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# Response of soil respiration to precipitation during the dry season in two typical forest stands in the forest–grassland transition zone of the Loess Plateau

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ABSTRACT

Forest ecosystems on the Loess Plateau are receiving increasing attention for their special importance in carbon fixation and conservation of soil and water in the region. Soil respiration was investigated in two typical forest stands of the forest–grassland transition zone in the region, an exotic black locust (*Robinia pseudoacacia*) plantation and an indigenous oak (*Quercus liaotungensis*) forest, in response to rain events (27.7 mm in May 2009 and 19 mm in May 2010) during the early summer dry season. In both ecosystems, precipitation significantly increased soil moisture, decreased soil temperature, and accelerated soil respiration. The peak values of soil respiration were 4.8 and 4.4 $\mu$mol $CO_2$ $m^{-2}$ $s^{-1}$ in the oak plot and the black locust plot, respectively. In the dry period after rainfall, the soil moisture and respiration rate gradually decreased and the soil temperature increased. Soil respiration rate in black locust stand was consistently less than that in oak stand, being consistent with the differences in C, N contents and fine root mass on the forest floor and in soil between the two stands. However, root respiration ($R_r$) per unit fine root mass and microbial respiration ($R_m$) per unit the amount of soil organic matter were higher in black locust stand than in oak stand. Respiration by root rhizosphere in black locust stand was the dominant component resulting in total respiration changes, whereas respiration by roots and soil microbes contributed equally in oak stand. Soil respiration in the black locust plantation showed higher sensitivity to precipitation than that in the oak forest.

## 1. Introduction

Soil respiration is one of the major processes controlling the carbon budget of terrestrial ecosystems. Increasing carbon sequestration in ecosystems may mitigate the increasing atmospheric $CO_2$ concentration. The total global emission of $CO_2$ from soils is recognized as one of the largest fluxes in the global carbon cycle (Fest et al., 2009; Kuzyakov, 2006; Schlesinger and Andrews, 2000; Xu and Wan, 2008). A model estimation of the global soil respiration rate of 76.5 Pg C $y^{-1}$ indicates its potential role in global warming, with the rate being about ten times that of fossil fuel burning and cement manufacturing combined (Chang et al., 2008). Although measurements of soil $CO_2$ efflux have been carried out in recent decades with much effort being devoted to various ecosystems, little information on soil respiration on the Loess Plateau region has been presented (Jiang et al., 2006; Li et al., 2008).

As one of the largest geographic units in China, the Loess Plateau approximately covers an area of 9° latitude and 11° longitude that has arid, semiarid and subhumid climates. The central part of the Loess Plateau in the northern Shaanxi Province of China, where the annual total precipitation is around 500 mm, is ecologically defined as a forest–grassland transitional zone (H.S. Chen et al., 2008; Du et al., 2007; Zhu et al., 1983). There was an extensive distribution of forests until the 1930–40s, at which time the population rapidly increased in the region. The area is now characterized by severely eroded landform with natural and artificial forests, grassland and farmland. Natural and artificial forests in the area showed various differences in stand structure, biodiversity and soil development (Tateno et al., 2007). It has been suggested that forest ecosystems in arid and semiarid regions will play increasingly important roles in the global biogeochemical cycle of carbon with global climate

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change (Li et al., 2008; McGuire et al., 1995; Ueyama et al., 2009). There is an obvious need for information about soil respiration characteristics in both artificial and natural forest ecosystems in such regions.

Furthermore, extreme weather (i.e., long dry season) is frequently occurring owing to global change, and the response of soil respiration to an extreme climate is consequently drawing much attention (Arnone et al., 2008; Ciais et al., 2005). Ecosystems on the semiarid Loess Plateau are also subject to the influence of water shortages. It is thus necessary to investigate the response of soil respiration *in situ* in forest ecosystems to precipitation for a dry climate at a plot scale in this region.

Among the environmental factors, soil temperature and moisture conditions are frequently addressed as those closely related to soil respiration. As a rainfall event can result in changes in both soil water content and temperature, the response of soil respiration to precipitation has been a subject of numerous studies (Borken et al., 2003; Clein and Schimel, 1994; Inglima et al., 2009; Lee et al., 2002, 2004; Merbold et al., 2009; Muhr and Borken, 2009; Muhr et al., 2010; Yuste et al., 2003). For example, Liu et al. (2002) found that both the soil volumetric water content and $CO_2$ efflux dramatically increased immediately after the addition of water, and then gradually decreased. However, many studies have been based on rainfall simulations, and thus there is disparity between their conclusions and the real world (Boer and Puigdefabregas, 2005; Lee et al., 2004). Though the positive relationship between soil temperature and soil respiration showed its significance in plots with experimental water addition treatments (S.P. Chen et al., 2008; Lee et al., 2004), investigations with soil moisture changes in natural field conditions have been few and the results were subject to variation (Liu et al., 2002; Schimel et al., 1999).

Soil respiration consists of respiration by plant roots and respiration from catabolism by heterotrophy, mainly by soil microbes (Jassal and Black, 2006). While both root respiration ($R_r$) and microbial respiration ($R_m$) may respond to changes in environmental factors, the response patterns may be different between ecosystems with different soil structure and nutrient conditions. To date, most studies point towards a contribution of each component to total soil respiration between 30% and 60% in temperate forest (Kuzyakov, 2006). Some studies found root-rhizosphere respiration in temperate forests to be more temperature sensitive than microbial respiration when measured during the course of a year (Epron et al., 2001; Ruehr and Buchmann, 2010; Saiz et al., 2006). However, information on responses of soil respiration components to precipitation is still rather limited, especially in the dry season.

The objectives of the present study are to (1) examine the effect of rainfall events on soil $CO_2$ efflux in forest ecosystems in the semiarid Loess Plateau region, (2) investigate the changes in soil $CO_2$ efflux in the post-rainfall period during the dry season, and (3) compare the changes in soil respiration components for two typical forest stands in the region, an exotic black locust plantation and an indigenous oak forest, with respect to their soil organic matter and fine root quantities.

