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Soil Respiration at Different Stand Ages (5, 10, and 20/30 Years) in Coniferous (*Pinus tabulaeformis* Carrière) and Deciduous (*Populus davidiana* Dode) Plantations in a Sandstorm Source Area

Xin Zhao [1,5], Fadong Li [1,*], Wanjun Zhang [2,*], Zhipin Ai [2,5], Huitao Shen [3], Xiuping Liu [2], Jiansheng Cao [2] and Kiril Manevski [4]

1 Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; zhaox.14b@igsnrr.ac.cn
2 Key Laboratory of Agricultural Water Resources, Hebei Key Laboratory of Agricultural Water-saving, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050021, China; zpai@sjziam.ac.cn (Z.A.); xiupingliusjz@163.com (X.L.); jianshengcao73@126.com (J.C.)
3 Institute of Geographical Sciences, Hebei Academy of Sciences, Shijiazhuang 050011, China; shenht80@126.com
4 Department of Agroecology, Aarhus University, Blichers Alle 20, Tjele 8830, Denmark; kiril.manevski@agro.au.dk
5 University of Chinese Academy of Sciences, Beijing 100049, China
* Correspondence: lifadong@igsnrr.ac.cn (F.L.); wjzhang1211@163.com (W.Z.); Tel./Fax: +86-10-6488-9530 (F.L.); Tel.: +86-311-8587-1750 (W.Z.)

Academic Editors: Philip J. Polglase and Eric J. Jokela
Received: 7 April 2016; Accepted: 21 July 2016; Published: 25 July 2016

Abstract: Understanding the effects of stand age and forest type on soil respiration is crucial for predicting the potential of soil carbon sequestration. Thus far, however, there is no consensus regarding the variations in soil respiration caused by stand age and forest type. This study investigated soil respiration and its temperature sensitivity at three stand ages (5, 10, and 20 or 30 years) in two plantations of coniferous (*Pinus tabulaeformis* Carrière) and deciduous (*Populus davidiana* Dode) species using an automated chamber system in 2013 in the Beijing-Tianjin sandstorm source area. Results showed that mean soil respiration in the 5-, 10-, and 20/30-year-old plantations was 3.37, 3.17, and 2.99 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for *P. tabulaeformis* and 2.92, 2.85, and 2.57 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for *P. davidiana*, respectively. Soil respiration decreased with stand age for both species. There was no significant difference in soil respiration between the two plantation species at ages 5 and 10 years ($p > 0.05$). Temperature sensitivity of soil respiration, which ranged from 1.85–1.99 in *P. tabulaeformis* and 2.20–2.46 in *P. davidiana* plantations, was found to increase with stand age. Temperature sensitivity was also significantly higher in *P. davidiana* plantations and when the soil water content was below 12.8%. Temperature sensitivity incorporated a combined response of soil respiration to soil temperature, soil water content, soil organic carbon, and fine root biomass and, thus, provided an ecological metric for comparing forest carbon dynamics of these species.

Keywords: forest type; soil respiration; soil temperature; soil water content; stand age; Q_{10}

1. Introduction

Soil respiration, ranging from 40%–90% of total ecosystem respiration, is the second largest carbon flux in terrestrial ecosystems [1]. Even a minor change in soil respiration may remarkably affect atmospheric CO_2 levels and therefore global warming [1–4]. Thus, a better understanding of soil

respiration assists predictions of future atmospheric CO_2 concentrations and contributes to accurate assessments of carbon balance under different climate change scenarios [5,6].

Stand age, as an indicator of forest successional status and, thus, carbon dynamics [7], plays a critical role in determining the distribution of global soil carbon pools, estimates of which range from 504 to 3000 Pg C (1 Pg C, 10^{15} g or billion tons of carbon) for the period between 1950 and 2010 [8–10]. Nevertheless, there is still no consensus on the effects of stand age on soil respiration, although three opinions predominate. One is that soil respiration increases with stand age because of increasing root biomass and accumulated organic carbon [11–13]. Another, opposite opinion, considers that soil respiration decreases with stand age because of decreasing fine root biomass and metabolic activity [14–16]. Lastly, others consider that no linear relationship exists between soil respiration and stand age [7,17,18]. The majority of these studies emphasized the effects of stand age on soil respiration in a single forest type. However, soil respiration may differ significantly among forest types due to forest-specific climatic conditions [19], productivity [20], litter quality and quantity [21], as well as soil physicochemical properties [22]. Comparisons of soil respiration for different stand ages conducted at the same sites in distinct forest types, such as coniferous and deciduous species, especially under afforestation conditions, are relatively scarce [23].

Soil temperature and water content are considered as the main factors that explain the temporal variations in soil respiration [2,15]. In addition, plant physiology, plant phenology [24], soil organic carbon [25], soil total nitrogen [17], fine root biomass [18], soil bulk density [26], and soil pH [27] may influence the rates of soil respiration. These factors are also used to model the temperature sensitivity of soil respiration, which is particularly important in the context of weather variability and climate change. Thus, it is imperative to explore how stand age and forest type affects temperature sensitivity to soil respiration [28].

Afforestation can mitigate emissions of greenhouse gases by increasing terrestrial carbon sequestration [29] and by controlling soil erosion [30]. A commonly accepted view is that afforestation can increase soil carbon accumulation [31], especially from degraded land to forest, through the establishment of higher plant biomass and, hence, increased input of resistant organic matter to soil [32]. In China, large-scale afforestation was initiated in the 1970s to solve the serious ecological problem due to spring sandstorms around Beijing, Tianjin, and other North China areas. Moreover, in 2001, the Beijing-Tianjin Sandstorm Source Control Project was launched by the Chinese government, initially aiming at wind prevention and sand fixation in Beijing-Tianjin and the surrounding areas [33]. By the end of 2010, 62 M· ha had been afforested [30,33]. The majority of the studies conducted in this sandstorm source area have been focused on the changes in soil physiochemical characteristics related to afforestation, carbon density and carbon stock estimates in the afforested plantations. For instance, it has been found that deciduous forests support high ground cover to better defend against wind erosion, and coniferous forests are suitable for this environment due to their relatively high soil carbon density [30,33]. However, the successional development of coniferous and deciduous plantations and their influence on soil respiration have not been studied.

