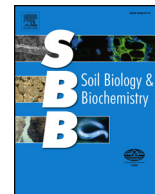




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Respiration of downed logs in pine and oak forests in the Qinling Mountains, China

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ABSTRACT

Approximately 70% of the carbon (C) stored in logs is released into the atmosphere, representing an important source of CO₂ lost from terrestrial ecosystems. Log respiration (R_{log}) has gained attention as a core issue in global C cycle research. In forest ecosystems that contain many logs, the R_{log} flux can convert forests from C sinks into C sources; thus, R_{log} should be considered in relevant research to avoid underestimating the CO₂ losses in the forest C cycle. Limited information is available regarding R_{log} from natural forests, and many uncertainties remain about the magnitude of R_{log}. In our study, R_{log} was measured *in situ* by infrared gas analysis in *Pinus armandi* and *Quercus aliena* var. *acuteserrata* forests in the Qinling Mountains, China. The objectives of this study were (1) to reveal the seasonal variation patterns of R_{log}; (2) to systematically analyze the relationships between R_{log} and various factors, including the tree species, decay class, temperature, water content, and chemical composition; and (3) to estimate the annual R_{log} flux in *P. armandi* and *Q. aliena* var. *acuteserrata* forests in the Qinling Mountains, China. This study presents a full year time series of R_{log} measurements for 30 logs (3 replicate logs × 5 decay classes × 2 tree species). The R_{log} measurements were repeated 468 times for each log from May 2014 to April 2015. The log temperature (T_{log}), air temperature (T_A), soil temperature (T_S) at a depth of 10 cm, and log water content (W_{log}) were measured simultaneously with R_{log}. Moreover, the log density (D_{log}) and chemical composition (C, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg)) were determined. Our results showed significant seasonal variation in R_{log} for both species, which corresponded to variations in T_{log} during the study period. The annual mean R_{log} of *Q. aliena* var. *acuteserrata* (1.69 ± 1.60 μmol m⁻²·s⁻¹) was higher than that of *P. armandi* (1.55 ± 1.43 μmol m⁻²·s⁻¹), but the difference was not significant (P = 0.61). The decay classes, T_{log}, W_{log}, and the N, P, Ca, and Mg concentrations were positively correlated with R_{log}. Moreover, the K concentration was negatively correlated with R_{log}, and the C concentration in logs was not correlated with R_{log}. The total annual R_{log} flux did not differ significantly between the *P. armandi* (67.25 ± 7.28 g C·m⁻²·y⁻¹) and *Q. aliena* var. *acuteserrata* (74.69 ± 9.31 g C·m⁻²·y⁻¹) forests (P = 0.26). These results provide insight into the factors responsible for seasonal changes in R_{log} and can improve estimates of the annual R_{log} flux in natural forests.

1. Introduction

Downed logs (hereafter referred to as logs) are defined as downed deadwood with a minimum diameter ≥ 10 cm at the widest point and a length ≥ 1 m that is in contact with the ground. A log can be produced via growth competition between trees, the natural death of trees at old ages, natural interference processes (e.g., wind, rain, snow, fire,

lightning, insects, debris flows, and fungal invasion) and human interference (logging) (Yuan et al., 2017a). The decomposition of log is a complex process that involves leaching, fragmentation and respiration (Harmon et al., 1986). During the decomposition of a log, approximately 70% of the C is respired to the atmosphere by microbial activities (Chambers and Schimel, 2001). Log respiration (R_{log}) has gained attention as a core issue in global C cycle research. In boreal forests, R_{log}

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comprises 1–54% of the C flux from the soil surface (Bond-Lamberty et al., 2002; Wang et al., 2002). In a temperate secondary broad-leaved forest in Japan, R_{\log} contributed to 10–16% of total heterotrophic respiration (Jomura et al., 2007). Logs can reduce the strength of the C sinks in many forests, and they can even convert forests from C sinks to C sources (Knohl et al., 2002); thus, R_{\log} should be considered in studies of forest C cycle.

R_{\log} is the outcome of various microbial and invertebrate animal physiological activities in logs that involve the oxidative decomposition of organic matter; it is a very complicated process that is affected by a combination of factors. Although a few studies have investigated R_{\log} , the results have been limited, fragmented, and not systemic; thus, many uncertainties persist. First, since microbial controls of R_{\log} are sensitive to environmental factors, obtaining reliable R_{\log} values remains challenging. Second, little is known about the mechanisms underlying R_{\log} . For example, numerous studies have demonstrated that the temperature (T_{\log}), water content (W_{\log}), decay status, wood structure, and chemical composition of logs have important impacts on R_{\log} (Ganjegunte et al., 2004; Herrmann and Bauhus, 2013; Mayuko et al., 2015; Wang et al., 2002; Wu et al., 2008; Yoon et al., 2015). However, how and why these various factors affect R_{\log} and the influence of these factors on R_{\log} *in situ* are difficult to predict because of the wide variation in environmental factors on daily and seasonal scales. In addition, estimates of the annual R_{\log} flux are subject to significant error. For example, since it is difficult to perform long-term continuous temperature observations of logs, air temperature (T_A) has instead been used to estimate the annual R_{\log} flux. Finally, R_{\log} varies with tree species and decay class, but models of the relationships between these factors and T_{\log} have not been established to allow the annual R_{\log} flux to be estimated.

The Huoditang Forest Region is in Ningshan County on the southern slope of the middle section of the Qinling Mountains. This forested area is rich in plant resources and has a vast variety of species, so it is an ideal place to conduct scientific studies. In the 1960s and 1970s, most of the Huoditang Forest Region was subjected to large-scale logging, resulting in many logs. However, since the implementation of the Natural Forest Protection Project in 1998, large-scale forest management activities have ceased in the Huoditang Forest Region, and the forests have been strictly protected and monitored. The existing forest vegetation is a natural secondary forest formed after the comprehensive forest cutting in the 1960s and 1970s and thus has an average age of 50–60 years. Compared to the 76-year-old *Castanopsis eyrei* forest in the Wuyi Mountains (7.35 Mg ha^{-1} , Li et al., 1996), this region has higher log masses of *Pinus armandi* ($12.15 \pm 2.82 \text{ Mg ha}^{-1}$) and *Quercus aliena* var. *acuteserrata* ($15.24 \pm 3.23 \text{ Mg ha}^{-1}$, Yuan et al., 2017b). The increased quantities of logs in this region have primarily resulted from local mortality pulses caused by extreme weather (strong winds), insects, and disease (*Dendroctonus armandi*). However, R_{\log} fluxes have long been neglected in C balance research in the Qinling forest ecosystem, and there have been few studies of the R_{\log} fluxes in the Qinling Mountains.

