Postprint: Factors Influencing Soil Respiration Rates in Forests of Different Ages at Mao' er Mountain

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Abstract

To investigate the variation trend of soil respiration (RS) and its influencing factors during the recovery process of temperate forests in Northeast China, we conducted one-year field in situ measurements in four stands of different ages (1a, 10a, 25a, and 56a) that were naturally regenerated after clear-cutting at Mao' er Mountain. The results showed that: (1) The annual RS fluxes of stands naturally regenerated for 1, 10, 25, and 56 years after clear-cutting differed significantly (P<0.05), with values of 686.5, 639.7, 733.3, and 762.3 g C m-2 a-1, respectively; the RS fluxes in both the growing season (May October) and non-growing season also showed significant differences, displaying a decreasing-then-increasing trend with stand age. The coefficients of variation for annual, growing season, and non-growing season RS with stand age were 7.6%, 6.3%, and 21.1%, respectively, indicating that the variability of RS flux in the non-growing season amplified the differences in annual RS flux. (2) The seasonal variation trends of Rs in the four stands were similar, and their main controlling factors varied with season: Rs showed a quadratic function relationship with soil moisture content from June to August (R2 fluctuated between 56% 79%), while during other periods it showed an exponential function relationship with soil temperature (R2 fluctuated between 85% 93%). (3) Growing season RS in stands of different ages showed a positive correlation with soil organic carbon (SOC) density in the 0 20cm soil layer (R2=0.434, P<0.05), while non-growing season RS showed a positive correlation with soil temperature at 5cm depth in the same period (R2=0.959, P<0.01). In our study area, clear-cutting of forests led to a decrease in RS, which continuously increased with forest recovery after clear-cutting, with the dominant drivers being the increase in SOC density and changes in soil temperature during the non-growing season.

Full Text

Factors Affecting Soil Respiration Rates in Stands of Different Ages in the Maoershan Region, Northeast China

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Abstract

To investigate the variation trends and influencing factors of soil respiration during the restoration of temperate forests in Northeast China, we selected naturally regenerated stands following clear-cutting in the Maoershan region. A chronosequence including four stand ages (1, 10, 25, and 56 years since logging) was established in 2014. Soil respiration (R_S) was measured using a LI-840 CO2/H2O analyzer from April 2014 to March 2015, along with soil temperature and water content at a 5 cm depth. Soil organic carbon (SOC) and fine root biomass (diameter < 0.5 mm) were measured at the end of the growing season. The results showed: (1) Annual R_S differed significantly among stands ($P < 0.05$), averaging 686.5, 639.7, 733.3, and 762.3 g C m^-2 yr^-1 for the 1-, 10-, 25-, and 56-year-old stands, respectively. R_S in both growing and non-growing seasons differed significantly among stands, showing a decreasing trend immediately after clear-cutting, then increasing with stand age. The coefficients of variation in R_S among stands were 7.6%, 6.3%, and 21.1% for the whole year, growing season, and non-growing season, respectively, suggesting that variability in non-growing season R_S amplified annual differences. (2) All stands showed similar seasonal R_S patterns, but controlling factors varied seasonally. Between June and August, R_S was significantly related to soil water content in a polynomial function ($R^2 = 56\%$–79%), whereas during other months it was significantly related to soil temperature in an exponential function ($R^2 = 85\%$–93%). (3) Growing season R_S was positively correlated with SOC content at 0–20 cm depth across all stands ($R^2 = 0.434$, $P < 0.05$), whereas non-growing season R_S was positively correlated with soil temperature at 5 cm depth in the same season ($R^2 = 0.959$, $P < 0.01$). These results suggest that R_S in these forests decreases after logging disturbance and increases with stand age, driven mainly by increased SOC content and changes in soil temperature during the non-growing season.

Keywords: seasonal change; chronosequence; driving factor; logging; soil respiration; forest restoration

Introduction

Soil respiration (R_S) represents the primary pathway for CO2 efflux from terrestrial ecosystems to the atmosphere and plays a crucial role in ecosystem carbon balance. The soil organic carbon pool, approximately 1500 Pg C, constitutes the largest carbon reservoir in terrestrial ecosystems—twice the size of the atmospheric carbon pool—and therefore exerts significant influence on the global carbon cycle. R_S is a key component of terrestrial ecosystem carbon cycling and the main route of soil carbon emission, with total global emissions estimated at 68-98 Pg C yr^-1. Even minor fluctuations in R_S could substantially impact atmospheric CO2 concentrations and global carbon balance, equivalent to carbon emissions from fossil fuel combustion.

R_S is influenced by numerous factors including climate change, soil properties, and stand age. As forests age, changes in species composition, biomass accumulation, and carbon allocation can significantly affect carbon exchange between forests and the atmosphere. However, research findings on how stand age affects R_S remain uncertain. Studies of tropical forests by Ewel et al. [16] reported that R_S increases with stand age, while research on Canadian boreal forests by Wang et al. [17] and on Douglas-fir chronosequences in the southern United States by Klopatek et al. [18] found that R_S first increases then decreases with age. Tang et al. [12] studying aspen chronosequences in the Great Lakes region reported that R_S first increases then decreases with stand age. These uncertainties may relate to disturbance type or study region.

Northeast China represents a key forest region where decades of logging have reduced forest area, eliminated primary forests, and simplified forest age structure. Since the implementation of ecological forestry programs such as the Natural Forest Protection Project and Grain-for-Green, large areas of naturally regenerated stands following clear-cutting have emerged [19–20]. However, the characteristics of R_S and its influencing factors across different-aged stands remain unclear. This study investigated R_S in naturally regenerated stands of different ages (1, 10, 25, and 56 years) in the Maoershan region to examine seasonal variation patterns and the effects of soil temperature and moisture on R_S fluxes across stand ages.

1. Study Area and Plot Setup

The study was conducted at the Maoershan Forest Ecosystem National Field Scientific Observation and Research Station in Heilongjiang Province (45°24 N, 127°40 E). The region has a temperate continental monsoon climate with cold, dry winters and short, hot, humid summers. Mean annual precipitation is 864 mm, concentrated in specific months; mean annual evaporation is 629 mm; mean annual temperature is 3.1°C; annual sunshine hours total 1857 h; and the frost-free period is 120–140 days. Elevation is approximately 400 m. The zonal soil type is dark brown forest soil. The vegetation belongs to the Changbai flora, with current vegetation representing secondary forests that developed through

secondary succession after repeated logging of the original broadleaved Korean pine forests, typical of forest types in the mountainous region of eastern Northeast China.

We selected stands representing four stages of natural regeneration following clear-cutting: 1-year-old (clear-cut site), 10-year-old, 25-year-old, and 56-year-old stands. All stands were secondary forests. Three replicate plots were established in each stand, with each plot measuring 20 m × 30 m.

2. Measurement of Soil Respiration and Environmental Factors

In early January, we installed soil rings (10.2 cm diameter, with one end sharpened to minimize soil compaction) in each plot, maintaining their positions throughout the measurement period. Soil respiration was measured using a LI-840 CO2/H2O analyzer (LI-COR, Lincoln, USA). Measurements were taken monthly during the growing season and monthly during the non-growing season. Soil temperature at 5 cm depth was measured near each soil ring using thermocouple probes. Soil volumetric water content at 0–5 cm depth was measured using a TDR100 soil moisture meter (Spectrum Technologies, USA). Due to soil freezing during some months, water content measurements were adjusted accordingly.

Fine root biomass was measured using the root core method. At the end of each growing season, soil cores were collected near each soil ring using a 5 cm diameter root auger to a depth of 50 cm. Soil samples were washed on a mesh sieve, and roots were separated into live and dead categories based on appearance and elasticity. Live roots were further divided into two diameter classes: <0.5 mm and 0.5–2 mm. Soil organic carbon (SOC) was measured on air-dried soil samples.

