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ORIGINAL PAPER

Response of soil respiration to a severe drought in Chinese *Eucalyptus* plantations

Shaojun Wang[1,2] · **Hong Wang**[1]

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Abstract Extreme droughts can adversely affect the dynamics of soil respiration in tree plantations. We used a severe drought in southwestern China as a case study to estimate the effects of drought on temporal variations in soil respiration in a plantation of *Eucalyptus globulus*. We documented a clear seasonal pattern in soil respiration with the highest values (100.9 mg C–CO_2 m^{-2} h^{-1}) recorded in June and the lowest values (28.7 mg C–CO_2 m^{-2} h^{-1}) in January. The variation in soil respiration was closely associated with the dynamics of soil water driven by the drought. Soil respiration was nearly twice as great in the wet seasons as in the dry seasons. Soil water content accounted for 83–91% of variation in soil respiration, while a combined soil water and soil temperature model explained 90–99% of the variation in soil respiration. Soil water had pronounced effects on soil respiration at the moisture threshold of 6–10%. Soil water was strongly related to changes in soil parameters (i.e., bulk density, pH, soil organic carbon, and available nitrogen). These strongly influenced seasonal variation in soil respiration. We found that soil respiration was strongly suppressed by severe drought. Drought resulted in a shortage of soil water which reduced formation of soil organic carbon, impacted soil acid–base properties and soil texture, and affected soil nutrient availability.

Keywords Drought · *Eucalyptus globulus* · Global change · Soil respiration

Introduction

Reducing soil CO_2 emissions is of importance for global climate change mitigation (Duarte et al. 2013; Wani et al. 2014). Reforestation, a major strategy for mitigating global climate change, can greatly affect soil CO_2 emissions by changing key physical and chemical properties that influence soil nutrient and carbon cycling, and microbial activity (Kumar et al. 2014). *Eucalyptus* is recommended by FAO for mitigating CO_2 emissions. The total area covered by *Eucalyptus* plantations has rapidly increased worldwide, especially in China (Wang 2012), and this might significantly affect soil CO_2 emissions (Piao et al. 2009; FAO 2010; Wani et al. 2014).

The CO_2 emitted from soil via soil respiration (SR), is a major component of total CO_2 emissions at ecosystem level and a critical pathway of the carbon (C) cycle, which exerts substantial effects on soil organic carbon (SOC) levels (IPCC 2006). Slight changes in SR can significantly impact the SOC storage of forest ecosystems and, ultimately, future atmospheric CO_2 concentrations (IPCC 2007). Understanding of the seasonal variations in SR and

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✉ Shaojun Wang
shaojunwang2009@163.com

[1] Department of Environmental Science and Engineering, Southwest Forestry University, Bailongsi, Kunming 650224, People's Republic of China

[2] Co-Innovation Center for Sustainable Forestry in Southern China, College of Biology and the Environment, Nanjing Forestry University, Nanjing 210037, People's Republic of China

its influencing mechanism in forest ecosystems can contribute to quantifying C accumulation in forests and to reducing the rate of global warming.

Soil water (SW) and soil temperature (ST) are among the most important factors controlling the dynamics of SR. Factors of substrate supply such as soil organic carbon and nitrogen, soil texture and soil pH also influence SR (Liu et al. 2006; Luo et al. 2012). Predicting temporal variation in SR and its potential response to global climate change requires an understanding of the effects of these factors on SR. SW deficits can reduce soil CO_2 emissions and minimize the influence of ST on SR (Wen et al. 2006). Moisture limitations can suppress microbial activity and root respiration regardless of ST, which in turn affects the temperature sensitivity of SR (Guo et al. 2009; Wallenstein et al. 2010; Zhang et al. 2010). However, the rate of SR depends on ST only when SW exceeds certain threshold values. Therefore, it is particularly important to expound the influencing mechanism of SW on SR.