## 2. Materials and methods

### 2.1. Study area and experimental site

The study site was located on Mt Gonglushan, near Yan'an city of Shaanxi province, China (36°25.40′N, 109°31.53′E; 1353 m a.s.l.). On the Loess Plateau, the amount of precipitation and the occurrence of forest gradually decrease northwestward, and the present study site is located in the forest–grassland transition zone (Cheng and Wan, 2002). The 20-year averages (1988–2007) of mean annual precipitation and air temperature are 498 mm and 10.6 °C. A study plot was set on a southeast-facing slope with a declination of 26° in a plantation of black locust (*Robinia pseudoacacia*), which is a main reforestation species in the region. A second plot was set on a northeast slope with a declination of 22° in a natural secondary forest dominated by oak (*Quercus liaotungensis*). The two stands were about 150 m apart. The oak forest was about 60 years-old and the black locust plantation about 30 years-old.

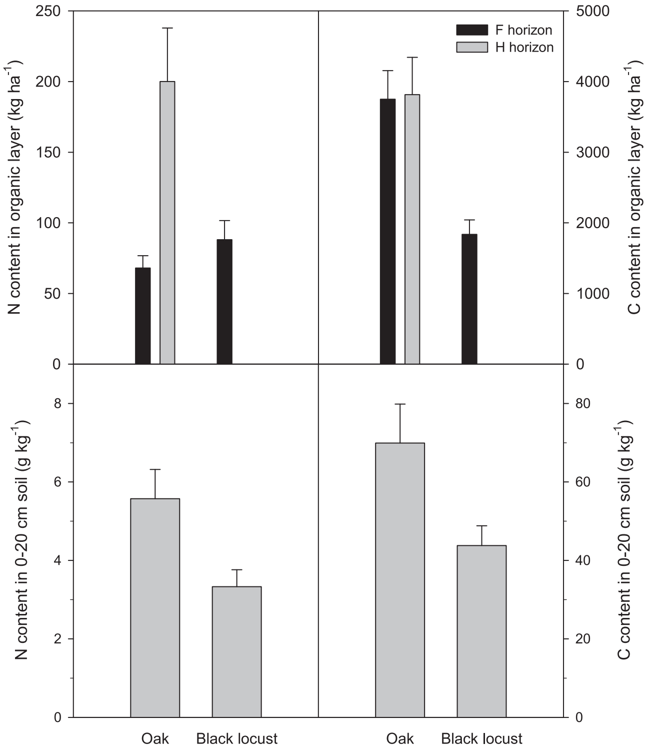

**Fig. 1.** Amounts of C and N on the forest floor (top figures) and C and N contents in the 0–20 cm soil (bottom figures) in the oak and black locust stands, respectively. Sampling of forest floor was applied to F and H horizons in oak stand, whereas only F horizon was observed in black locust stand. Error bars indicate standard errors. These graphs are based on the original data of Tateno et al. (2007).

Main observation plots with dimensions of 20 m × 20 m had been set in both stands for multipurpose investigations of, for example, forest structure and growth and litter fall collection. Previous investigation had revealed some differences in soil structure and nutrient contents between the two stands (Tateno et al., 2007). Whereas both the semi-decomposed, fragmented organic matter layer (F horizon) and humus layer (H horizon) had developed in the oak forest, only F horizon was observed in the black locust plantation. The total amount of C and N on the forest floor was significantly higher in the oak forest ($8565.4 \pm 932.5$ kg ha$^{-1}$ and $268.1 \pm 36.4$ kg ha$^{-1}$) than in the black locust plantation ($1836.0 \pm 205.6$ kg ha$^{-1}$ and $88.1 \pm 13.5$ kg ha$^{-1}$). Furthermore, both C and N contents in 0–20 cm soil were higher in the oak forest than in the black locust plantation (Fig. 1). Other characteristics for the study site were also described in former reports (Du et al., 2007; Otsuki et al., 2005; Tateno et al., 2007).

To avoid disturbance of the plots, four 5 m × 5 m subplots were set in the four corners of each plot in the early May of 2009. Five specially made polyvinyl chloride collars were placed in each subplot for measurements of soil total $CO_2$ efflux (Fig. 2).

### 2.2. Partitioning soil respiration

A trenching method was employed to partition total soil respiration ($R_t$) into $R_m$ and $R_r$. The root-free soil plots were created using micro-pore meshes with pore sizes smaller than the diam-

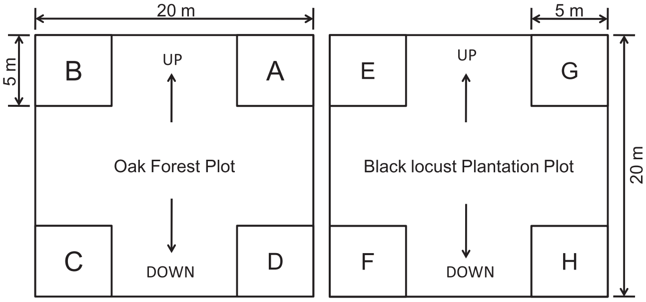

**Fig. 2.** Setting of the study plots for an oak (*Quercus liaotungensis*) forest and a black locust (*Robinia pseudoacacia*) plantation and the placement of four subplots in each plot. Black locust is a main reforestation species in the region and the study plot was set on a southeast-facing slope with a declination of 26°. The oak-dominated stand is a natural secondary forest common to the region and the plot was set on a northeast-facing slope with a declination of 22°. The two stands were about 150 m apart.

eter of a fine root, which prevented root growth into the plots and allowed the movement of water, bacteria, organic matter and minerals through the mesh and thus reduced the disturbance of natural soil conditions that could affect the decomposition of litter and soil organic matter (Moyano et al., 2007). $R_r$ is here defined as respiration by roots, their associated mycorrhizal fungi and other microorganisms in the rhizosphere directly dependent on labile C compounds released from roots.

In each stand, five small plots of 0.5 m × 0.5 m were established for the trenching experiment. These plots were within a distance of 5–6 m to a main plot (near the subplots A and E, respectively). Trenches of 0.2 m wide and 0.7 m deep were excavated around each small plot in March 2010. After lining the trench with Nylon mesh of 0.038 mm mesh size, soil was refilled into the trench. The soil encircled with nylon mesh remained undisturbed in the plot. Then a special collar (explained below) was placed in the small plot for $CO_2$ efflux measurements. It was assumed that the $CO_2$ efflux measured in the mesh treated plots was composed of only $R_m$ while $CO_2$ efflux measured in planted field was composed of both $R_m$ and $R_r$. Differences between mesh treatments and planted field were used to determine $R_r$. According to some measurements carried out before the experimental exclusion, there were no significant respiration differences among subplots in each stand.