3. Data Analysis

Soil samples were oven-dried at constant temperature to constant weight. One portion was air-dried for SOC determination. The relationship between R_S (mol CO2 m⁻² s⁻¹) and soil temperature was modeled using an exponential function [21]. The relationship between R_S and soil water content was modeled using a quadratic function [22]. Based on previous studies [10, 23–26], we used the following model to simulate the relationship between R_S and both soil temperature and water content [17], where h represents model parameters. Multiple linear regression was used to fit models separately for each stand age, calculating daily R_S values that were compared with measured values.

The study employed piecewise simulation because exponential function predictions deviated substantially from measured values for some months. During June–August, R_S was estimated using the quadratic relationship with water content, while for other months the exponential relationship with temperature

was used. For all stand ages, R_S showed highly significant exponential relationships ($P < 0.05$), but the models fit better when using piecewise simulation.

To compare R_S among stands of different ages, we could not directly compare each measured R_S value because measurements could not be taken simultaneously for all soil rings, and soil temperature and water content inherently differed among stands. Therefore, we first established regression models between measured R_S and simultaneously recorded soil temperature (T) from nearby automatic data loggers for each plot. Using continuous T data from the data loggers, we obtained continuous T values for each plot, then substituted these into the stand-specific R_S regression models. Daily R_S values were summed at a daily time step to obtain growing season, non-growing season, and annual R_S fluxes for each stand.

Repeated measures ANOVA was used to analyze the effects of stand age and measurement time on R_S. Multiple linear regression was used to analyze relationships between annual R_S and fine root biomass and SOC. Duncan' s test was used for multiple comparisons. All analyses were performed using SPSS 19.0 (SPSS Inc., Chicago, Illinois, USA) and SigmaPlot 10.0 (Systat Software Inc., San Jose, CA, USA) for graphing.

shows the regression models of soil respiration against soil temperature or soil water content for each stand age.

Results

3.1 Seasonal Dynamics of Soil Respiration and Their Controlling Factors

All stands exhibited similar seasonal patterns in soil temperature (T), with maximum values occurring during the growing season (July) and minimum values in winter. Seasonal patterns in soil water content (W) among stands were generally consistent except during certain months, showing greater variability during the growing season than the non-growing season. Differences in T among stands were smaller during the growing season than during the non-growing season [Figure 2: see original paper].

The four stands showed consistent seasonal dynamics in R_S, following a unimodal pattern with high rates during the growing season and low rates during the non-growing season. The seasonal dynamics could be divided into two phases: a soil water content control phase and a soil temperature control phase. During the temperature control phase, the model explained 85%, 93%, and 88% of R_S variability in the four stands. During the water content control phase, the model explained 56%, 63%, and 79% of R_S variability.

Repeated measures ANOVA revealed that stand age ($P = 0.013$) and measurement time ($P < 0.001$) had significant effects on R_S, but their interaction was not significant ($P = 0.076$). Annual, growing season, and non-growing season mean R_S values differed significantly among stands, ranging from 1.75–

2.09 g C m^-2 d^-1, 3.21–3.72 g C m^-2 d^-1, and 0.27–0.45 g C m^-2 d^-1, respectively .

Annual R_S fluxes ranged from 639.7 to 762.3 g C m^-2 yr^-1, within the range reported for temperate forests (122–1754 g C m^-2 yr^-1). Both annual and growing season R_S fluxes showed a decreasing-then-increasing trend with stand age since clear-cutting. The coefficient of variation in R_S flux with stand age was 7.6% for the growing season and 6.3% for the non-growing season, but 21.1% for the whole year, indicating that non-growing season variability amplified differences in annual R_S among stands.

3.2 Differences in Soil Respiration Among Stands and Their Driving Factors

Growing season R_S was significantly positively correlated with fine root biomass in the 0–10 cm soil layer ($P < 0.03$) and with SOC content in the 0–20 cm layer ($R^2 = 0.434$, $P = 0.02$). Non-growing season R_S was significantly positively correlated with stand density ($R^2 = 0.390$, $P < 0.05$) and with soil temperature at 5 cm depth ($R^2 = 0.959$, $P < 0.01$).

