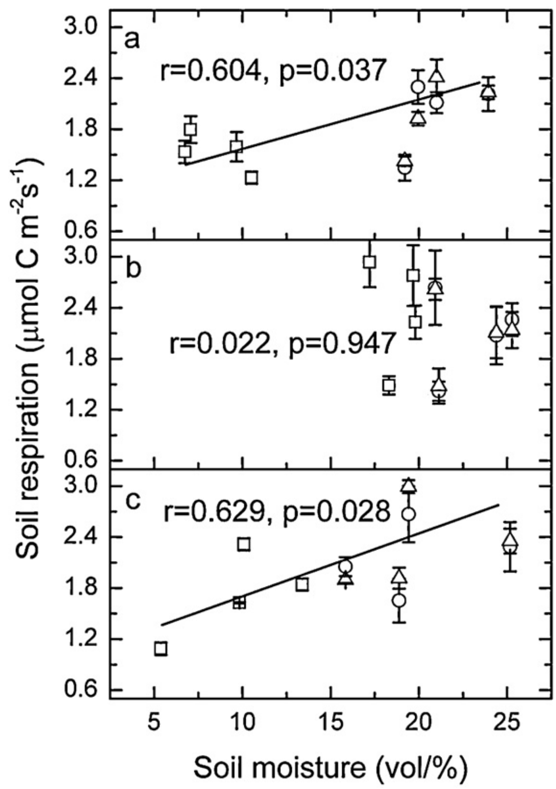

Fig. 3. The relationship between the soil respiration (R_S) and soil moisture at a soil depth of 10 cm during June to September 2009 (a), June to September 2010 (b) and June to September 2011 (c). The open square, open circle and open triangle indicate the points of data in the control, small gap and intermediate gap treatments, respectively. Error bars represent standard errors of the means ($n = 3$).