### 2.3. Soil respiration measurement

Soil respiration was measured using an automated soil $CO_2$ flux system (LI-8100, LI-COR, USA) equipped with a portable chamber (Model 8100-103). Polyvinyl chloride collars (20.3 cm in diameter and 10 cm in height) were inserted into the forest floor to a depth of 2.5 cm at each sampling point about two weeks before the first measurement for the collar. Small litter and branches were left in the collar and large items removed. All collars were left at the site for the entire study period.

Total soil respiration in response to precipitation was investigated in the dry season of 2009. The measurements were made twice on each sampling day in the morning (8:30–11:30 local time) and afternoon (14:30–17:30). The entire investigation period was from May 25 to July 1 in 2009, during which there was only 27.7 mm precipitation, which occurred on May 27–28 in 2009. Besides the two rainy days, measurements were not conducted on June 3–28 in 2009, a period of dry weather. The automatic measurement for each collar lasted approximately 4 min.

In May 17–22, 2010, measurements for both $R_t$ (subplot A and E) and $R_m$ (trenching plots) were carried out on each sampling day (8:30–11:30 local time). And there was 19 mm precipitation on May 14–16 before the measurements. Unfortunately we had lost an opportunity of measurement for the day right before this rainfall. Nevertheless, measurements for both $R_t$ and $R_m$ were successfully conducted on five post-rainfall days in 2010 and for $R_t$ on both pre- and post-rainfall days in 2009.

### 2.4. Estimation of fine root mass

For estimation of root biomass, soil core samples were collected from both forests using a cylindrical soil corer (20 $cm^2$ in area and 5 cm in depth). In each forest, five core samples were collected from each of six depths (0–5 cm, 5–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, 50–70 cm). For oak forest, we additionally collected five humus layer samples of 20 $cm^2$ in area using a cylindrical soil corer. Fine roots (<2 mm in diameter) in the soil cores were hand sorted to separate living from dead based on the morphology and condition. After sorting, the dry masses of roots were measured after drying at 70 °C for 72 h.

### 2.5. Measurements of soil temperature and moisture

The soil temperature and moisture near each collar were measured at the same time as the measurement of soil respiration. Soil temperature was measured at a depth of 12 cm using a thermocouple probe, while the soil volumetric water content was measured using a time-domain reflectometry moisture meter (TDR200, Spectrum, USA) at depths of 12 and 20 cm.

### 2.6. Statistical analysis

By using *t*-tests (at $P < 0.05$), we compared investigated variables between the black locust and oak stands, including soil respiration rate, soil volumetric water content at depths of 12 and 20 cm, soil temperature at a depth of 12 cm, and the amount of C, N and fine root mass on the forest floor and in soil. Two-way analysis of variance was applied to tests of the effect of rainfall on the soil respiration rate, soil volumetric water content and soil temperature using Duncan's test at $P < 0.05$. We used SPSS for Windows software (SPSS Inc., Chicago, USA) for all statistical analyses.

## 3. Results

### 3.1. Soil respiration changes across the study periods

The general pattern of the change in soil respiration during each study period was similar in the plots and subplots (Fig. 3). Before the precipitation in 2009, soil respiration rate was relatively low. The lowest values were 3.0 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ in the oak plot (subplot C) and 1.9 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ in the black locust plot (subplot F). Precipitation resulted in large increases in soil respiration rates. The peak values were 4.8 and 4.4 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ in the oak plot (subplot A) and black locust plot (subplot G), respectively. The soil respiration rate then gradually decreased as the dry period continued. After 33 days of dry period, the soil respiration rate reduced to about 1 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ in both plots.

On the whole, soil respiration rates decreased to their initial pre-rainfall levels within five days of the weather clearing. However, the soil respiration rate decreased more rapidly in the artificial plantation of black locust than in the natural oak forest.

The response pattern of $R_t$ to a rain event was basically the same in 2010 and 2009. Though we missed the pre-rainfall measurements in 2010, given the results obtained in 2009 and our general understanding of soil respiration dynamics, $R_t$ values were considered to be much lower before the rainfall event. The differences in $R_t$ peak values between 2010 and 2009 are not significant for both stands (Figs. 3 and 4a and b). However, in contrast to the similarity of changes in $R_r$ and $R_t$ that gradually decreased in the post-rainfall

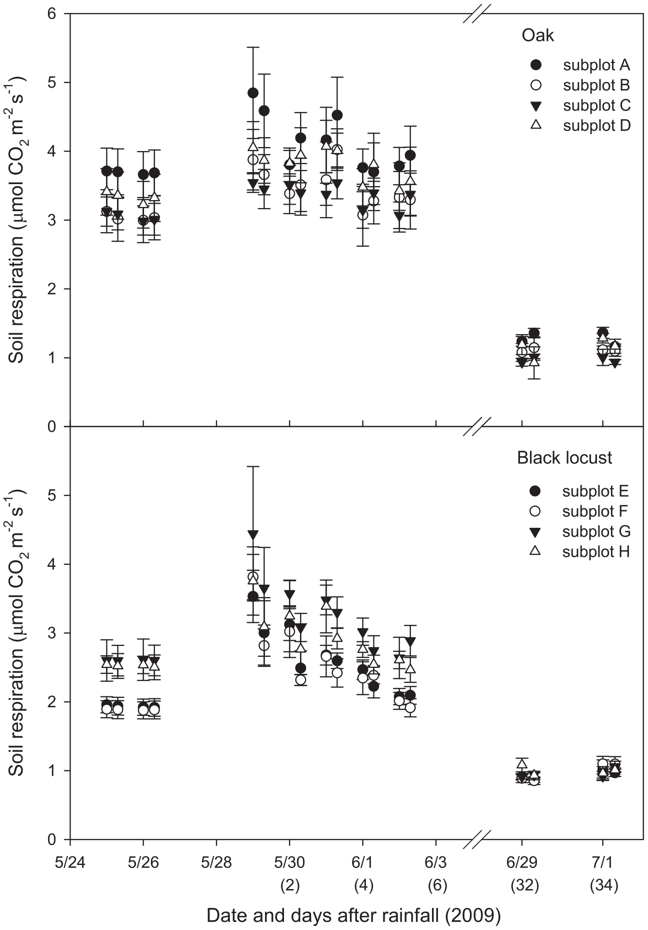

**Fig. 3.** Soil respiration rate in each subplot in the investigation period divided by a rain event (May 27–28, 2009). Persistent drought continued after the rainfall for more than one month and the measurements were suspended in the period of June 3–28. In addition to the calendar dates, days after the rainfall are also marked under the horizontal axes (in parentheses). The data are presented as means with standard errors ($n = 5$, same in the subsequent figures).