[Figure 3: see original paper] compares annual, growing season, and non-growing season R_S fluxes among stands. The consistent seasonal dynamics across the four naturally regenerated stands of different ages resemble patterns observed in boreal forests [12] and subtropical forests [27]. This similarity likely reflects strong control by soil temperature and water content [28–29], as air temperature and precipitation patterns drive comparable changes in soil temperature and moisture across stands, resulting in similar seasonal R_S trends [30].

During the temperature control phase, R_S showed highly significant exponential relationships with soil temperature across all stand ages, consistent with other temperate forest studies [12, 31–32], indicating that soil temperature is the dominant factor controlling temporal R_S dynamics during this period. During the water content control phase, R_S showed significant quadratic relationships with soil water content ($R^2 = 0.56$–0.79), similar to results from forest ecosystems on the Loess Plateau [33]. When soil water content is not limiting, temperature becomes the dominant factor controlling R_S. However, when water content is limiting, it becomes the dominant factor controlling R_S under temperature-driven conditions [9, 34–35]. Low soil water content inhibits diffusion of soluble substrates, while excessively high water content reduces gas diffusion and creates oxygen deficiency, both suppressing R_S [36–37].

Discussion

4.1 Seasonal Variation Patterns and Influencing Factors

The four stands exhibited similar seasonal R_S patterns, consistent with studies in boreal forests [12] and subtropical forests [27]. This similarity arises from

strong environmental control, as comparable trends in air temperature and precipitation produce similar soil temperature and moisture dynamics across stands [30], leading to analogous seasonal R_S patterns.

During the temperature control phase, exponential relationships between R_S and soil temperature explained 85–93% of variability, confirming soil temperature as the primary driver of R_S temporal dynamics in temperate forests [12, 31–32]. During the water content control phase, quadratic relationships explained 56–79% of variability. When soil water content is non-limiting, temperature dominates; when water is limiting, it becomes the primary control factor under temperature-driven conditions [9, 34–35]. Mechanistically, low water content restricts diffusion of soluble substrates, while excessive water reduces gas diffusion and creates anoxic conditions, both inhibiting R_S [36–37].

4.2 Stand Age Effects and Ecological Implications

Annual R_S fluxes ranged from 639.7 to 762.3 g C m^-2 yr^-1, showing a decreasing-then-increasing trend with stand age since clear-cutting. This pattern reflects initial reduction in fine root biomass following clear-cutting [42], followed by recovery as vegetation reestablishes. During early succession, reduced solar radiation reaching the soil surface due to canopy closure lowers soil temperature, while vegetation roots have not yet recovered, resulting in lower R_S. As forests mature, vegetation root systems recover and increasing litter production provides abundant substrates for microbial respiration, enhancing R_S [27, 43].

Non-growing season R_S accounted for 9.4–11.0% of annual fluxes (49.1–80.6 g C m^-2), consistent with reports for temperate forests (8–25%) [10]. Although the proportion is small, the coefficient of variation among stands (21.1%) was 3.35 times greater than during the growing season (6.3%), amplifying differences in annual R_S. This demonstrates that non-growing season R_S cannot be ignored when evaluating forest restoration effects. Winter R_S originates primarily from microbial respiration [44], with a critical temperature threshold around -3.5°C, below which microbial activity is inhibited by lack of free water [45–46].

Differences in non-growing season R_S among stands were driven mainly by soil temperature differences, likely due to varying litter layer thickness affecting long-wave radiation and insulation [47]. The 1-year stand (clear-cut site) may have higher soil temperature due to logging residue insulation. The trend of non-growing season R_S decreasing then increasing with forest recovery differs from some boreal forest studies showing opposite patterns [12, 48–49] or gradual declines [50], possibly because our chronosequence began at clear-cut stage and ended at 56 years, not representing the full secondary succession series. During succession, soil physicochemical properties [51–52], microbial community diversity [53], and extracellular enzyme activities [54] all change, affecting R_S. Further research is needed on mechanisms of soil microbial respiration changes

during forest restoration.

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Note: Figure translations are in progress. See original paper for figures.