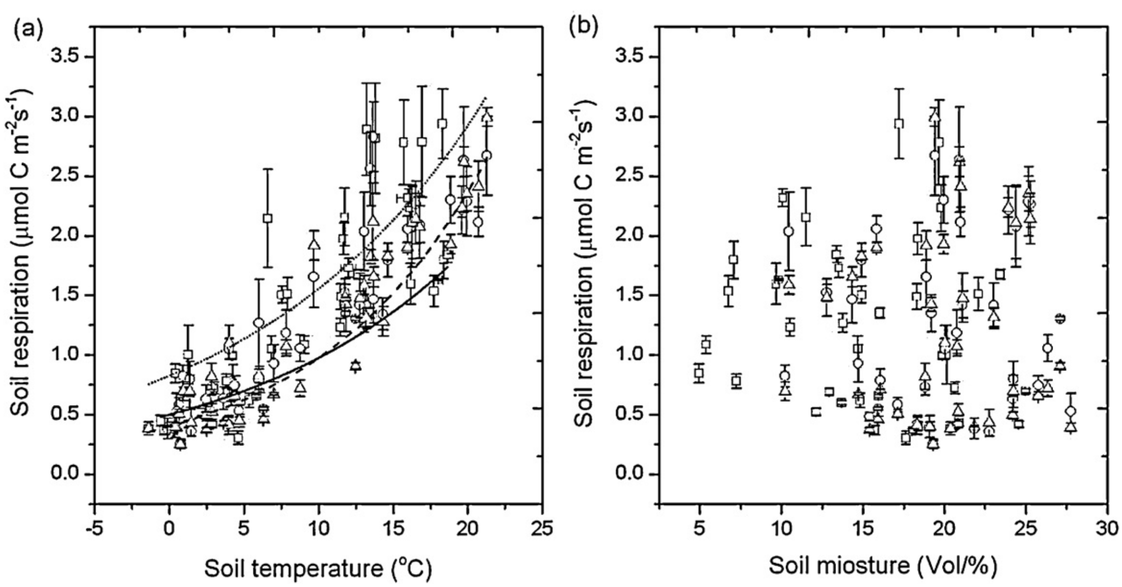

Fig. 2. The relationship between the soil CO_2 efflux rate (R_S) and soil temperature (a) and soil moisture (b) at a soil depth of 10 cm during period of July 2008 to June 2012. The open square, open circle and open triangle indicate the points of data in the control, small gap and intermediate gap treatments, respectively. The solid line ($y = 0.499\,e^{0.066x}$, $r^2 = 0.90$), dotted line ($y = 0.827\,e^{0.079x}$, $r^2 = 0.85$) and dashed line ($y = 0.402\,e^{0.089x}$, $r^2 = 0.95$) indicate the regression curves of the soil CO_2 efflux rate and soil temperature in the control, small gap and intermediate gap treatments, respectively. Error bars represent standard errors of the means ($n = 3$).

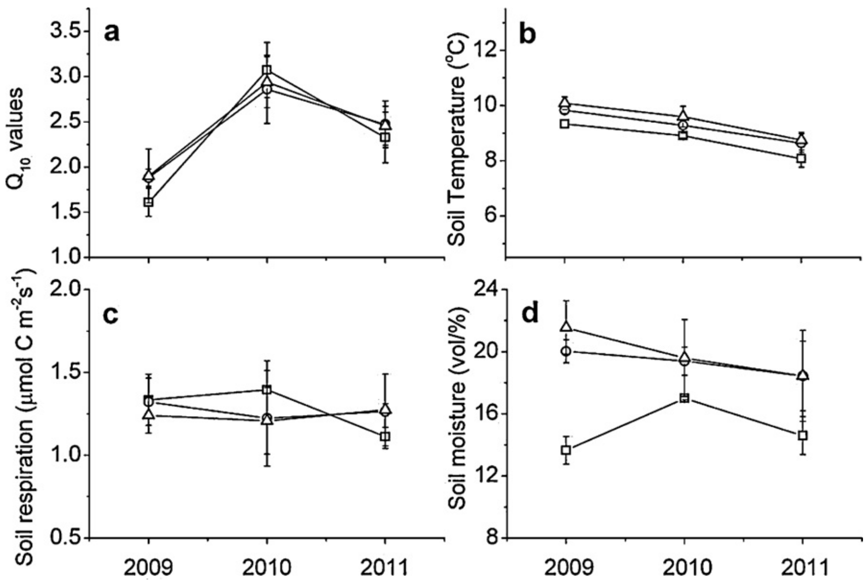

Fig. 4. Inter-annual variations of Q_{10}y (a), soil temperature (b), R_s (c) and soil water content (d), Q_{10} values (d) at 10 cm depth in different thinning treatments (control, open square; small gap, open circle, and open triangle) during the 3 years after thinning (2009–2011). Error bars represent standard errors of the means ($n = 3$).

2008 to June 2012), after thinning, R_s was significantly altered by thinning in the growing seasons ($P < 0.05$, Fig. 1c). Compared with the control, the thinning treatments increased the R_s during the growing season in 2009 and 2011 but decreased the R_s during the growing season in 2010 (Fig. 1c). In the first spring and fall after thinning (2009), the R_s rate was significantly higher in the control treatment than in the thinned treatments ($P < 0.05$). In the second year after thinning (2010), there was no significant difference in the R_s rate between the control and thinning treatments, although the R_s rate was slightly higher in the control treatment ($P = 0.103$). In the third year, R_s was higher in thinning treatments than in the control treatment ($P < 0.01$) (Fig. 1c). There was no significant difference in the R_s rate between the small gap and intermediate gap treatments ($P > 0.05$). We averaged the data for each year (from January to December) and did not find significant differences between the control and the thinning treatments in the annual R_s for the initial 3 years (2009–2011) after thinning ($P = 0.365$). R_s were 1.19 ± 0.34, 1.20 ± 0.36, 1.16 ± 0.38 µmol C m^{-2} s^{-1} in the control, small gap and intermediate gap treatments, respectively (Fig. 4c). Thinning treatment significantly affected average annual soil temperature ($P < 0.001$) and soil moisture ($P < 0.001$) (Fig. 4b and d).

