PATTERNS AND DRIVERS OF SOIL RESPIRATION AND VEGETATION AT DIFFERENT ALTITUDES IN SOUTHERN CHINA

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Abstract. The objective of the present study was to evaluate soil organic carbon stock and mineralization characteristics in forest ecosystems in subtropical China. We explored the factors underlying soil respiration and vegetation in 12 soils at different altitudes in Jiangxi province, Wuyi mountain national nature reserve. Soil organic carbon was applied to analysis field survey and indoor cultivation techniques. Our results showed uneven distribution of four perpendicular bands: meadow grassland, subalpine elfin, mixed coniferous and broad-leaved forests. Differences in total carbon (TC) and total nitrogen (TN) content in the soil were not significant. Soil pH was acidic. The crown density representing relative soil water content suggested fewer differences in low dissolved organic carbon (DOC) with altitude. The soil microbial biomass carbon (MBC) was the lowest in the meadow grassland soil, and in that of the mixed needle leaved forest. The NO_3^--N levels decreased with altitude and the changes in NH_4^+-N were not obvious. The respiratory rate of the meadow grassland soil was the lowest, and the respiratory rate of the subalpine elfin forest was high. Cumulative emissions without soil CO_2 increased with altitude showing regular changes related to vegetation. In mixed needle the soil respiration was significantly stronger than in the meadow grassland and broad-leaved forest soil. Carbon emissions produced by soil respiration and total carbon (TC) and C: N were positively correlated ($P < 0.05$), with no obvious correlation with MBC. The soluble and microbial carbon levels in the soils at different altitudes were positively but not significantly related. Soil pH and TC were negatively correlated with TN and NO_3^--N. The effect of soil total carbon, total nitrogen and crown density partially controlled soil respiration.
Keywords: *Wuyi mountain, altitude, soil organic carbon, soil respiration, vegetation*

Introduction

Climate change is a major environmental challenge. The carbon cycle plays a key role. Soil organic carbon dynamics underlying soil carbon cycle is a hot issue of climate change (Williams et al., 2004). Soil respiration is an important component of terrestrial ecosystem comprising soil and atmospheric CO_2 exchange (Pierce et al., 2004). Global climate change due to increased temperature accelerates mineralization of soil organic carbon (Schlesinger et al., 2000; Zerva et al., 2005). The CO_2 released from soil respiration into the atmosphere further aggravates global warming. Therefore, soil respiration is an important factor underlying global climate change (Schlesinger et al., 1997).

Soil respiration is a complex process, which is affected by a variety of factors including hot soil water, texture, vegetation types, and land use practice (Wang et al., 2005; Maljanen et al., 2006; Yashiro et al., 2008; Yang et al., 2010). Changes in altitude affect vegetation composition and alter the soil environment, resulting in a significant impact on the size and dynamics of soil respiration and sensitivity to

temperature (Maljanen et al., 2006; Yashiro et al., 2008). Wuyi mountain national nature reserve is the central Asian tropical forest ecosystem, representing a vertical spectrum of vegetation distribution. It includes subtropical evergreen broad-leaved forest, mixed needle leaf and subalpine elfin forest and alpine meadow. The complete vegetation zone provides convenient conditions to study spatial and temporal heterogeneity of soil respiration. Wuyi mountain is a tourist destination. Human interference has tourists altered the original land use pattern and forest vegetation composition, and accordingly changed the soil carbon composition. Altered dynamics of soil respiration with altitudinal gradient is a key factor in predicting global climate change (Williams et al., 2004; Norby et al., 2001). Current studies mainly focus on differentiation of soil carbon, nitrogen and organic matter, and biodiversity due to the complexity of soil composition of organic carbon and factors influencing diversity (Lu et al., 2012a). Studies reported soil respiration in subalpine thickets of monsoon forest, coniferous and broad-leaved mixed forest soil with altitude (Xu et al., 2015). Studies have also investigated the trends in temperature and moisture levels of broad-leaved Korean pine, spruce and fir forest and *Betula ermanii* in Changbai mountain with changes in altitude (Wang et al., 2003). However, these studies have not systematically analyzed the relationship between altitudinal gradient and soil respiration. Data pertaining to relative changes in dynamic and quantitative description of soil carbon mineralization with altitude are lacking. These studies cannot reflect the dynamic balance in carbon levels between tropical and subtropical biota. In this study, the soil samples had been analysed in Wuyi mountain nature reserve at different altitudes. We measured the soil nutrient and respiration levels in laboratory, to determine the mechanisms underlying altered soil properties and respiration with altitude.