The typical coniferous species *P. tabulaeformis* is characterized by strong survival capability under harsh conditions, whereas the deciduous species *P. davidiana* has a high growth rate and biomass. Thus, both plants have been widely planted in the sandstorm source area. In the present study, soil respiration was compared between coniferous and deciduous plantations differing in stand age. The main aim was to provide knowledge to predict the carbon sequestration potential, to control sandstorms, and to choose appropriate tree species for afforestation. Here, three stand ages (5-, 10-, and 30-year-old *P. tabulaeformis* and 5-, 10-, and 20-year-old *P. davidiana*) were selected to investigate the effects of stand age and forest type on soil respiration. The objectives of this study were to: (1) investigate the monthly dynamics of soil respiration at different stand ages in *P. tabulaeformis* and *P. davidiana* plantations; (2) compare the difference in soil respiration between the coniferous and the deciduous plantations at different stand ages; and (3) explore the variations in temperature sensitivity with stand age and forest type.2. Materials and Methods

2. Materials and Methods

2.1. Site Description

The study sites were located in Fengning Man Autonomous County (41°08′–41°09′ N, 116°42′–116°45′ E, 660 m above sea level), which is located in Hebei Province, China (Figure 1). The sites are part of the Beijing-Tianjin sandstorm source area. The climate is temperate, continental, and monsoon-influenced. The natural vegetation is sylvosteppe. Additional information on weather characteristics, such as air temperature, precipitation, potential evaporation, as well as a soil description can be found in Zhao et al. [34].

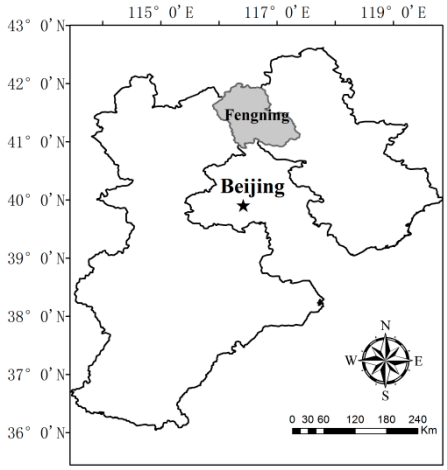


Figure 1. Location of the study area (denoted as the grey area). The black outlined area indicates this study area is located in Hebei Province, China.

2.2. Experimental Design

Two forest types and three age classes of plantations were chosen for this study, namely, 5-, 10-, and 30-year-old *P. tabulaeformis* (referred hereafter as PT5, PT10, and PT30, respectively), and 5-, 10-, and 20-year-old *P. davidiana* (referred hereafter as PD5, PD10, and PD20, respectively). The difference between PT30 and PD20 with respect to their stand age was due to different afforestation schemes. However, they both represent a closed canopy forest for their forest type. Stand age was obtained from the records of the local forestry authority and was assessed in 2013. The height and diameter at breast height of the trees were measured concurrently, and the canopy density was estimated as the ratio between vertically projected canopy cover and total forest cover. The stand characteristics are summarized in Table 1.

Table 1. The characteristics of plant communities in *Pinus tabulaeformis* and *Populus davidiana* plantations at three different stand ages.

Forest Type	SA (years)	CD (%)	H (m)	DBH (cm)	Understory Vegetation Composition
Pinus tabulaeformis	5	18 (3)	1.1 (0.16)	1.9 (0.15)	*Carex rigescens* (Franch.), *Artemisia sacrorum* Ledeb., *Elymus dahuricus* Turcz. ex Griseb., *Potentilla ancistrifolia* Bunge, *Sanguisorba officinalis* L.
	10	65 (7)	2.8 (0.13)	5.5 (0.34)	
	30	77 (9)	13.8 (0.77)	10.2 (0.77)	
Populus davidiana	5	37 (5)	8.6 (0.24)	7.6 (0.34)	*Artemisia verlotorum* Lamotte, *Potentilla discolor* Bunge, *Dendranthema indicum* L. Des Moul., *Setaria viridis* (L.) P. Beauv.
	10	70 (9)	20 (1.03)	12 (0.91)	
	20	83 (11)	24.8 (2.08)	23.1 (1.15)	

SA = stand age, CD = canopy density, H = tree height, DBH = diameter at breast height. Values in parentheses are standard errors.

Soil respiration was measured in plots (20 m × 20 m) with three replications for each stand age and forest type. Three randomly-located soil respiration PVC collars (subplots) were established in each plot. The PVC collars with a height of 10 cm and an inside diameter of 10 cm were inserted 5 cm into the soil after clipping live plants. The PVC collars were left in the same location (free of green vegetation) throughout the study period. The two types of plantations were initially established on bare land and received no management, such as irrigation and fertilization. The soil type of each site is classified as a Haplustalf according to the United States Department of Agriculture Soil Taxonomy [35]. Moreover, similar climate and soil type provide ideal stand age classes and forest types for studying their effects on soil respiration.

2.3. Measurements of Soil Respiration, Soil Temperature, and Soil Water Content

Soil respiration, soil temperature, and soil water content were measured once a month during the growing season (from May to October) in 2013. Measurements were not conducted during the winter months due to poor weather that made the study area inaccessible.