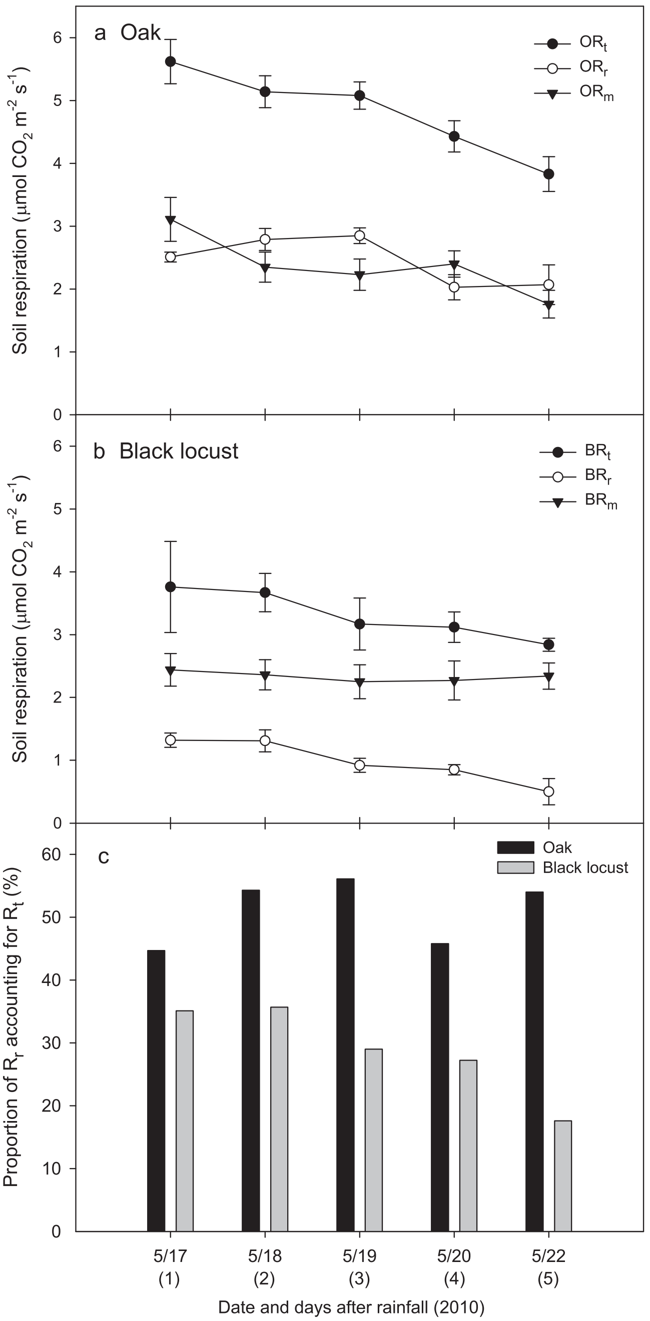

**Fig. 4.** Variation in soil respiration components in the stands of oak (a) and black locust (b) over five post-rainfall days in 2010, and the proportion of respiration by roots accounting for total respiration during the period (c). $OR_t$: total soil respiration in oak stand; $OR_r$: root-rhizosphere respiration in oak stand; $OR_m$: root-free soil respiration in oak stand; $BR_t$: total soil respiration in black locust stand; $BR_r$: root-rhizosphere respiration in black locust stand; $BR_m$: root-free soil respiration in black locust stand.

dry period for both stands, distinct decreases in $R_m$ were only found in the oak stand. The $R_m$ in black locust stand was almost constant during the post-rainfall measurement days (Fig. 4b). Furthermore, $R_r$ in oak stand was constantly higher than in the black locust stand during this period.

Fig. 4c shows the temporal variation in the proportion of $R_r$ accounting for $R_t$ after precipitation in 2010. Whereas the proportion of $R_r$ was relatively stable in the oak stand (around 50%), the proportion of $R_r$ in the black locust stand gradually decreased from 35% to 18% in the five dry days after precipitation. It is reported that the contribution of root respiration to total soil respiration varies from 10 to 90% (Hanson et al., 2000; Hogberg et al., 2001). Thus the 18% contribution of $R_r$ in this study was at a relatively low level and might be related to the dry condition. These results revealed that, in black locust stand, the changes in $R_t$ after precipitation were mainly attributed to the changes in $R_r$, whereas $R_m$ and $R_r$ contributed equally in the oak stands.

### *3.2. Variations in soil moisture and temperature during the measurement periods*

Soil volumetric water contents at depths of 12 and 20 cm and soil temperature at a depth of 12 cm in each subplot during the study period in 2009 are shown in Figs. 5 and 6. Before precipitation, soil volumetric water contents were relatively low in both plots. Precipitation resulted in significant increases in the water contents in both plots. In the days following the rainfall, the water contents gradually decreased and reached initial levels within about 5 days (Fig. 5). After one month of persistent dry days, the soil volumetric water contents decreased to levels much lower than the pre-rainfall levels. The water contents measured at a depth of 12 cm decreased more rapidly than those at a depth of 20 cm.

The precipitation events are generally associated with cooler air temperatures, resulting in lower soil temperatures. The soil temperature was back to the original levels before precipitation after five clear days (Fig. 6). Then it rose about 5 °C in the following month, corresponding with the usual trend at this time of year.