To address the above problems, the logs in the dominant forest types (*P. armandi* and *Q. aliena* var. *acuteserrata* forests) in the Huoditang Forest Region of the Qinling Mountains were studied, and R_{\log} was measured *in situ* by infrared gas analysis to accurately reveal the seasonal patterns and variations. Additionally, the relationships between R_{\log} and various factors, including the tree species, decay class, T_{\log} , W_{\log} , and chemical composition, were analyzed systematically. Finally, the annual R_{\log} flux was estimated for the main forest types in the area. We hypothesized that (1) R_{\log} differs significantly between tree species and displays significant seasonal variations and that (2) R_{\log} was significantly correlated with the decay class, T_{\log} , W_{\log} , and chemical composition.

2. Materials and methods

2.1. Study area

This study was conducted on the Huoditang Experimental Forest Farm of Northwest A&F University in the Qinling Mountains, Shaanxi Province, China. The farm covers an area of 2037 ha, the elevation is 800–2500 m, and the geographic coordinates are N33°18'–33°28' (latitude) and E108°21'–108°39' (longitude). The farm has a warm temperate climate, an annual average temperature of 10.50 °C, an annual precipitation of 1000 mm, and a frost-free period of 170 days. The abrupt and broken topography consists mainly of granite and gneiss. The mean slope is 35°, and the mean soil depth is 45 cm, with the soil units consisting of Cambisols, Umbrisols, and Podzols.

In March 2014, we selected *P. armandi* and *Q. aliena* var. *acuteserrata* forests for our permanent plots, and we established three repeated plots with an area of 60 m × 60 m in each forest type. Each plot was established on nearly flat terrain with similar site conditions, and a weather station was located 800 m from the furthest plot. To reduce disturbances, the plots were protected by an enclosure. Each plot was at least 50 m from the forest edge and was separated from the other plots by a buffer strip of at least 20 m. In the *P. armandi* forest, the elevation was 1524–1585 m, and the geographic coordinates were N33°26'3"–33°26'29" and E108°26'51"–108°27'20". The *P. armandi*-dominant forest (averaged 85% of the trees) was 60 years old, with an average canopy cover of 70%. The mean stand height, diameter at breast height (DBH), and stand density were 18 m, 25 cm, and 1418 trees·ha⁻¹, respectively. The height of the shrub layer varied from 18 cm to 350 cm, and the average percent cover was 24%. The major shrub species were *Euonymus phellomanus*, *Symplocos paniculata*, *Spiraea wilsonii*, *Litsea tsinlingensis*, and *Schisandra sphenanthera*, which were combined with herbs, e.g., *Carex leucochlora*, *Lysimachia christinae*, *Rubia cordifolia*, *Houttuynia cordata*, *Pinellia ternata*, *Sedum aizoon*, and ferns. The average height of the herbs was 24 cm, and the average percent cover was 42%.

The elevation of the *Q. aliena* var. *acuteserrata*-dominated forest (averaged 75% of the trees) was 1597–1658 m, and the geographic coordinates were N33°26'3"–33°26'31" and E108°26'12"–108°26'38". This forest was 50 years old, with an average canopy cover of 80%. The mean stand height, DBH, and stand density were 14 m, 20 cm, and 1824 trees·ha⁻¹, respectively. The height of the shrub layer varied from 64 cm to 560 cm, and the average percent cover was 18%. The major shrubs species were *Lonicera hispida*, *Sinarundinaria nitida*, *Symplocos paniculata*, *Lespedeza buergeri*, and *Rubus pungens*, which were combined with herbs, e.g., *Spodiopogon sibiricus*, *Epimedium brevicornu*, *Daphne tangutica*, *Urtica fissa*, *Paris quadrifolia*, and Pteridophyta. The average height of the herbs was 33 cm, and the average percent cover was 28% (Yuan et al., 2017a).

2.2. Log sampling

Each log was assigned to one of five decay classes based on internal and external tissue characteristics. Scores of 1, 2, 3, 4, and 5 represented the different decomposition stages, with 1 indicating the initial stage and 5 indicating the final stage (Table 1, Yan et al., 2007). In March 2014, we also documented the tree species, lengths and diameters of the basal and distal ends of each log in each plot.

We found that most of the logs in each plot were in the 20–30 cm size class, so 30 logs (3 replicate logs × 5 decay classes × 2 tree species) with diameters of 25 ± 5 cm (mean ± standard error) were selected. In March 2014, two fixed plates were mounted with silicon sealant at a random azimuth on each log for a total of 60 fixed plates on 30 logs.

Table 1
Characteristics of logs at different decomposition stages in the forest system.

Characteristics	Decomposition stages				
	1	2	3	4	5
Structural integrity	Sound	Sapwood slightly rotting, heartwood sound	Sapwood missing, heartwood mostly sound	Heartwood decayed	Soft
Leaves	Present	Absent	Absent	Absent	Absent
Branches	All twigs present	Larger twigs present	Larger branches present	Branch stubs present	Absent
Bark	Present	Present	Often present	Often absent	Absent
Bole shape	Round	Round	Round	Round to oval	Oval to flat
Wood consistency	Solid	Solid	Semisolid	Partly soft	Fragmented to powdery
Color of wood	Original color	Original color	Original color to faded	Original color to faded	Heavily faded
Invaded by roots	No	No	Sapwood area	Throughout	Throughout
Indirect measure	Cambium still fresh, died less than 1 year	Cambium decayed, knife blade penetrates a few millimeters	Knife blade penetrates less than 2 cm	Knife blade penetrates 2–5 cm	Knife blade penetrates all the way

2.3. Field measurements

A custom plexiglass cuvette with a volume of 800 cm³ and an 80 cm² opening was attached to the mounting plate just before each measurement. During each measurement, R_{log} was measured three times in succession three times per day at each cuvette. Measurements were taken every two weeks with an LI-6400 portable photosynthesis system (LI-COR, Inc., Lincoln, NE) from May 2014 to April 2015.