Soil respiration was measured using an Li-6400 portable CO_2 infrared gas analyzer linked to an Li-6400-09 chamber (Li-Cor Inc., Lincoln, NE, USA). For each measurement, the chamber reached a dynamic equilibrium state between the inside and outside environment when the CO_2 concentration was observed to be rising steadily [28]. To avoid soil respiration from aboveground plants, the litter and herbaceous plants were removed at the soil surface one day before each soil respiration measurement. Measurements were taken only on sunny days without precipitation or high winds to minimize equipment damage, measurement error, and to avoid a rainfall rich-effect [12]. To minimize daily variation and obtain representative daily average soil CO_2 efflux, the measurements were taken between 09:00 and 11:00 am. [28,32]. The mean soil respiration in each subplot was calculated as the average of three continuous cycles. The mean soil respiration for each plot was then calculated as the average of three subplots. Soil respiration rates for each stand age were calculated as the average of the three replicated plots.

Soil temperature was measured simultaneously with soil respiration using a copper thermocoupled penetration probe (Li6000-09 TC, LiCor Inc., Lincoln, NE, USA) inserted 5 cm into the soil in the vicinity of the respiration chamber. Soil samples were collected at 0–10 cm depth within 5 cm of the collars and dried at 105 °C to a constant weight to determine the soil water content [15].

2.4. Soil Sampling and Laboratory Analysis

Soil samples were collected monthly from August to October in 2013, at 0–10, 10–20, and 20–40 cm depths using a 10 cm diameter auger. For each plot, eight randomly-collected samples were combined to form a composite sample. In total, 54 soil samples were collected across all plots, ages, and forest types. Concurrently, soil bulk density was measured using the cutting-ring method. Before laboratory analysis, all soil samples were air-dried, ground, and passed through a 0.25 mm sieve. Soil organic carbon was measured using the Walkley–Black net oxidation method [36], and soil total nitrogen was determined by the Semimicro-Kjeldahl method [37]. A mixed soil suspension (soil:water = 1:2.5) with a glass electrode was used to determine soil pH [6]. Fine roots (<2 mm diameter) at 0–10, 10–20, and 20–40 cm soil depths were extracted in the vicinity of the soil collars and approximately 1 m away from the nearest tree in each plot from August 2013 to October 2013 using a soil auger (5 cm diameter) with a sharpened edge [15,33]. Fine roots were then sieved using a 0.1 mm screen, washed with clean water, picked using tweezers, oven-dried at 75 °C, and weighed to obtain the fine root biomass.

2.5. Statistical Analysis

A classic parametric exponential model (Equation (1)) was used to describe the relationship between soil respiration and soil temperature [38]:

$$y = ae^{bT} \quad (1)$$

where y is the measured soil respiration rate, T is the measured soil temperature at 5 cm depth, and a and b are regression coefficients.

The Q_{10} value, defined as the increasing rate of soil respiration corresponding to an increase in temperature of 10 °C, was used to describe the temperature sensitivity of soil respiration (see Equation (2)):

$$Q_{10} = e^{10b} \quad (2)$$

Repeated measures analysis of variance using the general linear model procedure with Duncan's post hoc test ($p \leqslant 0.05$) was conducted to test the effect of stand age on the soil respiration rates, soil temperature, and soil water content in each forest type over the study period. Independent sample t-tests were used to test for significance differences in soil respiration rates, soil temperature, and soil water content between the two forest types. One-way analysis of variance with Duncan's post hoc test ($p \leqslant 0.05$) was used to test for significant differences in soil organic content, soil total nitrogen, fine root biomass, and soil bulk density values among different stand ages at each soil depth. Chi-squared, with likelihood ratio tests ($p \leqslant 0.05$), were conducted to investigate whether significant differences in Q_{10} values varied with stand age and below- or above-threshold soil water contents. Correlation analysis was used to investigate the relationship between soil respiration and environmental variables. A multiple linear regression model was used to test for relationships between soil respiration and correlated variables. The regression was standardized by zero-mean normalization to compare the effects of each correlated factor. All variables were ln-transformed to decrease heteroscedasticity after checking for distribution normality (Shapiro-Wilk test) and variance homogeneity (Levene test). All statistical analyses were conducted using SPSS software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Meteorological Conditions

Precipitation and air temperature changed throughout the experimental period, as shown in Figure 2. The total precipitation was 377.4 mm, which is lower than the long-term mean precipitation from May to October of approximately 396.1 mm. The maximum and minimum precipitation occurred in July (120.1 mm) and May (21.9 mm), respectively. The long-term mean air temperature from May to October for the study site is 16.8 °C whereas, for the study period, the mean air temperature was 17.3 °C with a maximum value of 22.2 °C in July and a minimum value of 9.7 °C in October.

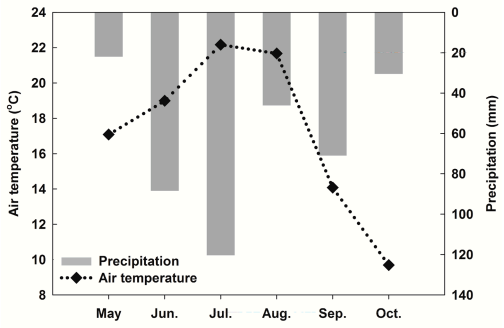


Figure 2. Monthly mean precipitation and air temperature during the experimental period [34].

3.2. Soil Respiration

Soil respiration in the three ages of *P. tabulaeformis* and *P. davidiana* plantations all showed significant single-peak curves ($p < 0.05$) during the growing season (Figure 3a). The mean soil respiration in PT5, PT10, and PT30 ranged from 2.10–4.57 μmol CO_2 $m^{-2} \cdot s^{-1}$, 1.90–4.66 μmol $\cdot$ $m^{-2} \cdot s^{-1}$, and 1.47–4.69 μmol CO_2 $m^{-2} \cdot s^{-1}$, respectively. Significant differences were found among the three stand ages ($p < 0.05$). The soil respiration decreased with stand age, being the highest in PT5 and

the lowest in PT30 (Table 2). Soil respiration in PD5, PD10, and PD20 ranged from 1.80–4.49 μmol CO_2 $m^{-2}\cdot s^{-1}$, 1.63–4.38 μmol CO_2 $m^{-2}\cdot s^{-1}$, and 1.25–4.04 μmol CO_2 $m^{-2}\cdot s^{-1}$, respectively. It was estimated that PD5 had significantly higher ($p < 0.05$) soil respiration rates compared with PD20, but was not significantly different from PD10 (Table 2). Furthermore, there was no significant difference ($p > 0.05$) in soil respiration between the two plantations, except for PT30 and PD20 ($p = 0.049$) (Table 2).

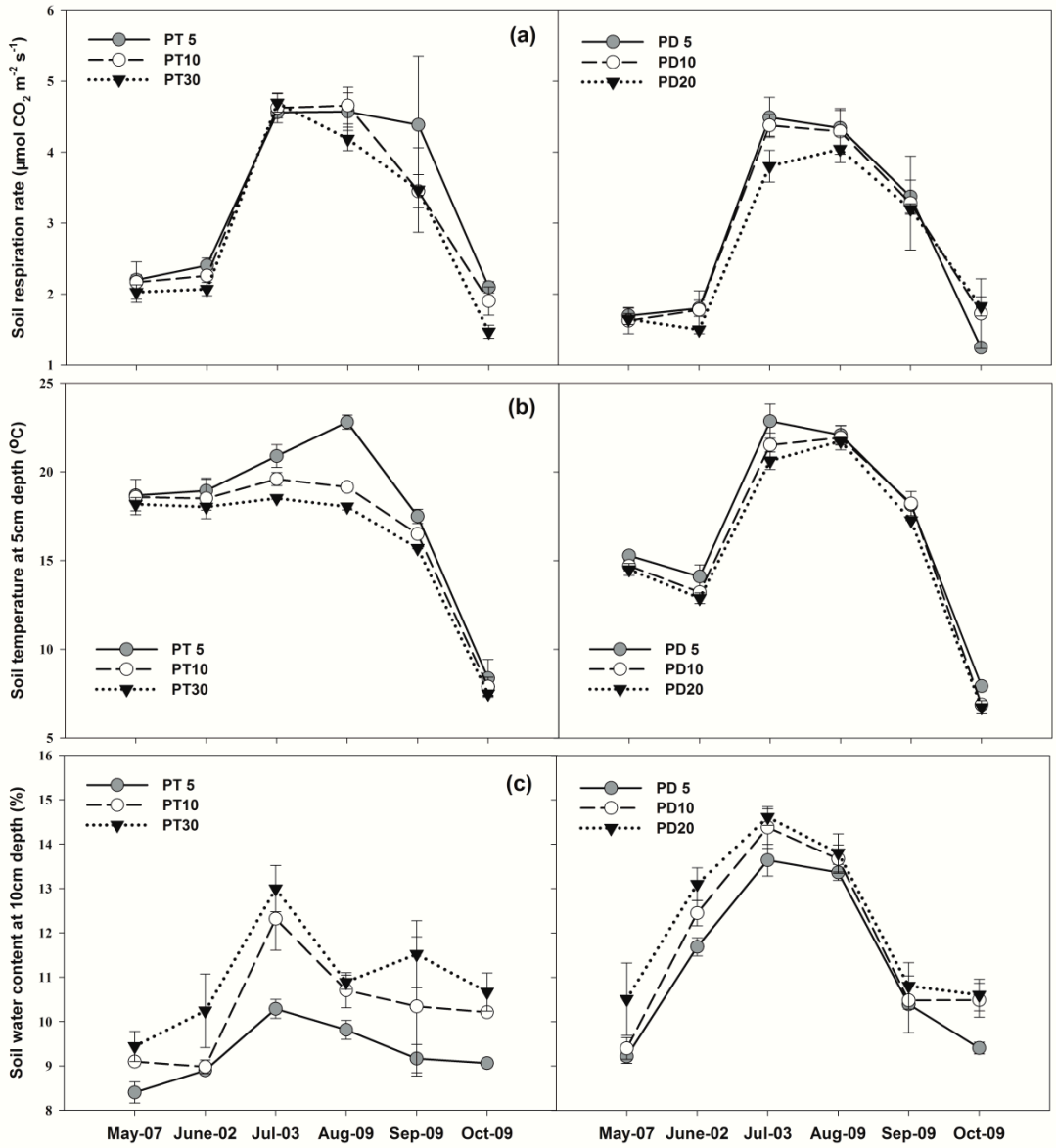


Figure 3. Monthly variations in the soil respiration rate (**a**); soil temperature at 5 cm depth (**b**); and soil water content at 10 cm (**c**) among different stand ages in *Pinus tabulaeformis* and *Populus davidiana* plantations during the growing season (from May to October) of 2013. PT and PD represent *P. tabulaeformis* and *P. davidiana* plantations respectively, and the digits represent stand ages. Bars indicate standard errors.

Table 2. Mean values for soil respiration (SR), soil temperature (ST), and soil water content (SWC) in *Pinus tabulaeformis* and *Populus davidiana* plantations at three different stand ages.

	Forest Type	5 Years	10 Years	30 Years/20 Years
SR ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	*Pinus tabulaeformis*	3.37 (0.26) a,A	3.17 (0.21) b,A	2.99 (0.20) c,A
	Populus davidiana	2.92 (0.19) a,A	2.85 (0.35) a,b,A	2.57 (0.11) b,B
ST (°C)	*Pinus tabulaeformis*	17.86 (1.13) a,A	16.70 (1.01) b,A	15.99 (0.95) b,A
	Populus davidiana	16.73 (1.25) a,B	16.08 (1.28) a,b,A	15.65 (1.30) b,B
SWC (%)	*Pinus tabulaeformis*	9.27 (0.99) b,B	10.27 (0.43) a,b,B	10.96 (0.35) a,B
	Populus davidiana	11.28 (0.22) b,A	11.81 (0.04) a,b,A	12.24 (0.26) a,A

Different lowercase letters within a row indicate significant difference between stand ages within a forest type. Different capital letters within a column indicate a significant difference between *P. tabulaeformis* and *P. davidiana* plantations. Values in parentheses are standard errors.