Extreme drought can have direct effects on SR in forest ecosystems (IPCC 2007; Reichstein et al. 2013). However, the effects of droughts on SR are uncertain. Severe drought can affect soil water, plant root dynamics, litter fall, soil organic matter and nutrient mineralization rates, all of which, in turn, influence SR processes (Reichstein et al. 2013). Suppression of SR under intense drought should lead to an increase in C sequestration, but this might depend on the relative decreases in SR and gross primary production (GPP) caused by water stress. Jassal et al. (2008) reported a decrease of C stock under reduction of SR in a 56-year-old Douglas fir stand because GPP declined by a wide margin in a severe drought year. Therefore, the response mechanism of SR to droughts is crucially important for understanding the feedback potentials of ecosystems to C uptake.

An extreme drought from 2009 to February 2013 in the Yunnan region of southwestern China was the driest period in the past 50 years. This extreme drought presented an opportunity for a case study of drought impacts on the dynamics of SR. In this study, we examined seasonal variation of SR, and its associated factors related to weather and soil (i.e., soil temperature, soil water constant, pH, bulk density, and soil nutrients) in plantations of *E. globulus* under severe drought stress in Kunming city, southwestern China. Our objectives were to answer the following questions: (1) Can extreme drought affect the dynamics of SR; and (2) Can changes in soil physico-chemical characteristics that are driven by the drought have an impact on temporal variation in SR?

Materials and methods

Site description

The study was conducted in northeastern Yunnan Province (25°03′25″N, 102°46′15″E). The site has a subtropical plateau monsoon climate. Annual mean temperature and average annual rainfall are about 15 °C and 1011 mm (average for 1971–2000, data from China Meteorological Administration), respectively. Precipitation is strongly seasonal with a rainy season (about 85% rainfall of annual precipitation) from May to October, and a dry season (about 15% of annual precipitation) from November to April.

Our study site was on 2–5% sloping terrain at elevations of 1985–2200 m. The plantations were dominated by 18-year-old *E. globulus*, with a density of 1480 trees ha^{-1} and average tree dimensions of 28 m high and 21 cm in diameter at breast height. Canopy closure was 55–75%. The surface organic layer was about 15 cm with a shallow surface litter layer (0–20 cm). The understory was mainly *Myrsine africana* and *Lysidice rhodostegia*. The mountain red soil in the plantation was derived from purple shale materials or purple sandstone, normally >1 m deep, with pH of 5.7–7.7. The soil was well-drained, stone-free, and with low organic matter content and compact texture.

Kunming experienced severe drought from 2009 to February 2013, based on precipitation data from Kunming and China Meteorological Administrations (Table 1). The total rainfall in Kunming from 2009 to 2012 was less than the average annual rainfall (1011.2 mm); February precipitation was 0 mm from 2009 to 2012, which had never occurred since meteorological recording began in 1951. The Kunming drought spanned the study sampling period (Mar. 2012–Feb. 2013). Total precipitation (789.4 mm) in 2012 was lower than average. The drought duration was longer in 2012; Rainfalls in January, February, April, June, July, August, October, November, and December 2012 were all lower than their long-term means. Precipitation in February and December 2012 was 0 mm. Rainfall in Jan-Feb 2013 was also much less than the long-term mean (Table 1).

Experimental design and measurements of SR and ST

Four sampling plots (30 m × 15 m) of *E. globulus* plantations with similar site conditions were selected with spatial arrangements at least 500 m apart. Within each plot, three 3 m × 3 m subplots were randomly sited to measure SR. SR measurements were conducted once (approx. day 20) each month from March to February 2012–2013. On

Table 1 Precipitation (mm) in Kunming from January (Jan) 2009–February (Feb) 2013

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1971–2000 (average)	15.8	15.8	19.6	23.5	97.4	180.9	202.2	204.0	119.2	79.1	42.4	11.3	1011.2
2009	7.1	0	10.7	22.4	51.6	153.8	90.8	169.7	28.3	9.1	21.8	0.5	565.8
2010	3.4	0	22.1	27.9	43.6	84.3	159.5	215.4	98.8	150.1	34.9	29.1	869.1
2011	22.2	0	18.6	31.2	29.1	130.3	102.7	57.2	212.9	21.0	19.7	14.1	659
2012	15.6	0	21.7	14.5	142.0	147.1	155.2	138.0	132.2	14.0	9.1	0	789.4
2013	10.1	0.9											