3.3. Seasonal and annual variation in Q_{10}

Regardless of the thinning and control treatments, Q_{10}s showed strong seasonal variation ($P < 0.001$) (Fig. 5). The Q_{10}s values ranged between 1.15 and 3.92, 1.56 and 4.94 and 1.55 and 4.38 in the control, small gap and intermediate gap treatments, respectively (Fig. 5). A linear regression was used to fit the relationship between Q_{10}s and soil temperature and soil moisture (Fig. 6). Q_{10}s was negatively correlated with soil temperature ($P = 0.039$) and positively correlated with soil moisture in the control plots (Fig. 6a). However, there was no correlation between Q_{10}s and soil temperature or moisture in the thinning treatment plots (Fig. 6b and c).

Q_{10}y also showed a significant inter-annual variability ($P < 0.001$) (Fig. 4a). In all three treatments Q_{10}y showed higher values in 2010 and lower values in 2009 (Fig. 4a). The highest Q_{10}y values of the control, small gap and intermediate gap treatments were 3.07 ± 0.31, 2.86 ± 0.38 and 2.94 ± 0.28, respectively. In contrast, the lowest Q_{10}y value appeared in 2009, being 1.61 ± 0.16, 1.88 ± 0.10 and 1.90 ± 0.30 in the control, small gap and intermediate gap treatments, respectively.

We also calculated the Q_{10} values after thinning using data collected during the experimental period (November 2008 to June 2012). The Q_{10} values were 1.93, 2.20 and 2.43 in control, small gap and intermediate gap, respectively (Fig. 2a).

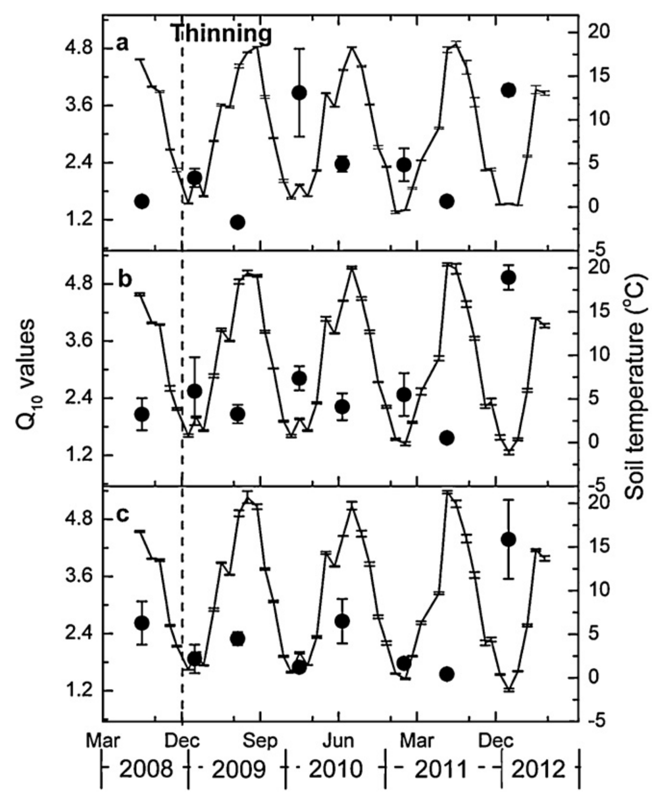

Fig. 5. Seasonal variations in Q_{10} (symbol) and soil temperature (curve) at a depth of 10 cm in a pine plantation in the eastern Tibetan Plateau from July 2008 to June 2012. (a) Control; (b) small gap; (c) intermediate gap. The error bars represent standard errors of the means ($n = 3$).