T_{log}, T_A, the soil temperature (T_S) at 10 cm, and W_{log} were measured simultaneously with R_{log}. T_{log} was measured 10 cm above the soil surface adjacent to each cuvette with a portable temperature probe that was part of the LI-6400 system, and T_A and T_S were measured by the weather station. A full suite of micrometeorological measurements, including T_A, humidity, photosynthetically active radiation, T_S, and precipitation, was collected at a weather station (HMP45C, Vaisala, Helsinki, Finland) located 1612 m from the study area. Data from all the sensors were recorded on data loggers (CR-1000, Campbell Scientific, Logan, UT) and were downloaded every two weeks to a laptop PC. To obtain W_{log} values during each respiration measurement, an approximately 2-cm-thick disk was cut from each log, immediately sealed in a plastic bag, and transported to the laboratory. W_{log} (g water/100 g log) was estimated from the dry weight (dried to a constant weight at 70 °C) and wet weight of these disk samples during each respiration measurement.

2.4. Log density and chemical composition

Log samples were collected in June 2014, October 2014, and March 2015. Ninety log samples (3 replicate logs × 5 decay classes × 2 tree species × 3 times) were collected to calculate the log density (D_{log}). An approximately 5-cm-thick disk was cut from each log sample, immediately sealed in a plastic bag, and transported to the laboratory. The volume of the disk (V_{disk}) was determined gravimetrically by water displacement, and D_{log} was estimated as the ratio of the dry weight of these disk samples (dried to a constant weight at 70 °C) to V_{disk}.

The sampling method used to determine the chemical composition of the logs (C, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg)) was the same as that used to obtain D_{log}. These log samples were dried in an oven at 70 °C for 72 h, and all the dried samples were then ground to pass through a 100-mesh screen (0.15 mm) for chemical analyses. Total C was determined by potassium dichromate oxidation titration, and total N and P were measured using the Kjeldahl N method and Mo anti-antimony colorimetry methods, respectively. The K concentration was measured using a flare photometer, and the Ca and Mg concentrations were determined by atomic absorption spectrometry (Dong, 1997).

2.5. Estimated annual R_{log} flux

We used an exponential equation to analyze the relationship between R_{log} and T_{log}:

$$R_{log} = R_0 e^{\beta T_{log}}$$

where R₀ and β are fitted parameters. The dependence of respiration on temperature is often described by the value of Q₁₀, which is termed the respiration temperature sensitivity and can be derived from Q₁₀ = exp(10β). Estimated parameters were used to predict R_{log} every 0.5 h over one year based on continuous temperature measurements from the weather station (Fig. 1). Continuous T_{log} values were calculated by linear models that simulated the relationships between T_{log} and T_A and T_{log} and T_S.

To scale R_{log} to the stand level (per unit forest area, 60 m × 60 m), we calculated the log surface area (S_{log}) of the five decay classes in the plots. Each log was considered a cylinder, so we used a formula to estimate the surface area from the length and the basal and distal cross-sectional areas of the cylinder:

$$S_{log} = \frac{\pi L(D_1 + D_2)}{2} + \frac{\pi(D_1^2 + D_2^2)}{4}$$

where L (m) is the length of the log and D is the diameter (m) at either end.

2.6. Statistical analyses

Repeated measures ANOVA, performed with SAS 8.0 software, was used to determine the effects of the log tree species, decay class, and

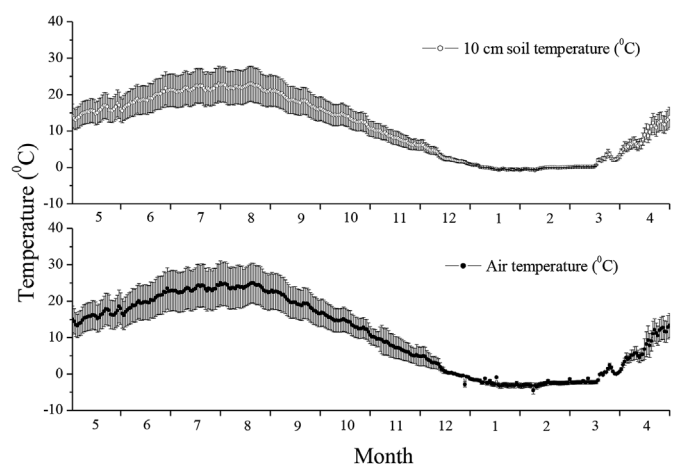


Fig. 1. Daily mean 10-cm soil temperature and air temperature. The errors bars are based on 0.5 h as the experimental unit (N = 48).