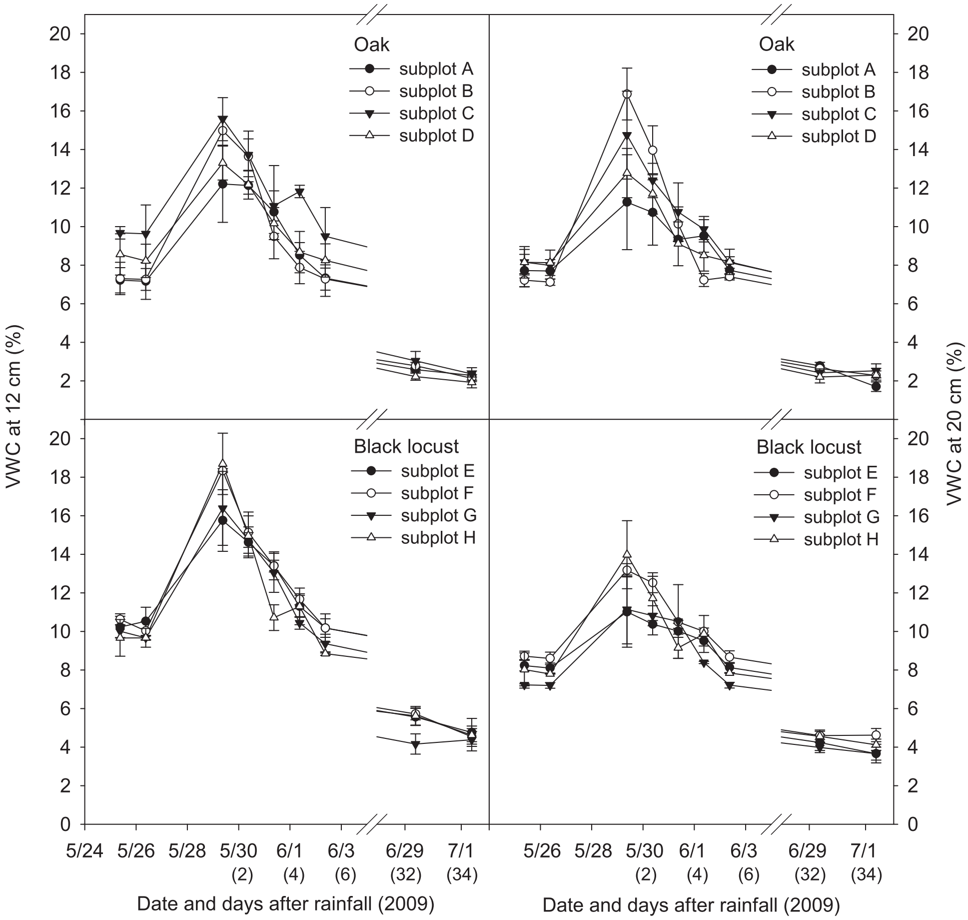

**Fig. 5.** Soil volumetric water content (VWC) during the investigation period at depths of 12 (left panels) and 20 (right panels) cm measured simultaneously with the measurement of soil respiration in 2009.

In the month of drought after the rainfall, the reduction in soil moisture in the oak plot was larger than that in the black locust plot, whereas the soil temperature rise was less in the oak plot than in the black locust plot. Furthermore, the variation in soil temperatures between morning and afternoon hours was larger in the black locust plot. These results were consistent with the greater amount of foliage in the oak stand and the resulting differences in water consumption and the under-crown environment between the two stands.

The changes in soil moisture and temperature after rainfall in 2010 were roughly the same as those in 2009. As the change patterns of soil moisture and temperature were more typical and dry period lasted longer than usual in the study period of 2009, the data of 2010 were not presented here.

### 3.3. *Spatial variations in soil moisture, temperature and respiration rate*

As the radiation conditions and root distributions should not be identical among the subplots, differences in soil moisture, temperature and respiration rates were detected to some extent. However, Duncan's variance test showed that differences among the four subplots were not significant in both stands, suggesting low spatial variation within a plot.

### 3.4. *Amount of fine roots in soil*

Fig. 7 shows distribution of fine roots in different soil depth in the two stands. The fine root mass decreased with soil depth in oak forest, whereas in black locust plantation it was almost evenly distributed across different soil layers. Fine roots in oak forest concentrated in the upper 20 cm soil layer (amounting 82.6% of the total in 70 cm soil layer). There were more fine roots in oak stand than in black locust stand, and the difference in fine root mass between the two stands was mainly contributed by the upper soil layers.

## 4. Discussion

It is generally accepted that both soil moisture and temperature strongly affect soil respiration rate. In semiarid ecosystems, however, their relative importance is still controversial (Huxman et al., 2004). It has been reported that the relationship between soil respiration and soil moisture can be fitted by several functions including linear, exponential and logarithmic, asymptotic and polynomial functions (S.P. Chen et al., 2008). Upon comparison of different functions, linear functions were applied to the datasets of soil respiration with either soil moisture or temperature in this study. The positive relationship between the soil respiration rate and soil volumetric water content suggests that soil moisture was a limiting factor in carbon decomposition in the season. In this study, the linear relations between respiration and soil water content covering all data sets in 2009 appear to be weak, suggesting an influence by the interaction of soil water content and temperature. However, after limiting the data sets to a narrower span of temperature (2 °C magnitude around the mid value, i.e. 13–15 °C for oak plot and 16–18 °C for black locust plot), stronger positive correlations between soil water content and respiration were reached expectably (Fig. 8).

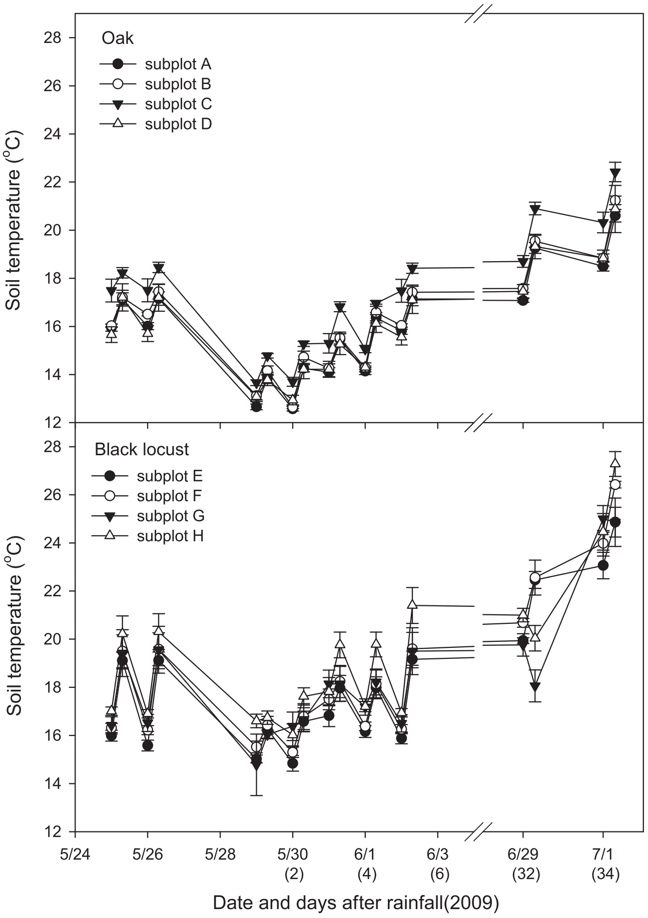

**Fig. 6.** Soil temperature during the investigation period at a depth of 12 cm measured simultaneously with the measurement of soil respiration in 2009.