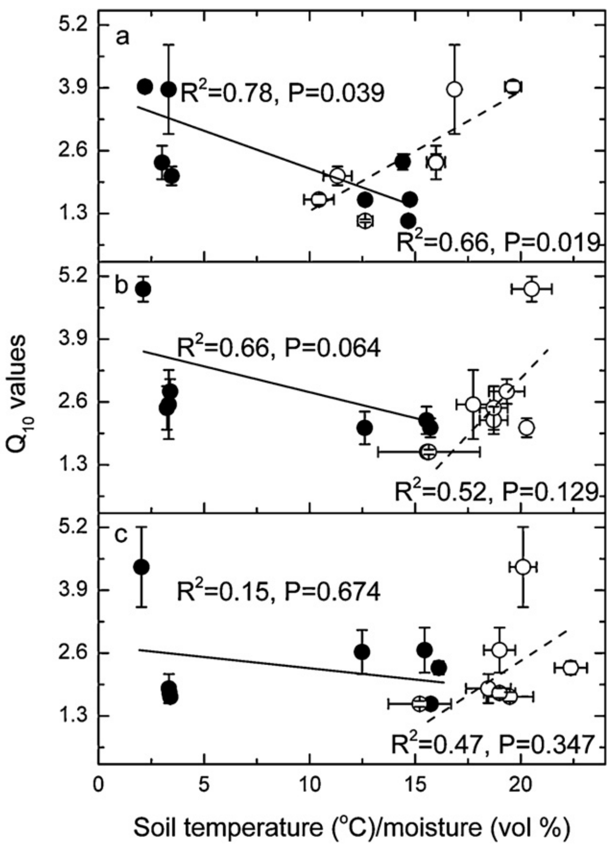

Fig. 6. The relationships between Q_{10} and soil temperature and soil moisture at a depth of 10 cm in a pine plantation in the eastern Tibetan Plateau from July 2008 to June 2012. The closed circles represent estimated Q_{10} versus soil temperature and the solid lines represent Q_{10} fitted versus soil temperature. The open squares represent estimated Q_{10} versus soil moisture and the dotted lines represent Q_{10} fitted versus moisture. (a) Control; (b) small gap; (c) intermediate gap. Due to the lack of soil moisture data before the thinning in 2008, the relationships among Q_{10}, soil temperature and soil moisture were not analyzed.

3.4. *The effect of thinning on Q_{10}*

Q_{10}s was significantly different between the control and the thinning treatments ($P_{control–small}$ = 0.049; $P_{control–intermediate}$ = 0.038), but there was no significant difference between the small gap and intermediate gap treatments ($P_{small–intermediate}$ = 0.950, Fig. 5). There were no significant (P = 0.145) differences in Q_{10}y between the control and thinned treatments (Fig. 4a), although Q_{10}y was higher (P = 0.034) during the period from January to June of 2012 in the thinning stands than in the control stands (data not shown).

4. Discussion

4.1. *The effect of thinning on soil CO_2 efflux rates*

The mean annual R_s did not significantly differ between the control and the thinning treatments during the initial 3 years (2009–2011) following thinning. But R_s during the growing seasons was significantly altered by thinning (P < 0.05). There are several possible mechanisms behind this result, such as different responses of heterotrophic and autotrophic respiration, climatic variability, and development of understory vegetation driven by the thinning treatment (Tang et al., 2005b; Tian et al., 2009).

First, reduction of respiration from tree roots can result in the decrease of R_s in thinned plots after thinning. This mechanism was likely an important one because R_s was significantly lower in the thinned plots than in the control plots (P < 0.05) during the first spring after thinning (February to April 2009) (Fig. 1c). This difference could be attributed to a decrease in root respiration resulting from a decrease of root biomass and photosynthesis after the removal of the forest crown during thinning (Tang et al., 2005b).