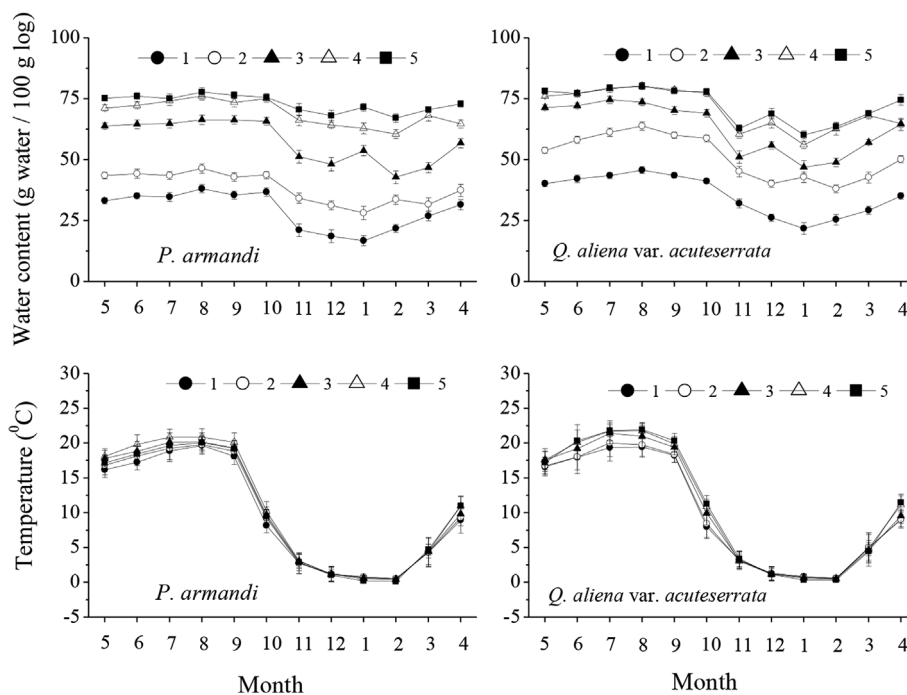


Fig. 2. Seasonal variations in the log water content and temperature in different decay classes of *P. armandi* and *Q. aliena* var. *acuteserrata*. The error bars are based on 3 repetitions \times 2 times as the experimental unit (N = 6).

month on R_{log} ; the effects of T_{log} , W_{log} , and D_{log} on the decay class; and the effects of the forest type and decay class on the annual R_{log} flux. If significant effects were detected, Duncan's *t*-test was used to calculate the pairwise differences.

The relationships among W_{log} , D_{log} , T_{log} , T_A , and T_S and the different decay classes were all fitted using a linear regression with Origin 8.0 software. Pearson's correlation coefficients (*r*) were calculated to test the dependence of W_{log} on the R_{log} of different decay classes and the relationship between the concentrations of the six chemical elements (C, N, P, K, Ca, and Mg) and R_{log} using SAS 8.0 software. The relationships between T_{log} and R_{log} for the different decay classes were fitted by exponential regression with Origin 8.0 software. The goodness-of-fit of the models was evaluated based on R^2 , and $P = 0.05$ was considered statistically significant in all analyses.

3. Results

3.1. T_{log} , W_{log} , and physicochemical properties

There was no significant seasonal variation in W_{log} in the *P. armandi* ($P = 0.90$) and *Q. aliena* var. *acuteserrata* ($P = 0.17$, Fig. 2) forests, but T_{log} exhibited significant seasonal variation in both forest types ($P < 0.01$), with the lowest values in the winter (December to February) and the highest in the summer (June to August). T_{log} did not differ significantly between the *P. armandi* and *Q. aliena* var. *acuteserrata* forests ($P = 0.81$) or among decay classes ($P = 0.93$ and $P = 0.92$, respectively).

The D_{log} value of the *Q. aliena* var. *acuteserrata* forest was significantly higher than that of the *P. armandi* forest for each decay class ($P < 0.01$, Fig. 3), and D_{log} significantly decreased with increasing decay class for *Q. aliena* var. *acuteserrata* and *P. armandi* ($P < 0.01$). The value of W_{log} did not differ significantly between *P. armandi* and *Q. aliena* var. *acuteserrata* ($P = 0.11$), but it increased significantly with increasing decay class ($P < 0.01$).

The concentrations of the six chemical elements (C, N, P, K, Ca, and Mg) varied significantly among decay classes in *P. armandi* and *Q. aliena* var. *acuteserrata* logs ($P < 0.05$, Fig. 4). The K concentration decreased

significantly with increasing decay class for *Q. aliena* var. *acuteserrata* ($P = 0.01$) and *P. armandi* ($P = 0.03$), but the C, N, P, Ca, and Mg concentrations increased significantly ($P < 0.05$).

Moreover, the C concentration of the *P. armandi* logs was significantly higher than that of the *Q. aliena* var. *acuteserrata* logs ($P = 0.03$, Fig. 4). However, other concentrations of the chemical elements (N, P, K, Ca, and Mg) did not differ significantly between *P. armandi* and *Q. aliena* var. *acuteserrata* logs ($P > 0.05$).

3.2. Factors affecting R_{log}

Significant seasonal variation was observed in the R_{log} values of the *P. armandi* and *Q. aliena* var. *acuteserrata* forests ($P < 0.01$), and the patterns were similar to those of T_{log} (Fig. 5). The *P. armandi* and *Q. aliena* var. *acuteserrata* R_{log} values ranged from 0.11 (February) to 4.82 (August) $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and from 0.08 (February) to 6.62 (August) $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively. The annual mean R_{log} of *Q. aliena* var. *acuteserrata* ($1.69 \pm 1.60 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was higher than that of *P. armandi* ($1.55 \pm 1.43 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), but there was no significant difference ($P = 0.61$). The decay classes, T_{log} , W_{log} , and the N, P, Ca, and Mg concentrations were positively correlated with R_{log} (Table 2); the K concentration was negatively correlated with R_{log} ; and the C concentration was not correlated with R_{log} . In addition, T_{log} was positively correlated with W_{log} and the N, P, Ca, and Mg concentrations. However, W_{log} was negatively correlated with the K concentration.

3.3. Estimated annual R_{log}

The seasonal variation in R_{log} was driven by temperature, and T_{log} was strongly exponentially correlated with R_{log} (Fig. 6). The variation in T_{log} explained 68%–80% of the variation in R_{log} among the different decay classes for *P. armandi* and *Q. aliena* var. *acuteserrata*. The Q_{10} value ranged from 1.95 ± 0.08 to 2.61 ± 0.17 (Table 3), but it did not differ significantly between *P. armandi* and *Q. aliena* var. *acuteserrata*. However, the Q_{10} value of *Q. aliena* var. *acuteserrata* was the highest for decay class 4 and the lowest for decay classes 1 and 2 (Table 3). For *P. armandi*, the Q_{10} value was the lowest for decay class 1 and the highest