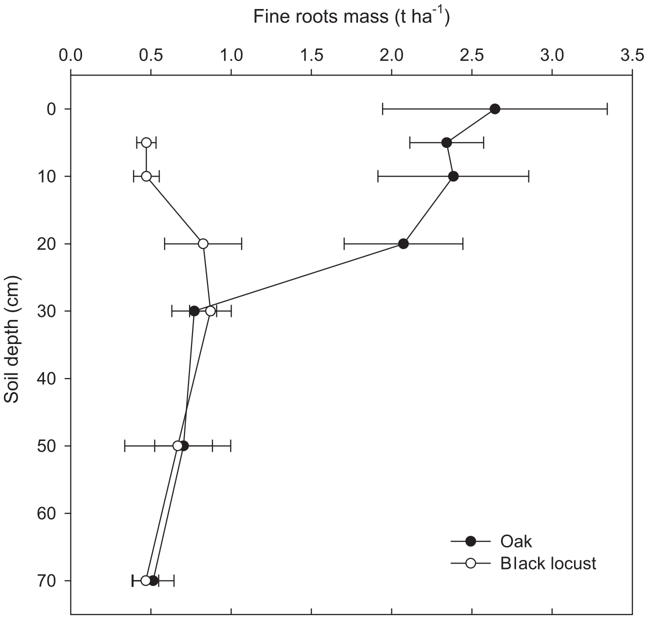

**Fig. 7.** The distribution of fine root mass over different soil depths in the oak and black locust stands, respectively.

In addition, the differences in regression slopes suggest that soil respiration in the black locust plantation is more sensitive than that in the oak forest. Also, the proportion of $R_r$ was almost stable in the oak stand, however, it showed a relatively rapid decrease during dry season in the black locust plantation. The $R_r$ in the black locust stand was the dominant component responsible for changes in $R_t$ in response to precipitation (Fig. 4). Likewise, our annual unpublished data for 2010 showed that the $Q_{10}$ value of $R_r$ (2.08 in oak plot and 3.37 in black locust plot) was higher than $R_m$ (1.68 for oak and 1.05 for black locust) in both forests and the $Q_{10}$ value of $R_r$ for black

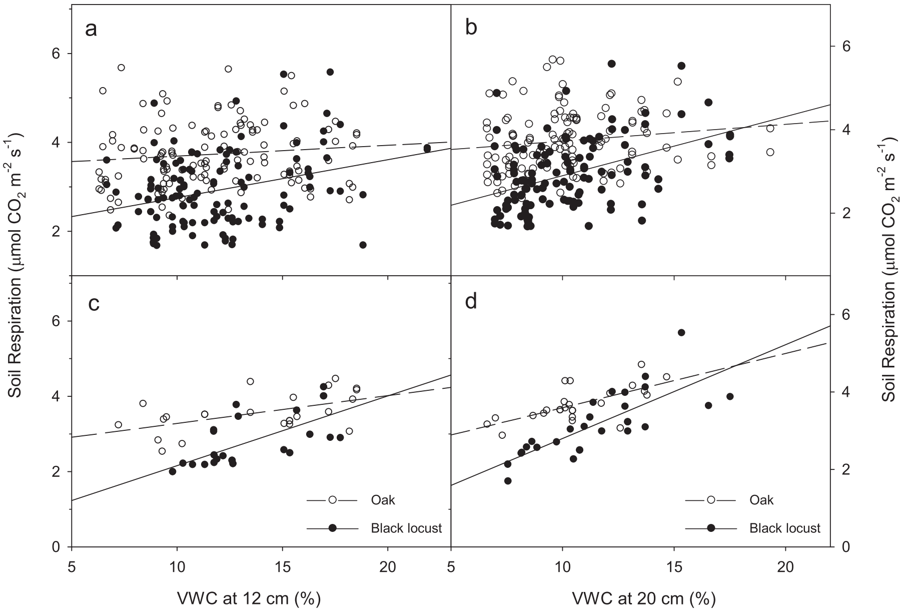

**Fig. 8.** Soil respiration rate in relation to soil volumetric water content (VWC) at a depth of 12 and 20 cm in the two study plots for the data of 2009 measurements (a and b). The dashed and solid lines represent linear fits to the datasets for the oak ($y = 0.024x + 3.446$, $R^2 = 0.02$, $P > 0.05$) and black locust ($y = 0.085x + 1.902$, $R^2 = 0.11$, $P < 0.001$) stands at the depth of 12 cm, and for oak ($y = 0.040x + 3.323$, $R^2 = 0.02$, $P > 0.05$) and black locust ($y = 0.142x + 1.478$, $R^2 = 0.20$, $P < 0.001$) stands at the depth of 20 cm, respectively. Sub-graphs (c and d) are data sets covering a narrow span of temperature, being limited to 2 °C magnitude around the mid value (13–15 °C for oak plot and 16–18 °C for black locust plot). The dashed and solid lines represent linear fits to the datasets for the oak ($y = 0.073x + 2.542$, $R^2 = 0.28$, $P < 0.001$) and black locust ($y = 0.185x + 0.303$, $R^2 = 0.45$, $P < 0.001$) stands at the depth of 12 cm, and for oak ($y = 0.140x + 2.188$, $R^2 = 0.45$, $P < 0.001$) and black locust ($y = 0.242x + 0.375$, $R^2 = 0.62$, $P < 0.001$) stands at the depth of 20 cm, respectively.