Materials and methods

Study site

This study was conducted in Wuyi mountain county, Jiangxi province national nature reserve, located in the transition zone of the subtropical marine and inland climate, southern China. Local meteorological data (2001-2010) show a mean annual precipitation of 2583 mm and a mean annual temperature of 15 °C, annual average relative air humidity of about 85%. The natural environment is unique, with a complex geological structure, and various types of landforms. Altitude in the area increases from 700 m in the northwest to 2100 m in the southeast. Huanggang mountain at 2160.8 m is the highest peak. Jiangxi province represents the main distribution area of virgin forest, with a wide variety of wild fauna and flora, and lush vegetation. The distribution of vegetation presents a perpendicular band spectrum, with vertical differentiation: evergreen broadleaf forest (EBF), 117°44.183'-117°44.183'E, 27°51.082'-27°51.082'N (altitude of 800-1100 m); coniferous broadleaf forest (CBF), 117°44.806'-117°44.806'E and 27°51.037'-27°51.133'N (altitude of 1100-1500 m); dwarf forest (DF), 117°45.447'-117°45.984'E, 27°50.329'-27°51.038'N (altitude of 1500-1900 m); and alpine meadow (AM), 117°46.214'-117°46.987'E and 27°50.362'-27°51.636'N (altitude above 1900 m), respectively. We tested selected samples representing the four vegetation types, respectively, at 1500 to 1900 m and random samples above 1900 m.

Experimental design and sampling

Soil samples were obtained in October 2013. In this study, we selected four different vegetation types across an altitude gradient to examine Rs variation, in soils of EBF, CBF, DF and AM, respectively. Samples of each vegetation type were tested in triplicate. There were totally twelve 20×20 m plots. Five soil sample replicates using a 7.5 cm diameter soil auger were mixed together at a depth of 0-20 cm, sieved using a 2 mm mesh, and stored at 4 °C in a refrigerator and until further laboratory analysis.

Soil respiration and properties

The soil samples were divided into two subsamples. One subsample was used to measure soil respiration using the alkali absorption method. In brief, we initially weighted 30 g of fresh soil and adjusted to 60% of the field water holding capacity (Chen et al., 2004). The adjusted soils were aerobically incubated at 22 °C in a 1L sealed glass jar. Soil respiration was trapped in 0.1 M NaOH and measured with 0.1 M HCl titration after 1, 3, 7, 14, 21, 28, 35, 42, 49 and 56 days. The total soil respiration was estimated by calculating the cumulative production of soil respiration from soils during the incubated 56 days.

Another subsample was used to measure soil properties: total carbon (TC), total nitrogen (TN), organic matter content (OM), dissolved organic matter (DOC), microbial biomass carbon (MBC), soil water content (SM) and pH. Briefly, TC and TN were measured using an elemental analyzer (Isoprime- EuroEA3000, Milan Italy). OM, DOC, MBC, SM and pH were measured by potassium dichromate oxidation-outer heating, high temperature catalytic oxidation, chloroform fumigation extraction, oven drying and potentiometric, respectively (Brookes et al., 1985; Vance et al., 1987).

Data analysis

Statistical analysis was carried out using SPSS 13.0 for Windows (SPSS Inc., Chicago, IL). Two-way ANOVA followed by Fisher's least significant difference (LSD) test was used to examine the effect of land use practice, soil depth and their interaction on soil properties. As Rs were measured repeatedly across time, we also used repeated measures ANOVA (RMANOVA) to examine variation in Rs with time. Simple linear analyses were used to examine the relationship of soil respiration with soil properties.