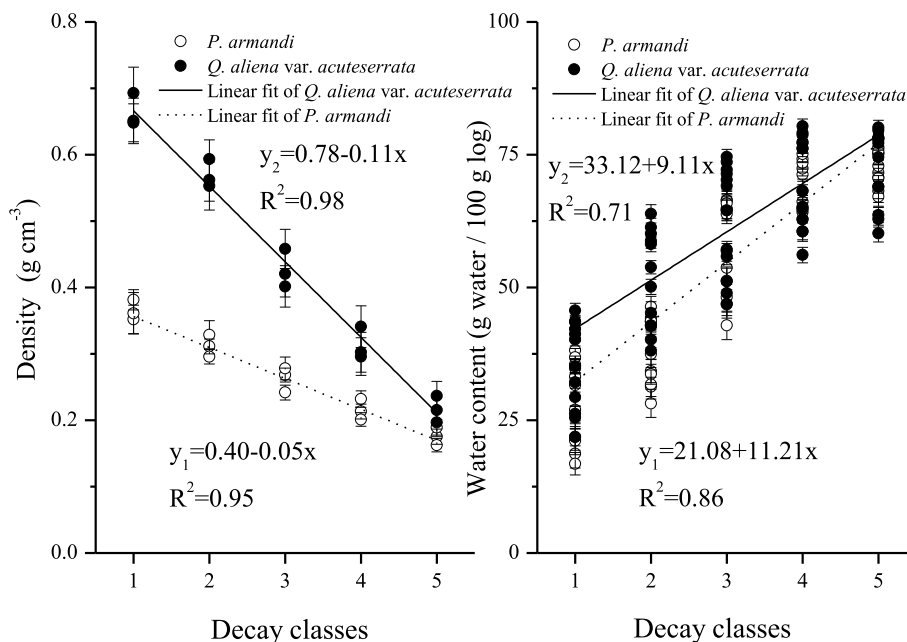


Fig. 3. Log density and water content in different decay classes of *P. armandi* and *Q. aliena var. acuteserrata*. The error bars of log density are based on 3 repetitions as the experimental unit (N = 3). The error bars of log water content are based on 3 repetitions × 2 times × 12 months as the experimental unit (N = 72).

for decay classes 4 and 5 (Table 3).

The S_{log} and annual R_{log} flux values of decay classes 4 and 5 were significantly higher in the *Q. aliena var. acuteserrata* forest than in the *P. armandi* forest, but for the other decay classes, these values were significantly higher in the *P. armandi* forest than in the *Q. aliena var. acuteserrata* forest (Table 4). The total annual R_{log} flux did not differ significantly between the *P. armandi* ($67.25 \pm 7.28 \text{ g C m}^{-2} \text{ y}^{-1}$) and *Q. aliena var. acuteserrata* ($74.69 \pm 9.31 \text{ g C m}^{-2} \text{ y}^{-1}$) forests, but the total S_{log} was significantly higher in the *P. armandi* forest ($983.45 \pm 75.21 \text{ m}^2$) than in the *Q. aliena var. acuteserrata* forest ($833.10 \pm 68.66 \text{ m}^2$). In addition, the S_{log} and annual R_{log} flux values of the *Q. aliena var. acuteserrata* forest were the highest for decay class 5 and the lowest for decay class 1 (Table 4). Conversely, the S_{log} and

annual R_{log} flux values of the *P. armandi* forest were the highest for decay class 3 (Table 4). For the *P. armandi* forest, S_{log} was the lowest for decay classes 4 and 5, and the annual R_{log} flux was the lowest for decay classes 1, 2, 4, and 5 (Table 4).

4. Discussion

4.1. The seasonal variation of R_{log}

Our study showed that R_{log} displayed significant seasonal variation that was driven by T_{log} , which was consistent with findings from other studies (Guo et al., 2014; Progar et al., 2000; Sun and Wang, 2007; Wang et al., 2002; Wu et al., 2008; Zhang et al., 2010). However, T_{log}

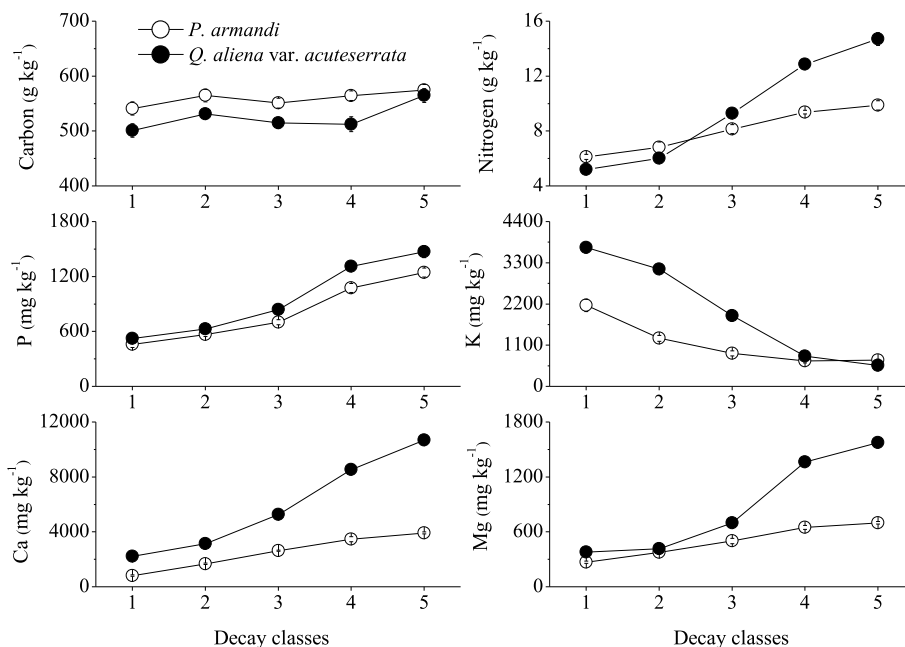


Fig. 4. The concentrations of the chemical elements in the *P. armandi* and *Q. aliena var. acuteserrata* logs in different decay classes. The error bars are based on 3 repetitions as the experimental unit (N = 3).