locust plantation was higher than for oak forest. Consequently, $R_r$ contributed to the higher sensitivity of $R_t$ to soil moisture and temperature changes in black locust stand than oak forest. Although soil respiration could be influenced by some biotic and/or abiotic factors, for example phenology and root growth dynamics, they should not be significant in such a dry season's short-term measurement. There has been report that microbial respiration decreases in dry conditions (Griffis et al., 2004). In this study, the main reason for the strong response of the black locus stand seems to be enhanced rhizosphere respiration ($R_r$) which slowed gradually after it had peaked during the first 2 days of rewetting (Fig. 4). This is likely attributed to the ecophysiological properties (Griffis et al., 2003; Yan et al., 2010). Du et al. (2011) suggest that the indigenous oak trees are less sensitive to temporally changes in soil water conditions than the fast-growing black locust trees. The exotic black locust was considered to be more drought-sensitive. Experiments with seedlings also suggest that black locust has some drought-sensitive characteristics (Yan et al., 2010). These findings are consistent with the suggestion in the present study that the activity of rooting system in black locust stand is more sensitive to precipitation than that in the oak stand.

There might be some uncertainty resulting from priming effect in trenching experiment. Priming, if present from root exudates, and inputs of recently dead roots, mycorrhizae and foliage, would enhance "native" soil C decomposition compared to that in the trenched collars (Chen et al., 2002; Fu and Cheng, 2002). In this study, however, the measurements were carried out at almost three months after trending. According to some research (Fenn et al., 2010; Sayer and Tanner, 2010), errors associated with the use of root exclusion, e.g. priming effect, can be avoided after such a period. Furthermore, recent reports accumulated more cases for successful application of this method (Fenn et al., 2010; Moyano et al., 2007).

Black locust, as a fast-growing exotic species, has been widely introduced for the reforestation of abandoned cropland in the Loess Plateau region. Reforestation may cause problems and changes related to productivity, nutrients, material cycling of local ecosystems and even groundwater deficits (Ohte et al., 2003). Thus, it is important to investigate differences between natural and artificially established ecosystems in terms of functional differences and their consequences (Otsuki et al., 2005; Tateno et al., 2007). In this study, we found that the soil respiration rate was generally higher before and after precipitation in the oak forest than in the black locust plantation. This result may be attributable to the different pool sizes of labile and recalcitrant carbon at the soil surface. The C, N contents and fine root mass on the forest floor and in soil are much higher in the oak forest than in the black locust plantation, supporting the results in this study (Figs. 1 and 7). It is thus suggested that in such a semiarid region, the total $CO_2$ quantity derived from soil respiration in the black locust plantation is less than that from the oak forest.

Nevertheless, when soil respiration rates were set into relation to soil organic matter content and root biomass, both $R_m$ and $R_r$ were much higher in the black locus stand (Fig. 9). The higher $R_r$ on the fine root mass basis might be related to a higher physiological activity of the species. Similarly, the higher $R_m$ on the organic material basis was consistent with a high decomposition activity of its organic layer. As a N-fixing species, black locust leaves had a lower C:N ratio and showed faster decomposition rates than oak (Tateno et al., 2007). Furthermore, a higher specific leaf area for black locust than oak may also have contributed to the higher decomposition rate of black locust (Cornelissen et al., 1999; Yan et al., 2010). The difference in decomposition rate between the stands reflected their difference in soil organic matter accumulation (Fig. 1).

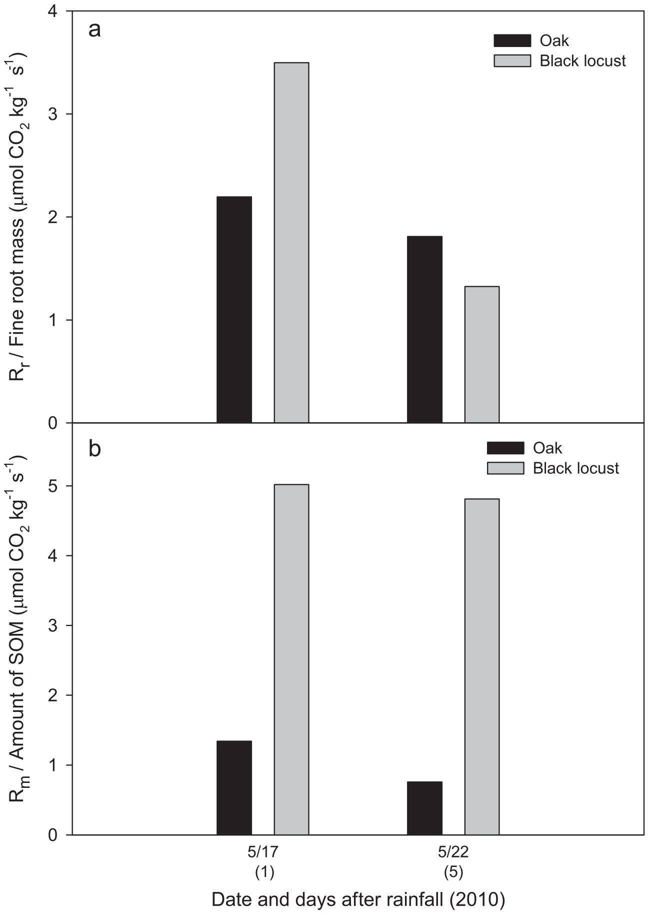

**Fig. 9.** (a) $R_r$ of per unit fine root mass, and (b) $R_m$ of per unit amount of soil organic matter (SOM) in the two stands on the first (5/17) and the fifth day (5/22) after rainfall in 2010.

There have been a number of reports on the effect of soil temperature on soil respiration in different places with different ecosystems (Gaumont-Guay et al., 2006a; Gu et al., 2008; Hashimoto et al., 2009; Jia and Zhou, 2009; Malcolm et al., 2009; Yuste et al., 2003). These studies generally suggest a positive relationship between soil temperature and soil respiration. However, our study was unable to reach such a conclusion (Fig. 10a). Similar results were also reported recently (Xu and Wan, 2008). This might be attributed to three causes. One is that our study site lies within the semiarid forest–grassland transition zone. As water plays a dominant role in the transient response of the ecosystem carbon balance, a change in soil temperature may not have a significant effect relative to the effect of the water element. The second is the small variation in soil temperature during the present measurement period that turned out to be a non-dominant factor for soil respiration. And the third is that high temperatures are routinely accompanied by low moisture (Xu and Wan, 2008). After limiting the data sets to a narrower span of soil moisture (10–12%), the negative relationships turned out to be weak, suggesting the temperature factor was not dominant in the condition (Fig. 10b).

Abrupt changes in soil respiration rate are commonly observed following rainfall events (Borken et al., 1999; Davidson et al., 2000; Kirschbaum et al., 2008; Lee et al., 2002, 2004; Yuste et al., 2003). Several researchers reported significant decreases in soil respiration after rainfall (Ball et al., 1999; Ito and Takahashi, 1997). In contrast, other studies on soil respiration in forest ecosystems suggested that the soil respiration rate significantly increases immediately after a rainfall event (Borken et al., 2003; Davidson et al., 2000; Lee et al., 2002; Li et al., 2008). These seem to be

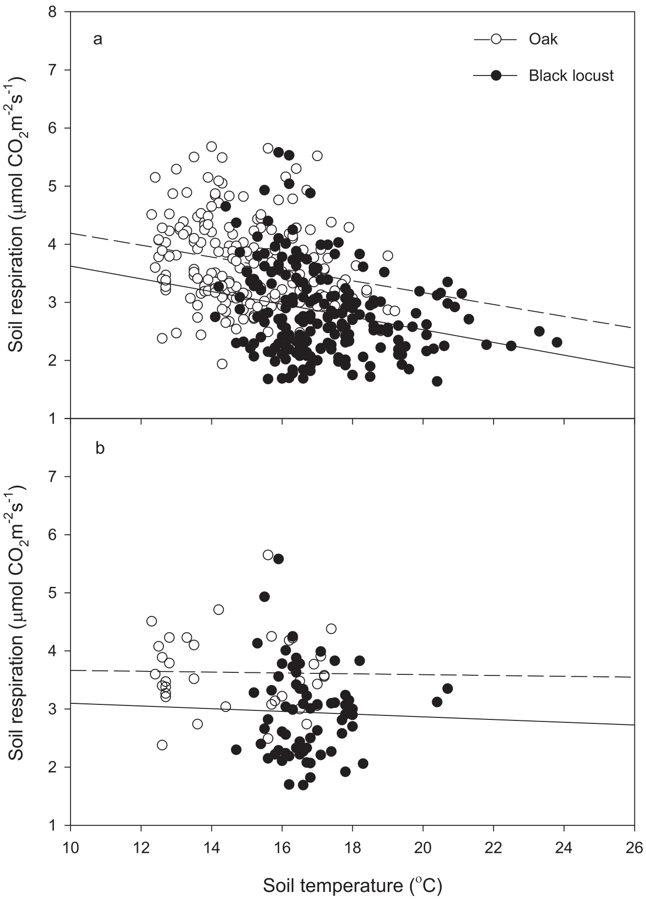

**Fig. 10.** Relationship between soil respiration and soil temperature at a depth of 12 cm in the two study plots for the data of 2009 measurements. Sub-graph (a) covers all measured data while sub-graph (b) covers only the data sets for soil moisture 10–12%. The dashed and solid lines represent linear fits to the datasets for the oak forest ((a) $y = -0.102x + 4.988$, $R^2 = 0.05$, $P < 0.05$; (b) $y = -0.007x + 3.737$, $R^2 = 0.001$, $P > 0.05$) and black locust plantation ((a) $y = -0.110x + 4.719$, $R^2 = 0.06$, $P < 0.05$; (b) $y = -0.023x + 3.333$, $R^2 = 0.001$, $P > 0.05$), respectively.

opposing conclusions on the effect of rainfall on soil respiration. However, a threshold value for soil moisture found in several studies explained this contradiction. When soil moisture is lower than the threshold, soil respiration increases with an increase in soil moisture due to rainfall. If soil moisture is higher than the threshold, further increases in soil moisture lead to a decrease in respiration (Dilustro et al., 2005; Gaumont-Guay et al., 2006b; Law et al., 2001; Li et al., 2008; Rey et al., 2002; Xu and Qi, 2001). Nevertheless, the threshold should be different over ecosystems and soil types.

In the present study, a 27.7 mm precipitation event increased soil respiration in the two forest stands in the forest–grassland transition zone of the Loess Plateau. The post-rainfall stimulation might result from a displacement of $CO_2$-rich air from within the soil, rapid decomposition of microbial biomass and an increase in the surface area of organic substrates (Li et al., 2008; Yuste et al., 2003). Enhancement of the activity of rooting systems may have made a particular contribution to the soil respiration increase in the present case. At the present study site, rainfall is unevenly distributed with a peak in July and August and a dry season in spring and early summer. Investigation in recent years suggests that single-event precipitation is generally less than 30 mm in the dry season of spring and early summer (unpublished data). It is thus deduced that a common rainfall event will lead to an increase in soil respiration at the site. In other words, even though the soil moisture threshold for the studied ecosystems was not determined, the studied 27.7 mm precipitation event can be considered smaller than the threshold event. Generally, soil field capacity of this type is around 26% in this area. As the soil water contents in this study were much lower than the soil field capacity, the relationship between soil respiration and soil water contents was constantly positive. In the present study, the two study periods belong to the same season of different years. The results should greatly contribute to the understanding of soil $CO_2$ efflux in these typical forest stands of the region. Further studies, with increased temporal and spatial scales, are needed to clarify the responsive mechanisms of these forest ecosystems to the environmental factors.

## 5. Conclusions

In an area of semiarid forest–grassland transition on the Loess Plateau, rainfall plays a dominant role in soil respiration in both an exotic black locust plantation and a native oak forest in a short-term investigation. Any common precipitation event in the region may increase soil respiration but the responses are different between ecosystems. Generally, soil respiration rate in the black locust plantation is less than that in the natural oak forest, but the rate is more sensitive to rainfall in the black locust plantation than in the oak forest. The $R_r$ in the black locust plantation is the dominant component responsible for changes in $R_t$, whereas $R_m$ and $R_r$ contributed equally in the oak forest. Both $R_m$ and $R_r$, when calculated on the bases of the stand organic layer amount and fine root mass, respectively, were higher in the black locust plantation than in the oak forest. From the viewpoint of global change and forest management, long-term changes in above- and below-ground carbon accumulation and soil respiration dynamics for these ecosystems require further investigation.

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