Results

Plant diversity

Climate conditions affected plant species as a dominant factor of vegetation distribution. Changes in terrain redistribution of precipitation and heat affected plant community and vertical zoning. Elevation was the primary factor controlling the pattern of mountain species distribution. Our results suggested that the distributions of vegetation types varied with altitude (*Table 1*).

Effect of different altitudes on soil physicochemical properties

No significant differences were found among soil TC and TN concentrations along altitudinal gradient (*Table 2*). The soil in the alpine meadow was acidic, but had a

significantly higher pH than the dwarf forest ($P < 0.01$). Bulk density in coniferous broadleaf forest was significantly lower than that in alpine meadow ($P < 0.01$). Forests in lower altitudes, including evergreen and coniferous broadleaf forests, had significantly higher crown densities than the other two vegetations in higher altitudes ($P < 0.01$). Soil moisture in evergreen and coniferous broadleaf forest was significantly lower than that in the other two vegetations (*Table 2*). In addition, there was an increasing trend in soil moisture along altitudinal gradient. Soil DOC concentrations were 1.693-2.196 mg g^{-1} and increased with increasing altitude. Soil MBC content was the highest in meadow grassland and the lowest in coniferous broadleaf forest. The NO_3^--N content decreased with an increase in altitude.

Table 1. *The distributions of vegetation types varied with altitude*

Altitude	Species	Vegetation types
1900 m	*Calamagrostis brachytricha, Stranvaesia davidiana, Berberis julianae, Rhododendron fortune, Pyrus calleryana, Pinus tanwanensis, Rhododendron latoucheae, Rhododendri Daurici, Symplocos paniculata, Clethra cavaleriei, Spiraea chinensis*	Alpine meadow
1500-1900 m	*Symplocos paniculata Cyclobalanopsis multinervis, Eurya saxicola, Eurya muricata, Stewartia sinensis, Illicium simonsii, Tsuga chinensis, Cryptomeria fortune, Erythroxylum sinensis, Toxicodendron succedaneum, Carpinus viminea, Lauraceae. Obtusiloba, Greyblue Spicebush, Actinidia chinesis, Fargesia spathacea, Rubus lambertianus, Symplocos wikstroemiifolia, Eurya loquaiana, Camellia fraternal, Pieris Formosa, Hydrangea chinensis, Daphniphyllum macropodum, Schima superba, Clethra cavaleriei, Rhododendri Daurici, Rhododendron fortune, Rhododendron latoucheae, Pinus tanwanensis*	Elfin and coniferous broadleaf forests
1100-1500 m	*Rhododendron ovatum, Betula luminifera, Liquidambar formosana, Glochidion wilsonii, Lindera erythrocarpa, Indocalamus latifolius, Schima superba, Camellia fraternal, Illicium simonsii, Rhododendron latoucheae, Cyclobalanopsis multinervis, Pinus tanwanensis, Symplocos Wikstroemiifolia, Eurya loquaiana, Eurya muricata, Tsuga chinensis, Symplocos chinensis*	Coniferous and coniferous broadleaf forests
800-1100 m	*Castanopsis carlesii, Cunninghamia lanceolata, Caulis Sargentodoxae, Pueraria lobata, Oligostachyum oedogonatum, Phyllostachys heterocycla, Glochidion wilsonii, Actinidia chinesis, Eurya loquaiana, Liquidambar formosana, Schima superba, Indocalamus latifolius, Lindera erythrocarpa, Cryptomeria fortunei*	Evergreen broad-leaved forests

Table 2. *Basic properties of soil along an altitudinal gradient*

Vegetation types	TC%	TN%	pH	BD g.cm^{-3}	Canopy density %	Moisture %
Alpine meadow	6.25±0.87a	0.46±0.05a	5.13±0.13a	0.99±0.03a	15±8c	65.74±1.97a
Dwarf forest	8.56±0.90a	0.57±0.04a	4.70±0.17b	0.89±0.04ab	50±11b	57.79±2.16b
Coniferous broadleaf forest	9.20±1.94a	0.54±0.10a	4.85±0.12ab	0.87±0.05b	85±3a	44.47±1.92c
Evergreen broadleaf forest	7.72±1.36a	0.58±0.12a	4.88±0.11ab	0.93±0.02ab	90±0a	37.45±3.09c

TC: total soil C concentrations; TN: total soil N concentrations; BD: bulk density. Differences are significant when lowercase letters are different

Effect of different altitudes on soil efflux

Soil respiratory rate

The patterns of soil respiratory rate were similar among different vegetations, with a decrease with incubation time (*Fig. 1a*). The respiratory rate sharply decreased after 7 days of incubation time and kept stable from the 14th days (*Fig. 1a*). It was the lowest in alpine meadow and highest in dwarf forest. Soil respiration in broad-leaved and coniferous broadleaf forests decreased faster after cultivation for 14 days. After 14 days, it decreased as follows: subalpine elfin forest > coniferous broadleaf forest > needle forest > meadow grassland. The soil respiration rate in subalpine elfin forest was significantly higher than that in meadow grassland ($P < 0.01$).
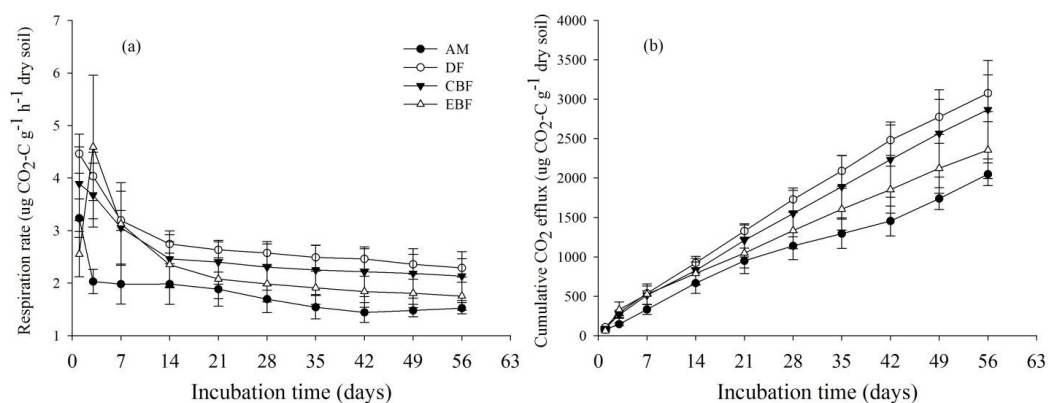

Figure 1. Changes in (a) the rate of respiration, and (b) cumulative CO_2 efflux during 56-day incubation in soils of different treatments. The abbreviations of vegetation types are the same as Figure 1

Soil cumulative CO_2 efflux

The soil respiratory emissions of CO_2 rapidly increased within 7 days of culture. Soil organic matter rapidly decomposed in soils regulated to 60% water holding capacity, due to microbial activity. The soil carbon emissions slowly increased after incubation for 7 days at different altitudes. No significant differences were seen between soil CO_2 accumulation emissions and altitude. However, soil CO_2 emissions were related to vegetation. The soil respiration in coniferous broadleaf forest was significantly stronger than in meadow grassland and broad-leaved forest soil ($P < 0.01$).

Correlation between soil carbon emissions and vegetation types

The vegetation types and soil nutrients were analyzed by principal component analysis (PCA) of soil at different altitudes. Our results showed that the differences in soil physiochemical properties were complex at different altitudes, and the first and second principal components explained 40.95% and 20.27% of the variation, respectively (*Fig. 2*). The soil carbon emissions and TC, and C: N were positively correlated ($P < 0.05$), but not between soil carbon emissions and MBC. No significant difference between DOC and MBC was observed at different altitudes. The soil pH and TC, TN and NO_3^-N were negatively correlated ($P < 0.05$). In this study, we found that TC, TN, and crown density also played important roles in regulating *Rs* under different altitude gradients.
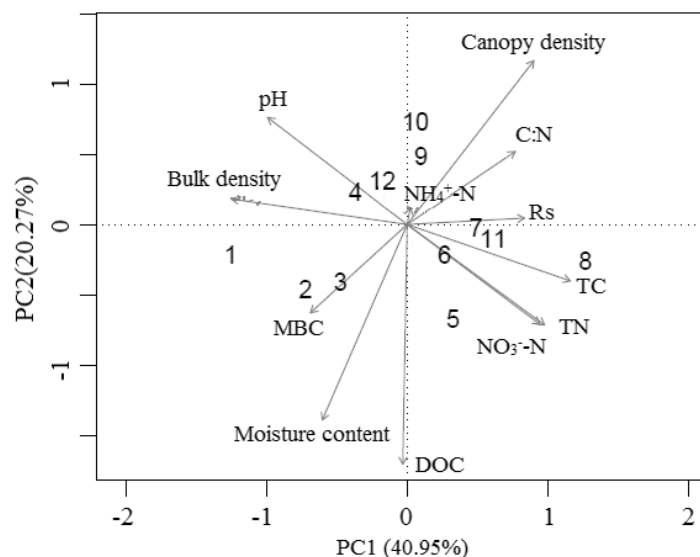
Figure 2. Principal component analysis (PCA) of physicochemical properties of soils from forests at different altitudes

Discussion and conclusion

Vegetation type is heterogeneous in the Nature Reserve, dominated by the evergreen broad-leaf and coniferous broadleaf forests. The variation coefficients of different vegetation types were larger along the altitudinal gradient. The vegetation types along the altitudinal gradient are: artificial vegetation, bamboo forest, evergreen broad-leaved forest, coniferous broadleaf forest, coniferous forest, broadleaf needle elfin wood and mid-mountain meadow. The distribution of various vegetation types overlapped substantially at each altitudinal zone.

Zonal climate condition is the dominant factor of vegetation distributions by affecting plant species compositions. The temperature decreased with increasing altitude. The precipitation, solar radiation and atmospheric composition also changed in altitude. Changes in terrain redistribution of precipitation and heat affected plant community and vertical zoning. Altitude was the primary factor governing the pattern of mountain species distribution. However, the terrestrial factors affecting vegetation type and the contribution of soil nutrients, water availability and altitude alone and their interactive effect on *Rs* variation was still unknown. The zonal climate was the dominant factor for the distribution of plant species within the Wuyi Mountain Nature Reserve (Rouget et al., 2015). A vertical variation in hydrothermal factor along with decreased temperature with increases altitude was observed (Sarrazin et al., 2015). Terrain changes redistribution of precipitation and energy, affecting vegetation and vertical zonal distribution. Altitude is the primary factor controlling the pattern of mountain species distribution (Lou et al., 2000; Dolezal et al., 2002). Our results also demonstrated four perpendicular bands, and lack of typical and alpestrine mountain vegetation perpendicular band. The order of perpendicular bands with increase in altitude included evergreen broad-leaved forest, coniferous broadleaf forest, elfin wood and mid-mountain moss, and mid-mountain meadow vegetation types. Zonal warm coniferous forests were present at 1650-1700 m. The main vegetation types included evergreen broad-leaved and coniferous broadleaf forests, with an uneven distribution,

and an obvious vertical band with change of altitude in sites. The vegetation was limited by growing conditions above 1900 m. The vegetation was replaced with elfin forest or meadows for hilltop effect, elfin forest and coniferous broadleaf forest at 1500-1900 m and coniferous forest and coniferous broadleaf forest at 1100-1500 m. The hydrothermal condition was mainly observed at 800-1100 m, and the vegetation included evergreen broad-leaved forest.

Soil respiration is one of the important indicators of soil quality and reflects the strength of soil biological activity and metabolism. Soil respiration represents an index of soil biological activity, fertility and permeability (Li et al., 2010). