Soil Biology and Biochemistry 127 (2018) 1–9

Contents lists available at ScienceDirect

Soil Biology and Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

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

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ARTICLE INFO

Keywords:
Log respiration
Physicochemical properties
Log temperature
Log water content
Decay classes

ABSTRACT

Approximately 70% of the carbon (C) stored in logs is released into the atmosphere, representing an important source of CO_2 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 CO_2 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* ($1.69 \pm 1.60\,\mu mol\,m^{-2} \cdot s^{-1}$) was higher than that of *P. armandi* ($1.55 \pm 1.43\,\mu mol\,m^{-2} \cdot s^{-1}$), 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* ($67.25 \pm 7.28\,g\,C \cdot m^{-2} \cdot y^{-1}$) and *Q. aliena* var. *acuteserrata* ($74.69 \pm 9.31\,g\,C \cdot m^{-2} \cdot y^{-1}$) 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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https://doi.org/10.1016/j.soilbio.2018.09.012
Received 23 April 2018; Received in revised form 8 September 2018; Accepted 11 September 2018
Available online 12 September 2018

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 ± 2.82 Mg ha^{-1}) and *Quercus aliena* var. *acuteserrata* (15.24 ± 3.23 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.