Source data from Kunming and China meteorological administrations

each measurement day, we measured between 10:00 and 16:00 h in small polyvinyl chloride (PVC) collars (10 cm in diameter and 5 cm in height) installed 2–3 cm into the soil two weeks in advance. All ground vegetation in the collars was removed by clipping to avoid interference caused by respiration of plants. SR was measured using the Li 6000-09 chamber (LiCor Inc, Lincoln, NE, USA) connected to a portable infrared gas analyzer (LiCor Inc). Data were recorded at 5 s intervals by the data logger in the LI-Cor 6400 console, after placing the chamber on the collar, scrubbing the CO_2 to sub-ambient levels, and determining soil CO_2 efflux over several 5 s periods. Each measurement usually took 1–3 min. ST was monitored simultaneously with SR using a copper/constantan thermocouple penetration probe (Li6000-09 TC, LiCor Inc) inserted in the soil to a depth of 5 cm in the vicinity of the SR chamber.

Soil sampling and analysis

Soil cores (6 cm diam.) were sampled from the soil surface down to 5 cm in the locations of PVC collars where SR chambers were placed following respiration measurements in each subplot. On each measurement day, 12 compound samples (500–1000 g) were collected to analyze soil properties (i.e., soil water content, pH, bulk density, soil organic matter, total soil nitrogen, and soil available nitrogen). Soil samples were sieved to remove visible plant material and then air-dried prior to measurements of soil properties. SW at depths was determined gravimetrically after drying approximately 20 g of fresh soil at 105 °C for 48 h. pH was measured by direct potentiometry. SOC was determined by the dichromate oxidation with external heating procedure, total N (TN) by the Kjeldahl digestion method, and soil available nitrogen (AN) by the alkaline hydrolysis diffusion method (Lu 2004).

Data analysis

The relationship between *SR* and *ST* was fitted with the functions of exponential regression [Van't Hoff Eq. (1)], and nonlinear regression [Arrhenius Eq. (2)], and [Lloyd and Taylor Eq. (3)] (Lloyd and Taylor 1994; Borken et al. 2002). We also performed linear, power and quadratic regression analyses of *SR* against *SW* using Eq. (4) as follows:

$$SR = \mathrm{a}e^{\mathrm{b}ST}, Q_{10} = e^{10b} \tag{1}$$

$$SR = \mathrm{a}e^{-\mathrm{E/R}(ST+273.2)} \tag{2}$$

$$SR = SR_{ref}e^{\mathrm{Eo}(1/\mathrm{STref}-\mathrm{STo})-1/(ST-\mathrm{STo}))} \tag{3}$$

$$\text{Linear:}\, SR = \mathrm{a} + \mathrm{b}\,SW,\ \text{Quadratic:}\, SR = \mathrm{a} + \mathrm{b}\,SW + \mathrm{c}SW^2 \text{or Exponential:}\, SR = \mathrm{a}\,SW^b \tag{4}$$

where a and b are fitted parameters, Q_{10} is the temperature sensitivity of *SR*, E is the fitted apparent activation energy (J mol^{-1}), and R is the universal gas constant (8.134 J mol^{-1} k^{-1}). SR_{ref} (μmol m^{-2} s^{-1}) and ST_{ref} are the SR and ST under standard conditions. E_0 is the activation-energy-type parameter whereas ST_0 is the lower temperature limit for *SR*.

Next, the following linear and nonlinear models [Eqs. (5)–(7)] were used to express the relationships among *SR*, *ST* and *SW* (a, b and c are fitted constants):

$$SR = \mathrm{a} + \mathrm{b}\ (ST\,SW) \tag{5}$$

$$SR = \mathrm{a} + \mathrm{b}\,ST + \mathrm{c}\,SW \tag{6}$$

$$SR = \mathrm{a}e^{\mathrm{b}\,ST}SW^{\mathrm{c}} \tag{7}$$

Statistical nonlinear regression and means testing analyses were performed using SPSS 17.0 (SPSS for Windows, Chicago, IL). The normality of data and equivalences of variance were tested. Regression analysis was applied to describe the relationship between SR, and SW and ST. Simple regression analyses were carried out to investigate the relationship between possible driving variables (i.e., pH, bulk density, SOC, TN, and AN) and temporal variability of SR.

Results

SR ranged from 28.7 mg C–CO_2 m^{-2} h^{-1} to 100.9 mg C–CO_2 m^{-2} h^{-1} (Fig. 1a). The minimum value occurred in winter (January) and the maximum value in summer

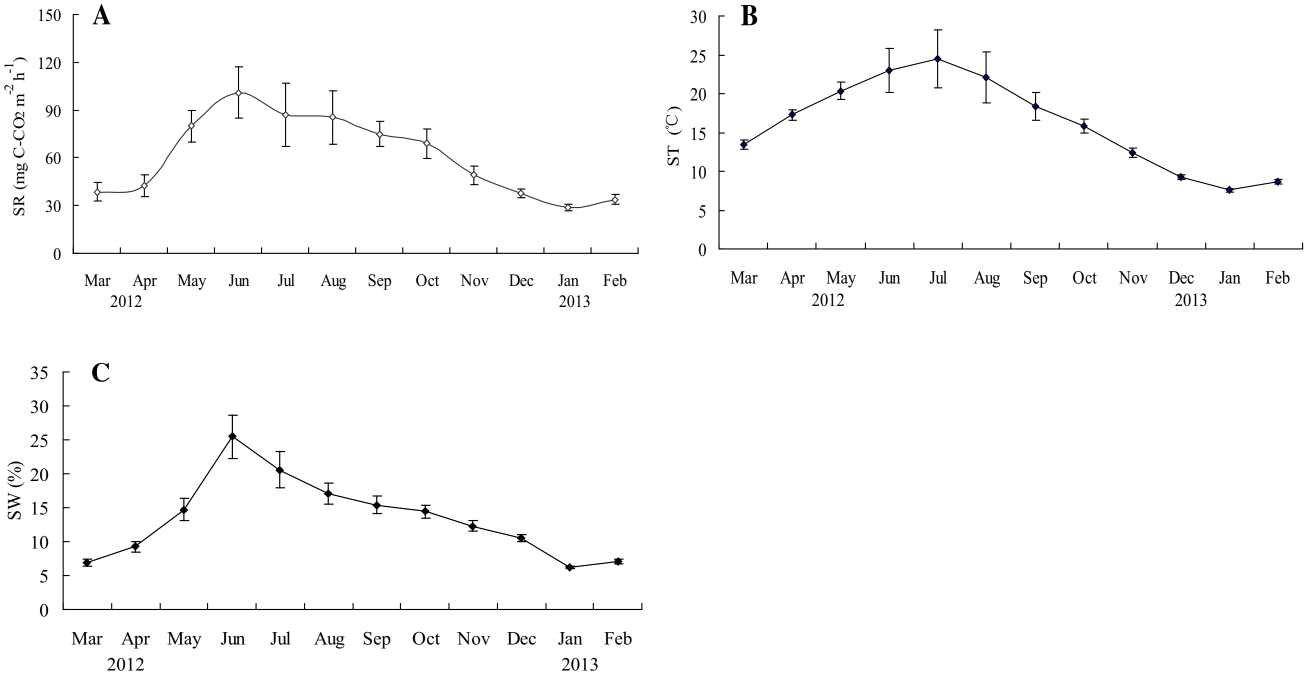

Fig. 1 **a** Seasonal variations of soil respiration (SR), **b** soil temperature (ST), and **c** soil water (SW) at the 5 cm depth in the *Eucalyptus* plantations

(June), consistent with the dynamics of SW (Fig. 1c). SR was nearly twice as great in wet seasons as in dry seasons. SR declined to 50 mg C–CO_2 m^{-2} h^{-1}, while SW dropped below 12.32%, indicating soil water stress strongly limited SR.