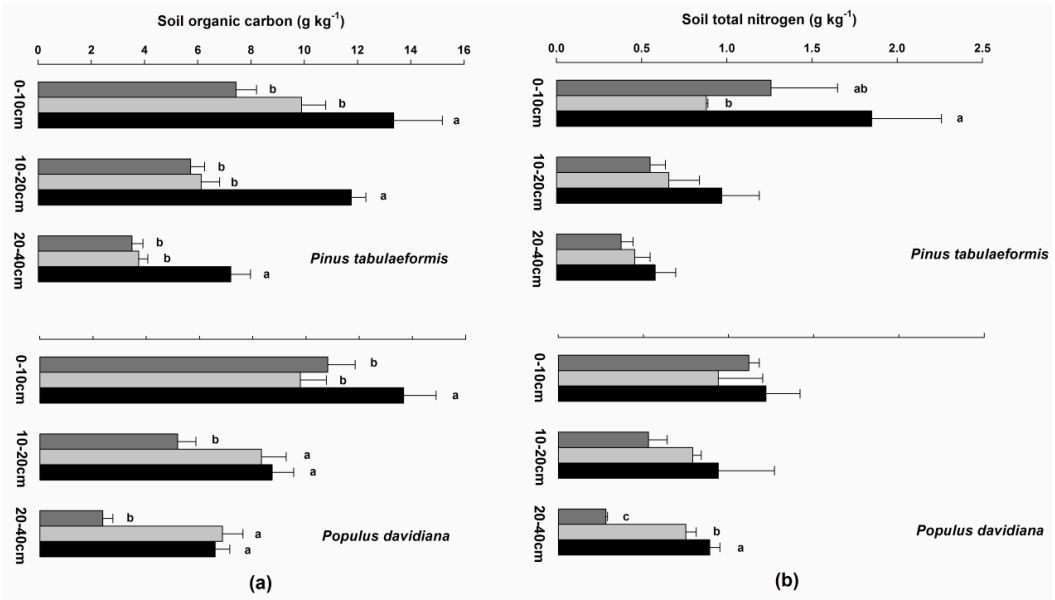
3.3. Soil Temperature and Soil Water Content

Soil temperature at a depth of 5 cm and soil water content at a depth of 10 cm in both *P. tabulaeformis* and *P. davidiana* plantations changed distinctly during the study period (Figure 3b,c). PT5 and PD5 had higher soil temperatures than the other two stand ages, whereas PT30 and PD20 had the lowest soil water contents.

Stand age significantly affected the soil temperature and soil water content. Soil temperature at a depth of 5 cm in PT5 and PD5 was significantly higher than that in PT30 and PD20 ($p < 0.05$). Soil water content at a depth of 10 cm in PT5 and PD5 significantly differed from that in PT30 and PD20 ($p < 0.05$), but PT10 and PD10 did not differ from the other two stand ages ($p > 0.05$) (Table 2).

3.4. Soil Organic Carbon, Soil Total Nitrogen, Fine Root Biomass, and Soil Bulk Density

Soil organic carbon decreased as soil depth increased (Figure 4a). For *P. tabulaeformis*, soil organic carbon in PT30 was the highest among all stand ages ($p < 0.05$), whereas PT5 and PT10 did not differ significantly ($p > 0.05$), and this trend was depicted at all soil depths, i.e., 0–10, 10–20, and 20–40 cm. For *P. davidiana*, soil organic carbon in PD20 and PD10 was significantly higher than that in PD5 at 10–20 and 20–40 cm whereas, at 0–10 cm, the value for PD20 was higher than for the other two stand ages.



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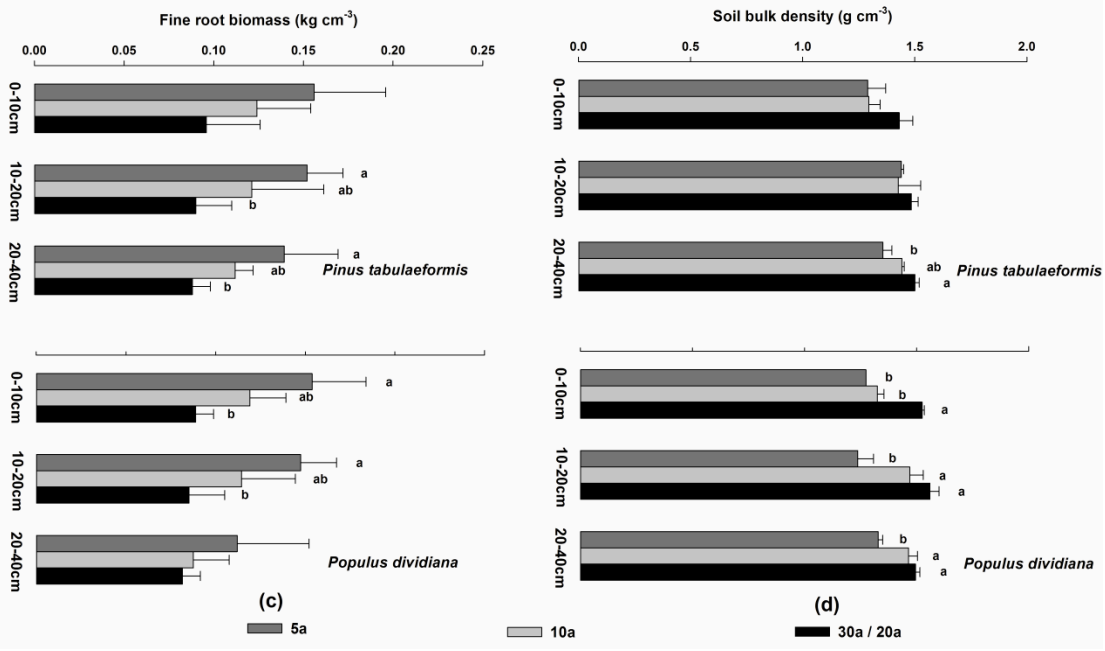

Figure 4. Soil organic carbon (**a**); soil total nitrogen (**b**); fine root biomass (**c**); and soil bulk density (**d**) at three different depths (0–10, 10–20, and 20–40 cm) in *P. tabulaeformis* and *P. davidiana* plantations. Different lowercase letters indicate a significant difference between the stand ages within the same soil depth. Bars indicate standard errors.

Soil total nitrogen also decreased with soil depth, but was not significantly different among stand ages at all soil depths (Figure 4b). Soil total nitrogen at 0–10 cm in the PT30 plantation was significantly higher than that in PT10, but there was no difference compared with PT5. PD30 was the highest among the three stand ages at the 20–40 cm soil depth.

As shown in Figure 4c, fine root biomass varied with soil depth. A decreasing trend was found as the stand age increased. Fine root biomass was the highest in PT5 and the lowest in PT30 ($p < 0.05$) for the 10–20 and 20–40 cm soil depths. The respective highest and lowest values occurred in PD5 and PD20 for the 0–10 and 10–20 cm soil depths ($p < 0.05$).

Soil bulk density increased with soil depth in PT10, PT30, and PD20. For other stand ages, however, the bulk density was the highest for the middle soil depth (10–20 cm) and the lowest for the other two soil depths (0–10 and 20–40 cm), or exhibited the opposite pattern. The values in PD20 and PD10 were significantly higher than in PD5 at three soil depths ($p < 0.05$) (Figure 4d).

3.5. Relationships between Soil Respiration and Soil Temperature and Soil Water Content

Soil respiration responded to soil temperature at a depth of 5 cm, according to the exponential model, for the different stand ages in both *P. tabulaeformis* (R^2 = 0.28 to 0.48) and *P. davidiana* (R^2 = 0.70 to 0.91) (Figure 5a). The Q_{10} value apparently increased with stand age. The values for *P. tabulaeformis* ranked as 1.85, 1.85, and 1.99, whereas those for *P. davidiana* were 2.20, 2.51, and 2.64, respectively (Figure 5, Table 3). Chi-squared with likelihood ratio tests showed that stand age significantly influenced the Q_{10} value in *P. tabulaeformis* (p = 0.029) and *P. davidiana* (p = 0.000) plantations. Furthermore, the Q_{10} value in *P. tabulaeformis* plantations was significantly lower than in *P. davidiana* plantations (p = 0.001). Although soil respiration did not exhibit an exponential response to soil water content at a depth of 10 cm (Figure 5b), all data points in the figure could be divided into two groups according to mean soil respiration in each forest type (presented in Figure 5b as the horizontal grey line). Relatively higher soil respiration rates were observed at a water content above 12.8% for the *P. davidiana* plantations, but there was no similar influence of soil water content in

P. tabulaeformis plantations. Soil respiration was most sensitive to soil temperature when the soil water content was below 12.8% for the *P. davidiana* plantations (p = 0.019) (Table 3).

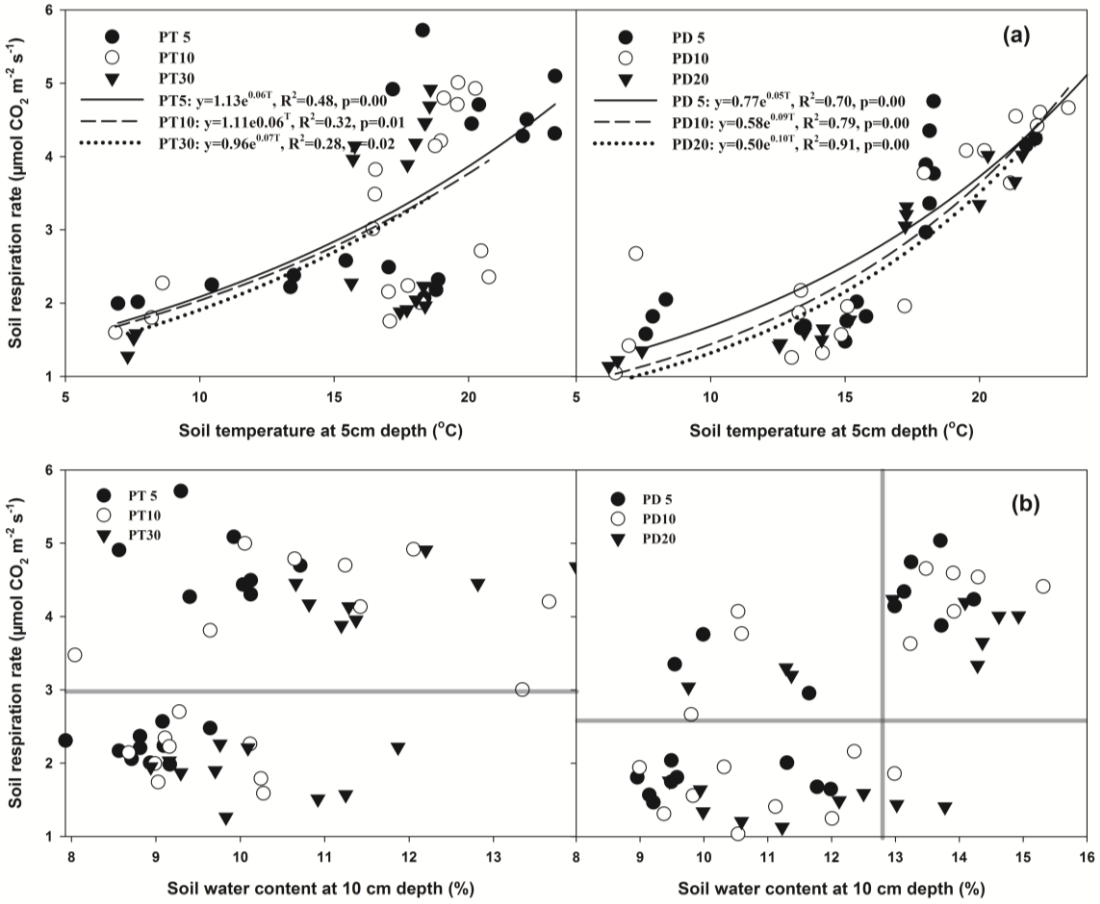

Figure 5. Relationships between soil respiration and soil temperature at a depth of 5 cm (**a**) and soil water content at 10 cm (**b**) at different stand ages in *P. tabulaeformis* and *P. davidiana* plantations during the growing season (from May to October) of 2013. PT and PD represent *P. tabulaeformis* and *P. davidiana* plantations, respectively, and the symbols represent stand ages. Each value represents the mean of nine measurements in each stand. The solid line, dashed line and dotted line indicate the exponential curves of the soil respiration rate and soil temperature at a depth of 5 cm at three stand ages (5-, 10-, and 30/20-year-old) in the *P. tabulaeformis* and *P. davidiana* plantations. Grey horizontal lines in Figure 5b indicate mean soil respiration in each forest type, and the grey vertical line indicates a threshold point for soil water content in *P. davidiana*.

Table 3. Q_{10} values, regression coefficients, and determination coefficient of relationships between soil respiration (SR) and soil temperature (ST), according to $y = ae^{bT}$, in different aged *Pinus tabulaeformis* and *Populus davidiana* plantations and at a soil water content (SWC) below or above 12.8% in *P. davidiana* plantations.

Pinus tabulaeformis						***Populus davidiana***					
	a	b	R^2	p	Q_{10}		a	b	R^2	p	Q_{10}
5 years	1.13	0.06	0.48	0.00	1.85	5 years	0.77	0.05	0.70	0.00	2.2
10 years	1.11	0.06	0.32	0.01	1.85	10 years	0.58	0.09	0.79	0.00	2.51
30 years	0.96	0.07	0.28	0.02	1.99	20 years	0.50	0.10	0.91	0.00	2.64
All stands	1.06	0.06	0.37	<0.01	1.90	All stands	0.62	0.09	0.79	<0.01	2.42
						SWC < 12.8%	0.58	0.09	0.53	<0.01	2.48
						SWC > 12.8%	0.90	0.07	0.72	<0.01	2.05

3.6. Factors Related to Soil Respiration

Soil respiration was positively correlated with soil temperature and fine root biomass but negatively correlated with the soil water content and soil organic carbon. No significant correlations were found between soil respiration and soil total nitrogen, soil bulk density, and pH (Table 4). Furthermore, a multiple linear regression model was used to determine the relative importance of the correlated factors including soil temperature, soil water content, soil organic carbon, and fine root biomass. After standardizing soil respiration and the covariates, the final multiple regression model was: ln(SR)= −0.107ln(ST) − 0.671ln(SWC) − 0.057ln(SOC) + 0.258ln(FRB) (R^2 = 0.730, p = 0.001) where SR is soil respiration, ST is soil temperature, SWC is soil water content, SOC is soil organic carbon, and FRB is fine root biomass.

Table 4. Correlations between soil respiration (SR) and environmental factors.

	ST	SWC	SOC	STD	FRB	SBD	pH
SR	0.881 *	−0.978 **	−0.779 *	−0.482	0.740 *	−0.688	−0.237

ST = soil temperature, SWC = soil water content, SOC = soil organic carbon, STD = soil total nitrogen, FRB = fine root biomass, SBD = soil bulk density. The sample size of SR, ST, and SWC is 324, the sample size of SOC, STD, FRB, SBD, and pH is 54. * and ** denote significance at $p < 0.05$ and $p < 0.01$, respectively.

This model indicated that the soil water content exerted the greatest influence on soil respiration, followed by fine root biomass, soil temperature, and soil organic carbon.

4. Discussion

4.1. Stand Age and Soil Respiration

Soil respiration varied with stand age in the *P. tabulaeformis* and *P. davidiana* plantations in the sand storm source area. The average soil respiration rates of these two plantations ranked in the order of 5-year-old > 10-year-old > 30-year-old and 20-year-old, indicating that soil respiration decreased with stand age. This result is consistent with previous studies [14–16,25].

McCarthy and Brown [39] suggested that canopy density may significantly influence soil respiration by affecting the soil temperature and soil water content. As shown in Table 4, soil respiration was positively correlated with soil temperature, but it was negatively correlated with the soil water content. Lower canopy density in younger plantations probably increased the solar net radiation on the forest floor [40,41] which, in turn, increased soil temperature and decreased the soil water content, as also depicted in Figure 3b,c.

Several studies have indicated that soil respiration is closely related to root biomass and that 30%–90% of the total soil respiration is from root respiration [42,43]. PT5 and PD5 had the highest fine root biomass (Figure 4c), which might be explained by a greater input of nutrients to the below-ground tissues [44]. As forests mature, less dry matter is partitioned to the roots [45]. The advantage of high metabolic activity, strong nutrient intake, and transport ability [16] in fine roots may accelerate the rhizosphere microbial activity and may stimulate soil respiration [46,47].

Another possible explanation for variations in soil respiration might be the substrate availability [17]. Despite having the smallest soil respiration, PT30 and PD20 had the largest amount of soil organic carbon (Figure 4a), which might be related to the accumulation of recalcitrant carbon in the soil. A higher recalcitrant carbon content lead to a higher stability of soil mineral particles, which results in lower soil respiration [48,49].

Furthermore, soil disturbance should be taken into account when explaining the decline in soil respiration with stand age. Frequent disturbance, which occurred in younger plantations, could accelerate the decomposition rate of debris, litter, and soil organic matter [50], and finally increase soil respiration.

4.2. Forest Type and Soil Respiration

Soil respiration may also be affected by forest type. It has been estimated that soil respiration in coniferous forests is 10% lower than in broad-leaved forests for the same soil type [43]. However, Borken et al. [51], Hibbard et al. [52], and Raich and Potter [53] found that there was no statistical difference in soil respiration between coniferous and deciduous forests. Wang et al. [54] noted that comparison of soil respiration among different forest types was unrealistic due to the difference in biophysical conditions, measuring protocols, and calculation methods. Thus, to date, there is no consensus on the effect of forest type on soil respiration. The findings of the present study point to an insignificant difference in soil respiration between coniferous and deciduous plantations except for the oldest stand ages (PT30 and PD20, Table 2).

The accumulated monthly soil respiration in *P. tabulaeformis* and *P. davidiana* plantations during the growing season (from May to October) was 601.9 ± 12 and 526.7 ± 20 $g \cdot C \cdot m^{-2}$, respectively. These values are lower than 789~1070 $g \cdot C \cdot m^{-2}$ obtained in *P. tabulaeformis-Platycladus orientalis* in Shanxi, China [55] and are also lower than 699 $g \cdot C \cdot m^{-2}$ reported for aspen-birch forests in Northeast China [54]. This may be ascribed to different climatic and edaphic conditions, for instance, our study area was characterized by lower soil temperature and soil water content than those in the previous two studies, which probably limited dissolved substrate diffusion and restrained root and microbial respiration [56]. Coarse-textured soil in this area also led to low soil water holding capacity and good soil water infiltration, reducing the microbial population and enzymatic activity [57]. All of these factors would consequently lead to lower soil respiration [58].

4.3. Temperature Sensitivity to Soil Respiration

The Q_{10} values ranged from 1.85–1.99 in *P. tabulaeformis* and from 2.2–2.64 in *P. davidiana*, and they increased with stand age (Table 3). Similar fluctuating patterns for Q_{10} were also reported by Yan et al. [15] and Ma et al. [6]. These results highlight the importance of stand age in regulating the Q_{10} value of soil respiration. Soil temperature and soil water content were considered as the likely explanation for this observed pattern. Published results showed that a higher Q_{10} value generally occurs under lower temperature and higher soil water content at well-shaded sites [59–61]. Higher temperature could reduce enzymatic activity and substrates used for respiration, resulting in a lower Q_{10} value. On the other hand, a higher soil water content impedes oxygen diffusion into the soil, which decreases soil respiration and subsequently, the Q_{10} value [61]. The younger plantations had a lower canopy density and, therefore, higher soil temperature and lower soil water content (Table 2). It has been shown that Q_{10} values tend to increase before reaching a threshold value [54]. It is noteworthy that soil water content below or above 12.8% exerted a significant influence on the Q_{10} value in *P. davidiana* plantations ($p = 0.019$). The Q_{10} value (2.48) below 12.8% soil water content was higher than the Q_{10} value (2.05) above 12.8% soil water content, which meant that limited water could increase temperature sensitivity to soil respiration. This phenomenon is especially evident for highly water-consumptive tree species, such as *P. davidiana.*

Temperature sensitivity of soil respiration is not a constant value because it incorporates combined responses to variations in soil temperature, soil water content, soil physiochemical properties, litter input, root biomass, snow melting, and other factors [33,61,62]. Previous studies showed that Q_{10} values were significantly higher in the non-growing season (November to April) than in the growing season (May to October) due to lower photosynthesis and microbial metabolism [60,63]. If this study period was extended to the whole year, the Q_{10} value would probably have increased [33,63,64].

We showed that the Q_{10} value of *P. tabulaeformis* was lower than that of *P. davidiana* plantations. Given the higher soil temperature and lower soil water content in the *P. tabulaeformis* plantations, lower Q_{10} values could be expected, together with differences in plant physiology and phenology. There are also differences in below-ground root processes between coniferous and deciduous plantations [64]. Due to increased root activity in spring, deciduous plant phenological activities are more significant than those of coniferous species [64], which leads to higher Q_{10} values [65]. Yuste et al. [64] and

Xu et al. [65] also concluded that the temperature sensitivity of deciduous forests was higher than that of coniferous forests. Therefore, differences in Q_{10} values between coniferous and deciduous plantations might be considered when choosing tree species for afforestation management in this area.

5. Conclusions

Plantations in the Beijing-Tianjin sandstorm source area were well-suited for examining the influence of stand age and forest type on soil respiration. Soil respiration decreased with *P. tabulaeformis* and *P. davidiana* stand age, which seems to be related to differences in canopy density, fine root biomass, and soil substrates. In contrast, forest type had no effect on soil respiration, whereas soil water content was not directly correlated with soil respiration. The temperature sensitivity of soil respiration was significantly affected by stand age, forest type, and soil water content. This study highlighted how soil respiration and Q_{10} values were affected by stand age and forest type, thus emphasizing how afforestation management choices can affect soil carbon cycling in this sandstorm source area.

Acknowledgments: We are greatly thankful for the help provided by Shiqi Lian and Changbai Liu with the field data collection. We appreciate Xinhua Zeng, Nannan Zhang, and Bin Zhang for their help with laboratory assistance. We appreciate the help of the editor and two anonymous reviewers for their constructive comments on the manuscript. This study was supported by the National Natural Science Foundation of China No. 31170414, the 100 Talents Program of the Chinese Academy of Sciences No. 41201514, and the Strategic Priority Research Program of the Chinese Academy of Sciences No. XDA05060600.

Author Contributions: Fadong Li and Wanjun Zhang designed the experiments; Xin Zhao, Zhipin Ai, and Huitao Shen performed the experiments; Xin Zhao and Xiuping Liu analyzed the data; Fadong Li, Wanjun Zhang, Jiansheng Cao contributed reagents/materials/analysis tools; Xin Zhao wrote the paper; Kiril Manevski revised the paper and modified the language.

Conflicts of Interest: The authors declare no conflict of interest.

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