Second, climatic variability combined with vegetation condition could also affect the R_s after thinning. In the growing season, although root respiration may be higher in the control plots due to their higher living root biomass (Selig et al., 2008; Tang et al., 2005a), abiotic factors may also exert a strong control on the R_s rates during this period (Ohashi et al., 1999). We observed a significant decrease of R_s in the growing seasons (June to September of 2009 and 2011) in control plots relative to the thinned plots (Fig. 1c), most likely because the higher temperature in the thinned treatments and lower moisture in the control plots dominated the effect on R_s (Fig. 1a and b). There was a significantly higher temperature in thinned plots than in the control plots from July to September of 2009 and 2011 (P < 0.001) (Fig. 1a), which might play a role in increasing R_s during this period because soil temperature was significantly and exponentially correlated with R_s (Fig. 2a). Soil moisture can exert an important control in causing differences in R_s between control and thinned plots in this period. In dry periods such as June to September of 2009 and 2011, the R_s in the control plots was significantly limited by soil moisture (<14%) (Figs. 1b and 2a and c), which was also lower than in the thinned plots. But during wet periods (soil moisture > 17%) (June to September of 2010), there was no significant difference for R_s between control and thinned plots (Figs. 1b and 2b). There was a significant positive correlation between R_s and soil moisture during dry periods (Fig. 3a and c), but not during wet periods of 2010 (Fig. 3b). Therefore, although soil moisture had no significant effect on the R_s at the annual time scales, soil moisture did produce significant effects on soil CO_2 efflux during the drought periods. The low soil moisture level might affect root growth and activity, thus leading to low root respiration rates during this period. The interannual difference in soil moisture was primarily caused by the high precipitation (935.8 mm) in 2010 (Fig. 1b) and the high transpiration rates of pine trees during the growing season. Additionally, the amount of rainfall that actually reached the soil was lower in control plots due to the higher forest crown interception during light rainfall events (Bao et al., 2004); for example, over 60% of the annual rainfall was intercepted by the pine canopy (Bao et al., 2004). Our observation of lower soil moisture and lower R_s in the control stands than in the thinned stands during the growing season of 2009 has also been reported in other studies, especially in dry regions (Defreitas and Enright, 1995; Dore et al., 2010; Grady and Hart, 2006; Zhu et al., 2009). It is clear that in regions with dry seasons, the primary control on R_s rate could be soil moisture.

Third, root respiration from the newly developed understory vegetation might offset the reduction of tree root respiration in thinned plots a few months after thinning. We observed that percent plant cover and species richness of the understory plants was significantly higher in the thinned plots than in the control plots (Yan et al., unpublished data). This indirectly indicated that the decrease in root respiration associated with the removed trees was probably compensated for by an increase in photosynthesis and R_s associated with the new understory vegetation. But we had no data to ascertain how much R_s was from the newly developed understory plants in thinned plots. Results from other studies have indicated that as much as 50% of net primary production by the shrubs and fine roots was transferred to the belowground system, and increased the light use efficiency of the thinned stands by 60% over that of un-thinned plots (Campbell et al., 2009; Dore et al., 2010; Gauthier and Jacobs, 2009). In addition, the decomposition of dead roots 6 months after thinning could partially contributed to the increased soil CO_2 efflux rates (Chen et al., 2010; Wang and Yang, 2007).

Therefore, these results suggest that the changes in the soil CO_2 efflux rates due to thinning could result from the combined effects of the changes in soil temperature and soil moisture, tree root removal, and the new development of understory vegetation after thinning. But each of these variables can play a different role at different points in time following thinning (Campbell et al., 2009; Dore et al., 2010; Kim, 2008).

4.2. The effect of thinning on Q_{10}

During the study period after thinning (November 2008 to June 2012), the Q_{10} values in the small gap and intermediate gap stands significantly increased by 13.9% and 25.5%, respectively, relative to the Q_{10} values in the control stands (Figs. 2a and 5a–c). This increase in Q_{10} values might have resulted from the higher available soil moisture and larger variability of soil temperature (high temperature in summer and low temperature in winter) in thinned plots (Fig. 1a and b).

The Q_{10}s was significantly higher in the non-growing season (November to April) than in the growing season (May to October), except for the intermediate gap plots (Fig. 5a–c). The low Q_{10}s in non-growing season in intermediate gap plots might result from the reduction of tree root respiration, which tends to have higher Q_{10} values than heterotrophic respiration (Högberg et al., 2001). We also found that the annual Q_{10}y fluctuated during 2009–2011 following thinning (Fig. 6a). Similar fluctuating patterns in Q_{10}s and Q_{10}y were also reported by Chen et al. (2010), although the absolute values of Q_{10}s and Q_{10}y in our study are lower than theirs. This finding could be attributed to the lower temperature and higher altitude of their study area, where the top 10 cm layer of soil was frozen in the winter. Some studies have also reported that higher Q_{10} values tend to occur under low temperature conditions than under high temperature conditions (Chen and Tian, 2005; Peng et al., 2009).

In general, our results showed that the thinning treatments caused an increase in the temperature sensitivity of R_s. This increase in Q_{10} of soil respiration in the thinning treatments should not have resulted from the reduced root activity because root/rhizosphere respiration has been shown to have a higher Q_{10} value than soil microbial respiration (Boone et al., 1998). Following the forest crown removal by thinning, root respiration could decrease rapidly due to the decrease in substrate supply because tree cutting has reduced the photosynthesis rates (Högberg et al., 2001). In the growing season, root activity reached a maximum, which comprised a large percentage of the soil respiration (Luan et al., 2011; Wang and Yang, 2007; Yi et al., 2007). Therefore, the component of soil respiration from root respiration should be higher in the control plots than in the thinned plots. But our results did not support this. On the contrary, Q_{10}s in the first growing season were lower in control plots than in thinned plots (Fig. 5a–c). This suggested that reduction in Q_{10}s from tree root respiration in thinned plots might have been over-compensated by changes of other factors such as substrate availability, temperature and moisture.

Published results have shown that altering soil temperature and moisture can affect the Q_{10} of soil respiration (Davidson and Janssens, 2006; Kirschbaum, 1995; Peng et al., 2009). In our thinning treatments, the annual mean soil temperature in the small gap and intermediate gap after thinning treatments increased by 5.52% and 8.02%, respectively (Figs. 1a and 6b), with higher increases in summer than in winter. From 2009 to 2011, the annual mean soil moisture also increased by 43.7% and 56.2% in the small gap and intermediate gap treatments, respectively, compared with the control treatment (Fig. 1b). Increases in both soil temperature and moisture might accelerate the turnover of soil organic carbon, increase the activity of the plant roots and the transportation of substrates (Wang et al., 2010), which might have contributed to the increase in Q_{10} in the thinned stands. Furthermore, our results indicated that the seasonal Q_{10} values were negatively correlated with soil temperature and positively correlated with soil moisture in the control plots (Fig. 6a). However, Q_{10}s values were not correlated with soil temperature or soil moisture in thinned plots (Fig. 6b and c). These results suggested that other factors such as substrate availability might be responsible for the increased Q_{10} values of soil respiration in the thinned plots, as both theoretical and empirical evidence showed that increasing substrate availability can lead to an increase in Q_{10} (Davidson et al., 2006; Gershenson et al., 2009).

5. Conclusions

Forest thinning by gap formation could slightly increase soil temperature and moisture immediately following thinning. Soil temperature was the dominant factor controlling R_s and Q_{10}. But during the relative dry period soil moisture played an important role in controlling R_s. Although there was a slight increase in R_s and Q_{10} shortly after thinning, the difference in R_s between the control and thinned stands disappeared 1 year after thinning. Therefore, we conclude that forest thinning has a relatively small impact on soil CO_2 emissions and Q_{10} as compared to the greater role of interannual climatic variability.

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