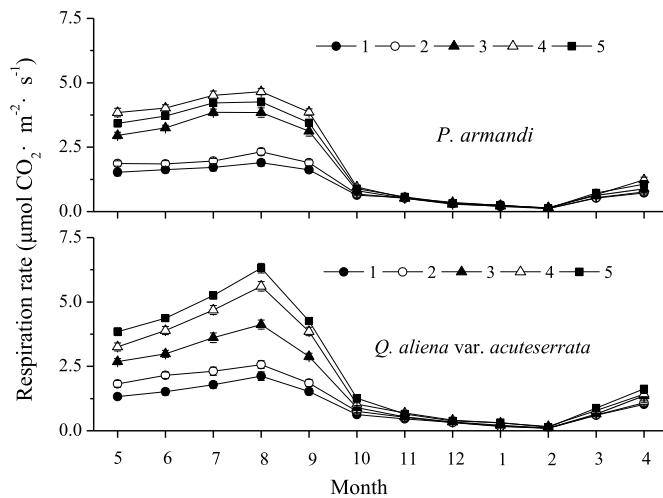


Fig. 5. Seasonal variation in R_{log} in different decay classes of *P. armandi* and *Q. aliena* var. *acuteserrata*. The error bars are based on 3 repetitions \times 2 times as the experimental unit ($N = 6$).

did not differ significantly between the two species in this study, which was consistent with the results of Sun and Wang (2007), who measured the T_{log} values of 11 species in the eastern mountainous area of Northeast China. Due to microbial decomposition, heat would be released from the logs, thus increasing T_{log} . Additionally, differences among different tree species and the number of microorganisms in the log decomposition process may cause differences in T_{log} (Zhang et al., 2010), but these differences were not significant in this study. Furthermore, there was no significant difference in T_{log} among the different decay classes in this study, potentially because the changes in the thermal capacity and thermal conductivity of the logs were not significantly associated with decomposition (Harmon et al., 1986).

4.2. Correlation of R_{log} with T_{log} , W_{log} , the decay class, and the chemical composition

T_{log} was significantly positively correlated with R_{log} at our sites, which was similar to the findings in previous studies (Guo et al., 2014; Progar et al., 2000; Wang et al., 2002). Notably, microbial activity is enhanced as T_{log} increases, which accelerates log decomposition, the mineralization of organic matter and the release of CO_2 (Harmon et al., 1986). T_{log} explained 68%–80% of the variation in R_{log} among the different decay classes of *P. armandi* and *Q. aliena* var. *acuteserrata* (Fig. 6). This result was similar to that of Wu et al. (2008), who estimated that T_{log} explained 67%–76% of the variation in R_{log} in the Changbai Mountains in northeastern China.

The temperature dependence of respiration is often described by the Q_{10} value, which did not differ significantly among the tree species in

our study; specifically, T_{log} and the annual mean R_{log} values did not differ significantly among the tree species in our study. This conclusion differed from that of Harmon et al. (2000), who suggested that species-specific wood traits were responsible for highly variable respiration and potentially altered Q_{10} . However, there was a significant difference in Q_{10} among the different decay classes (Table 3). Gough et al. (2007) concluded that the variation in Q_{10} was related to the decay class, with intermediate decay classes exhibiting the greatest temperature response, which may be caused by more chemical compounds that are difficult to decompose reducing microbial activity in the advanced decay classes (Harmon et al., 1986; Yatskov et al., 2003). Q_{10} ranged from 1.7 to 4.1 for the different decay classes in various ecosystems (Bond-Lamberty et al., 2002; Wang et al., 2002; Wu et al., 2008), and our results fell within this range. Furthermore, the Q_{10} value was significantly affected by the temperature range, mainly because the temperature necessary for the growth of most bacteria in decaying wood ranges from 3 to 40 °C. The limiting effects of temperature on microorganisms weaken above this temperature range (Chen et al., 2004). For example, the Q_{10} value was 4.1 from 5 to 20 °C and 1.7 from 20 to 42 °C in a boreal black spruce forest in Canada (Wang et al., 2002).

Unlike T_{log} , the D_{log} values of both species decreased linearly with increasing decay class (Fig. 3), and this finding is consistent with the results of a study by Liu and Wang (1992) on *Betula ermanii* in the Changbai Mountains. Additionally, W_{log} increased linearly with increasing decay in both tree species, which is consistent with the changes in W_{log} in *Cryptocarya concinna* (Lv et al., 2006a), *Castanea henryi* (Lv et al., 2006b), and *Schima superba* (Yang et al., 2009) in the Dinghushan Mountains and *B. ermanii* in the Changbai Mountains (Liu and Wang, 1992). During the rainy season, higher log decay classes have a looser wood structure, making it easier for water to be absorbed; during the dry season, W_{log} gradually increases with the decay class in the low-temperature and high-humidity environment. Furthermore, as the decay class increases, various plants would become established and grow, which may explain why W_{log} gradually increased with the decay class. As more plants invade, W_{log} increases, and W_{log} is a component of the water cycle in woodland areas and an important water source for tree seedlings. However, there were no significant seasonal changes in the W_{log} values of the two species, potentially due to the high relative humidity (greater than 70%) and abundant rainfall in the Huoditang Forest Region of the Qinling Mountains (Yuan and Zhang, 2012).

W_{log} was also significantly positively correlated with R_{log} (Table 2), which was consistent with the result of other studies (Mayuko et al., 2015; Wang et al., 2002). This is mainly caused by influencing microbial activities (Harmon et al., 1986). W_{log} affects the growth of wood-decaying fungi in two ways: the water supply is restricted at low moisture contents, and the water-filled void space limits gaseous exchange (Bond-Lamberty et al., 2002; Liu et al., 2012; Mayuko et al., 2015). Wu et al. (2008) conducted a study on the R_{log} values of *Pinus koraiensis* and *Tilia amurensis* in the Changbai Mountains and found that the R_{log} of dry logs increased approximately linearly with increasing

Table 2
Correlation analysis between R_{log} and influential factors.

	Decay classes	T_{log}	W_{log}	C	N	P	K	Ca	Mg	R_{log}
Decay classes	1.00									
T_{log}	0.05	1.00								
W_{log}	0.86**	0.42**	1.00							
C	0.50	0.01	0.26**	1.00						
N	0.87**	0.05	0.75**	0.25	1.00					
P	0.95**	0.05	0.82**	0.31	0.94**	1.00				
K	-0.81**	-0.04	-0.63**	-0.67*	-0.74*	-0.71*	1.00			
Ca	0.72*	0.05	0.66**	-0.02	0.93**	0.86**	-0.47	1.00		
Mg	0.76*	0.05	0.67**	0.06	0.97**	0.90**	-0.57	0.98**	1.00	
R_{log}	0.32**	0.88**	0.59**	0.11	0.32**	0.32**	-0.27**	0.28**	0.29**	1.00

** $P < 0.01$, * $P < 0.05$; T_{log} , log temperature; W_{log} , log water content; C, carbon concentration; N, nitrogen concentration; P, phosphorus concentration; K, potassium concentration; Ca, calcium concentration; Mg, magnesium concentration; R_{log} , log respiration.