ST explained 72.4–81.6% of the seasonal change using the Van't Hoff, Arrhenius, and Lloyd and Taylor models, while Q_{10} values were the highest at 1.99 with the Van't Hoff regression (Table 2). However, SW showed a stronger significant effect on SR using either linear, power or quadratic models, which explained 83.7 to 91.1% of SR variations ($p < 0.001$, Table 3). The significance of fitted equations describing the relationship between SR and SW increased when SR values were normalized to the SR at 10 °C (Table 3). The combined effects of ST and SW on SR (R^2 of 0.901 to 0.995) were larger in comparison with the one-dimensional equation above with three equations (Eqs. 5–7), and exponential equation showed the best fit (Table 4).

Regression analyses were carried out to investigate the relationships among some possible driving variables (pH, bulk density, and soil nutrients) and temporal variability of SR (Fig. 2). The results showed that mean SR rate was positively correlated with pH ($R^2 = 0.721$, $p = 0.008$), SOC ($R^2 = 0.825$, $p = 0.014$), and AN ($R^2 = 0.754$, $p = 0.0046$) (Fig. 2a, b, d). In contrast, SR rate and bulk density were negatively correlated ($R^2 = 0.601$, $p = 0.0388$) (Fig. 2e). Mean SR and TN were not correlated ($R^2 = 0.497$, $p = 0.103$) (Fig. 2c).

Discussion

SR fluctuated widely from 28.7 mg C–CO_2 m^{-2} h^{-1} to 100.9 mg C–CO_2 m^{-2} h^{-1} during the severe drought. The distinct seasonal patterns were in accordance with the dynamics of SW. Our results were in agreement with Epron et al. (2004) who reported similar research in a *Eucalyptus* plantation subject to severe drought. The fast growth of *Eucalyptus* is highly depended on the water supply and extreme drought then greatly affected SR dynamics in the plantations. Simultaneously, the rate of SR declined

Table 2 Regression analyses of soil respiration (*SR*) and Q_{10} against soil temperature (*ST*) at 5 cm soil depth in the *Eucalyptus* community

Name	Equation	SR_{10}	Q_{10}	R^2	*F*	*P*
Van't Hoff	$SR = 0.455\ e^{0.069\ ST}$	0.905	1.99	0.816	684.529	0.002
Arrhenius	$SR = 83{,}042.548\ e^{-32{,}932.56/8.134\ (ST+273.2)}$	0.821	1.86	0.768	676.303	0.020
Lloyd and Taylor	$SR = 0.745\ e^{289.31(1/76.02-1/ST-227.13)}$	0.745	1.74	0.724	597.867	0.014

Q_{10} was the temperature sensitivity of *SR*

Table 3 Regression analyses of soil respiration (*SR*) and SR_{10} against soil water (*SW*) at 5 cm soil depth

Name	Equation (*SR-SW*)	R^2	*P*	Equation(SR_{10}-*SW*)	R^2	*P*
Linear	$SR = 0.412 + 0.08\ SW$	0.906	0.0002	$SR = 0.362 + 0.06\ SW$	0.915	0.0012
Quadratic	$SR = 0.207 + 0.112SW - 0.001SW^2$	0.911	0.0003	$SR = 0.153 + 0.104SW - 0.002\ SW^2$	0.924	0.0001
Exponential	$SR = 0.647\ SW^{0.057}$	0.837	0.0004	$SR = 0.635\ SW^{0.045}$	0.938	0.001

SR_{10} was normalized soil respiration fitted with the Q_{10} function at 10 °C (*ST*)

Table 4 Regression analyses of soil respiration (*SR*) against soil water (*SW*) and soil temperature (*ST*) at 5 cm soil depth in the Eucalyptus community

Equation	R^2	a	b	c	*p*
$SR = a + b\ (ST\ SW)$	0.901	0.400	1.397	–	0.0003
$SR = a + b\ ST + c\ SW$	0.984	0.012	0.008	0.085	0.0002
$SR = a\ e^{b\ ST}\ SW^c$	0.995	4.375	0.091	0.808	0.0001

sharply at SW values of 6.85–10.51% during dry seasons. In water-limited soils, the uptake and emission of soil CO_2 were limited (Zhou et al. 2011; Reichstein et al. 2013; Thomey et al. 2014). SW was so low that the vitality of root and microorganism growth was suppressed. Low SW might also limit diffusion of soluble substrates necessary for microbial growth, which could affect SR rates (Allison et al. 2010). Thus, SR was significantly reduced by lack of soil water during the dry seasons, indicating that severe drought can exert a strong effect on SR dynamics. Furthermore, the variation in SR can be closely associated to the storage process of SOC. SOC storage usually results from the accumulation of mineralizable SOC through the SR process (Armas-Herrera et al. 2013). Reduced SR by the direct effects of SW can induce a significant decrease in the releases of easily mineralizable SOC, so the variation in SR could affect SOC storage in the plantations. Yunnan has experienced severe droughts in recent years (Qiu 2010), which can have a great effect on the changes of SR and SOC storage. Since drought may both reduce SR rate and carbon sequestration in *E. globulus* plantations, we should think much more about how decrease in SOC storage due to drought can be managed under the reduce in SR. Strategies for conserving or increasing SOC including

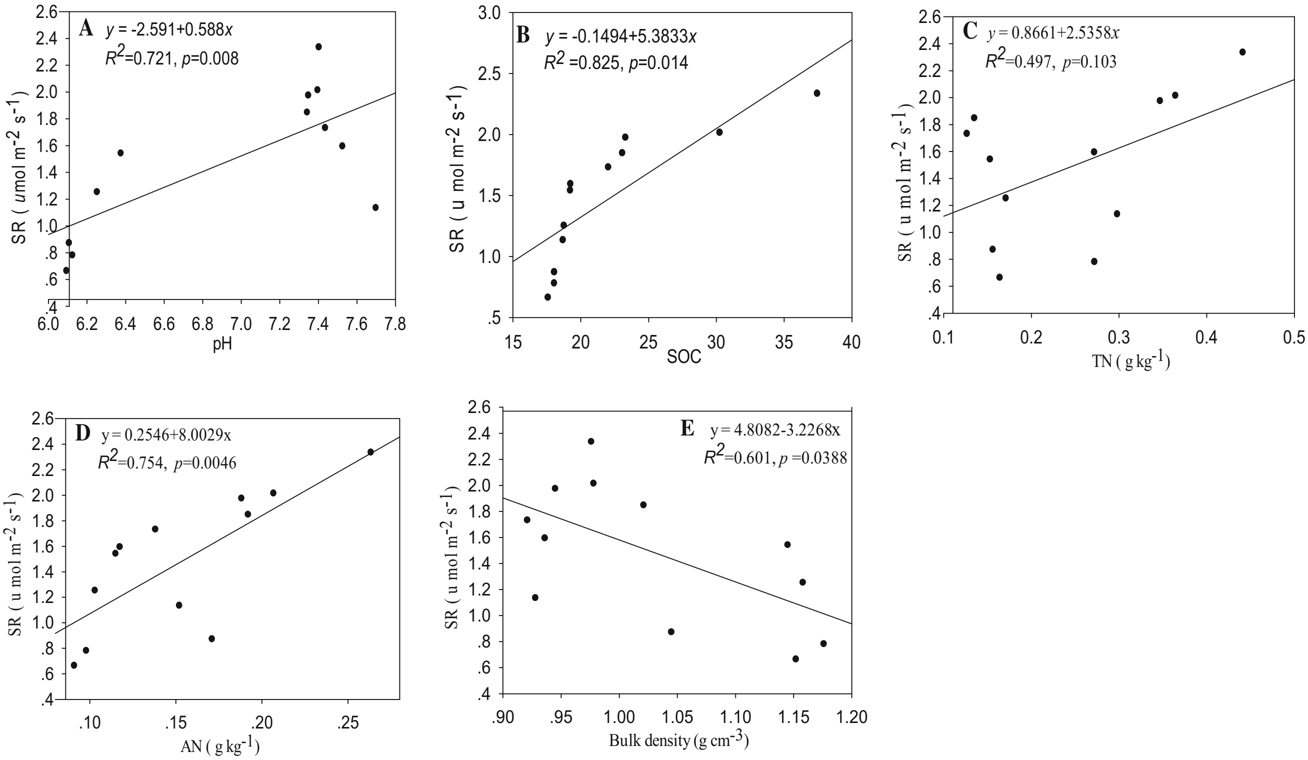

Fig. 2 Relationships between mean soil respiration (SR) and associated factors at 5 cm soil depth. Those factors included pH (**a**); Soil organic carbon (SOC) (**b**); Total nitrogen (TN) (**c**); Available nitrogen (AN) (**d**); Bulk density (E)

fertilizer applications can be taken to improve soil fertility and physical protection to prevent loss of SOC during extreme drought period.

A positive correlation between SR and SW was found, and polynomial equations provided the best fit between SR and SW in this study (Table 3). The relationship between SR and SW is complex, and both linear and nonlinear relationships have been reported (Chen et al. 2010). SR may not always show a linear or exponential increase with increased SW. SR can be depressed at high SW due to reduced oxygen diffusion, whereas low SW with enough free water in the soil pores can maintain higher SR. The effect of SW on SR increased when SR values were normalized to 10 °C ST. A combined SW and ST model explained 90–99% of the variation in SR. These results also suggest that SW and ST play a complicated role in influencing SR. Furthermore, the stress of SW decoupled SR when SW content declined below 6.85–10.51%, suggesting that SW below certain threshold values may have caused desiccation stress on microbial decomposers. The hysteresis in SR during drought could be also be influenced by changes of soil structural properties that compound the effects of SW on soil microbes and mobility of enzymes and substrates. Soil water repellency and aggregate structure can change with soil drying, affecting SW holding capacity, surface tension, and other properties upon rewetting (Goebel et al. 2011). Water repellency due to prolonged drying can prevent the homogenous rewetting of the organic horizon, which could delay the recovery of SR (Muhr and Borken 2009). Therefore, the effecting mechanism of SW on SR could be complicated especially in the context of increasing drought severity.

Bulk density, pH, SOC, and AN significantly contributed to the variation of SR under drought conditions. These results were similar to those reported by Wani et al. (2014) who concluded that shortage of SW can influence SR by suppressing transformation of soil organic matter, the improvement of soil construction, the receding of soil bulk density and the enhancing of soil porosity. Lower soil bulk density is associated with higher soil porosity, thus resulting in higher soil oxygen availability which facilitates microbial activities leading to the increase in SR (Chen et al. 2010). Soil pH can influence SR directly by affecting the tolerance of the bacterial community because the biological activity of soil microorganisms usually occurs in a pH range of 3–8. SOC had significant effect on SR in the study, because SR involves the process of converting organic into inorganic C, which is limited by C substrate supply (Wan and Luo 2003). Not all soil nitrogen components can stimulate microbe and root respiration (Sun et al. 2014). So no significant correlation between TN and SR was seen, whereas AN had a significant effect on SR due to the metabolism dependence of microbes and roots on available components of soil nitrogen (Ceccon et al. 2011). Therefore, a significant effect on SR variation can be induced by soil physical, chemical, and biological properties during severe drought.

Conclusions

In the study, we found that extreme drought exerted a pronounced effect on the variations of soil respiration in the *Eucalyptus* plantations. The dynamics of soil respiration were mainly controlled by changes in soil water during the drought. Soil water content accounted for 83.7–91.1% of the variation in soil respiration, while a combined soil water and temperature model explained 90.1–99.5% of the variation in soil respiration. Soil respiration was markedly decreased at soil water threshold values of 6.85–10.51% in the drought periods. Furthermore, the change in soil respiration during the drought was significantly related to soil variables bulk density, pH, soil organic carbon, and available nitrogen. We conclude that the effect of drought on soil respiration was closely associated with soil water dynamics and soil physico-chemical properties.

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Compliance with ethical standarads

Conflict of interest The authors declare that they have no conflict of interest.

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