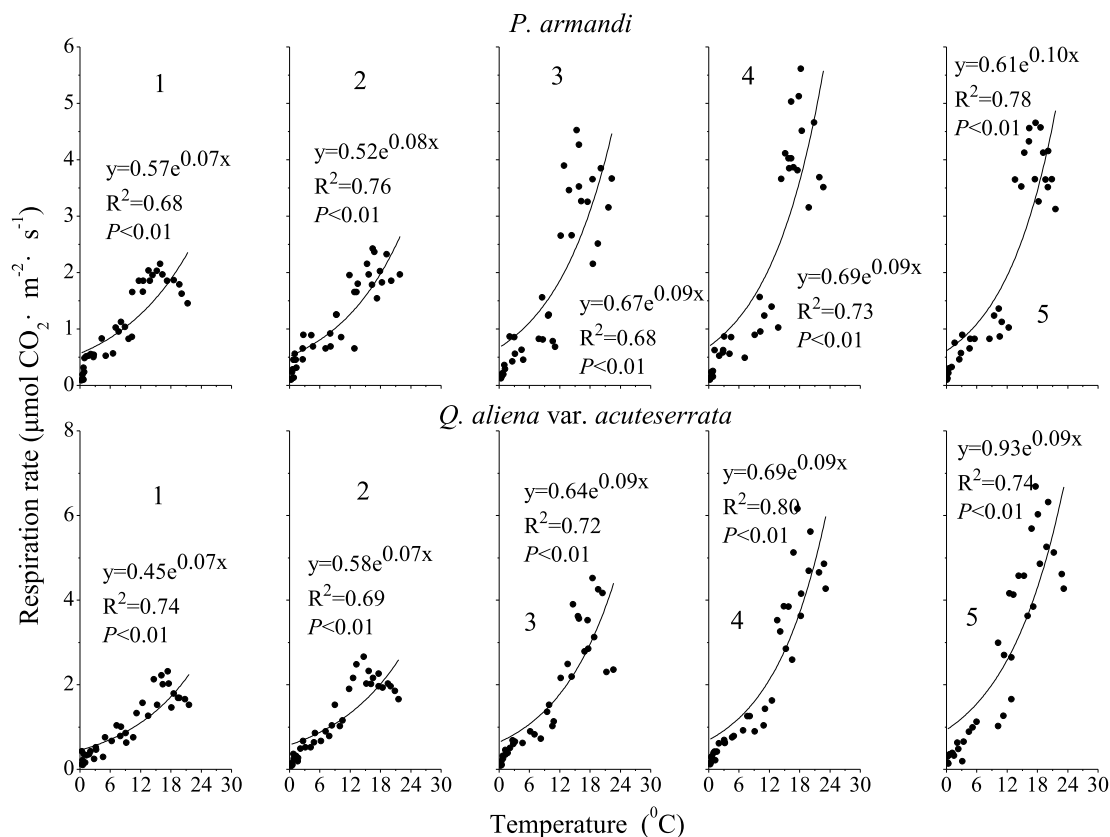


Fig. 6. The exponential correlation between R_{log} and T_{log} in different decay classes of *P. armandi* and *Q. aliena* var. *acuteserrata*.

Table 3
 Q_{10} for different decay classes of *P. armandi* and *Q. aliena* var. *acuteserrata*.

Tree species	Decay classes				
	1	2	3	4	5
<i>P. armandi</i>	1.95 (0.08) a	2.11 (0.15) a	2.34 (0.18) a	2.51 (0.16) a	2.61 (0.17) a A
<i>Q. aliena</i> var. <i>acuteserrata</i>	2.10 (0.12) a	2.00 (0.09) a B	2.34 (0.14) a	2.54 (0.18) a	2.33 (0.15) a

Standard errors are shown in parentheses (N = 3), and different small letters within the same column or capital letters within the same row are significantly different ($P < 0.05$).

W_{log} ; when W_{log} exceeded a certain range, R_{log} slowly increased or declined. However, we did not observe limitations to the respiration rate at a high moisture content in our study. This result may be because

Table 4
The surface area (S_{log} , m^2) and annual R_{log} flux ($g C \cdot m^{-2} \cdot y^{-1}$) in different decay classes of downed logs in *P. armandi* and *Q. aliena* var. *acuteserrata* forests.

Forest types	Decay classes										Total	
	1		2		3		4		5		S_{log}	R_{log} flux
	S_{log}	R_{log} flux	S_{log}	R_{log} flux	S_{log}	R_{log} flux	S_{log}	R_{log} flux	S_{log}	R_{log} flux		
<i>Q. aliena</i> var. <i>acuteserrata</i>	88.34 (9.64) b E	3.76 (0.46) b E	102.15 (12.11) b D	5.22 (0.65) b	168.38 (17.92) b C	12.99 (1.83) b C	203.75 (25.55) a B	20.53 (2.84) a B	270.48 (31.35) a A	32.19 (4.86) a A	833.10 (68.66) b	74.69 (9.31) a
<i>P. armandi</i>	222.15 (24.16) a B	10.59 (1.52) a B	228.23 (24.41) a B	11.32 (1.82) a B	280.64 (30.54) a A	22.35 (2.81) a A	117.25 (15.29) b C	11.26 (1.68) b B	135.18 (15.94) b C	11.73 (1.51) b B	983.45 (75.21) a	67.25 (7.28) a

Standard errors are shown in parentheses (N = 3), and different small letters within the same column or capital letters within the same row are significantly different ($P < 0.05$).

the high W_{log} did not limit the growth of wood-decaying fungi. Yuan et al. (2017c) studied fungal community structure of fallen pine and oak wood in this region and concluded that a high W_{log} enhanced fungal diversity.

Undoubtedly, the decay class was significantly positively correlated with R_{log} in our study, which was consistent with findings from other areas (Guo et al., 2014; Sun and Wang, 2007; Wu et al., 2008). The density, water content, temperature, structure, chemical composition and microbial diversity of logs varied with different decay classes, and all these factors affected R_{log} (Harmon et al., 1986). In this study, R_{log} was the lowest for class 1, mainly because the compact structure and complete bark characterizing this class made the logs resistant to invasion by microorganisms. Logs with higher decay classes had looser structures and lower D_{log} values, i.e., they had a higher surface area per unit weight than logs that were less decayed. These characteristics resulted in a large contact area between the logs and air that was conducive to invasion and decomposition by microorganisms, leading to high R_{log} values.

Surprisingly, the C concentration was not significantly correlated with R_{log} , which differed from the results of Mayuko et al. (2015), who concluded that C had a large negative direct effect on the respiration rate. C is the most important chemical component in logs, and its decomposition greatly contributes to the loss of log quality. Some C is released into the air by microbial decomposition in the form of CO_2 , whereas the remaining C is lost through leaching. Differences in the C concentration between the two species might result from the different timber qualities, for which the microbial community and log decomposition rate may vary with species (Li and Li, 1992).

However, the N, P, Ca, and Mg concentrations were significantly positively correlated with R_{log} (Table 2). During the log decomposition process, the N concentration gradually increased due to N fixation by fungi and N input during rainfall (Garrett et al., 2008; Wilcke et al., 2005). The losses of P, Ca, and Mg were low relative to the mass loss of logs (Yuan et al., 2017a); thus, the concentrations of P, Ca, and Mg gradually increased. N, P, Ca, and Mg are necessary for the growth of most microorganisms in decaying wood (Harmon et al., 1986). Overall, the increases in the N, P, Ca, and Mg concentrations may affect the species composition and number of microorganisms and enhance microbial activity, which accelerates log decomposition and CO_2 release (Harmon et al., 1986).

The K concentration was significantly negatively correlated with R_{log} (Table 2). Generally, the K concentration in bark is significantly higher than that in heartwoods and sapwoods, so the rapid decomposition of bark is significantly correlated with large K losses (Lv et al., 2006b). The increase in the K concentration may inhibit the growth of some microorganisms, reduce microbial activity, and enhance chemical compounds that are difficult to decompose, which may slow log decomposition and CO_2 release (Chi et al., 2004; Chang et al., 2014).

4.3. Annual R_{log} flux

Although the S_{log} values of the *P. armandi* forest were significantly higher than those of the *Q. aliena* var. *acuteserrata* forest, there was no significant difference in the annual R_{log} flux (Table 4). This result is mainly because the S_{log} of the *P. armandi* forest was significantly higher than that of the *Q. aliena* var. *acuteserrata* forest in the early and middle stages of decomposition (1–3), whereas the S_{log} of the *Q. aliena* var. *acuteserrata* forest was significantly higher in the late decomposition stages (4 and 5). Logs with high levels of decomposition also had high respiration rates, so there was no significant difference in the annual R_{log} flux between forest types. However, Tang et al. (2008) studied R_{log} values in the Great Lakes region of northern Michigan, United States, and found that the annual R_{log} flux in a broadleaf forest ($43 \text{ g C m}^{-2} \text{ a}^{-1}$) was higher than that in a *Tsuga chinensis* forest ($29 \text{ g C m}^{-2} \text{ a}^{-1}$).

The annual R_{log} fluxes in these two forest types were higher than that in the temperate deciduous forest in the northern Great Lakes region of North America ($21 \text{ g C m}^{-2} \text{ a}^{-1}$, Gough et al., 2007) and the *P. koraiensis* and *T. amurensis* forests in the Changbai Mountains ($26.9 \text{ g C m}^{-2} \text{ a}^{-1}$, Wu et al., 2008) but lower than the annual R_{log} fluxes in a forest in the Amazon basin ($171.8 \text{ g C m}^{-2} \text{ a}^{-1}$, Rice et al., 2004). These results may be related to the successional stage of the forest area in this study, which was a natural secondary forest that formed after comprehensive logging. The forest stands were an average of 50–60 years old and were in the initial stage of forest succession. The trees exhibited good growth, and the spatial density was relatively sparse. Although this area has been constantly affected by extreme weather, insects, and disease, the log mass under high levels of decomposition (4 and 5) was low, which contributed to only 16%–30% of the overall mass (Yuan et al., 2017b). Therefore, the R_{log} flux was low. Moreover, climatic conditions also affected the annual R_{log} flux. In mid- to high-latitude areas, the cold environment slowed the decomposition of logs, resulting in lower R_{log} values; in low-latitude areas, high-temperature and high-humidity environments promoted rapid

decomposition, resulting in higher R_{log} values.

Based on eddy covariance measurements, the annual ecosystem respiration was estimated as $780.4 \pm 82.18 \text{ g C m}^{-2} \text{ y}^{-1}$ in this area (Yuan et al., 2018). The total annual R_{log} flux contributed to 7%–12% of the total ecosystem respiration in these warm temperate natural secondary forests, which demonstrated that R_{log} was an essential component of forest ecosystem respiration.

5. Conclusions

In our study, R_{log} was measured *in situ* by infrared gas analysis in the Qinling Mountains, China. This study presents a full year time series of R_{log} measurements of *P. armandi* and *Q. aliena* var. *acuteserrata* logs from May 2014 to April 2015. R_{log} exhibited significant seasonal variation and was predominantly controlled by T_{log} . Notably, microbial activity is enhanced with increasing T_{log} , which accelerates log decomposition, the mineralization of organic matter and the release of CO_2 . The total annual R_{log} flux contributed to 7%–12% of total ecosystem respiration in these warm temperate natural secondary forests, which demonstrated that R_{log} was a significant component of forest ecosystem respiration. This study provides more accurate data to inform forest C cycle research and clarify the contribution of logs to the C cycle at regional and global scales, thereby elucidating the mechanisms and processes that drive the C cycle in forests while providing a theoretical basis for log management. To avoid high R_{log} values in forests, logs should be placed over cool and dry areas of the forest floor. The results from our study can be used in the preparation of greenhouse gas inventories and construction of carbon cycle models in the future.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.soilbio.2018.09.012>.

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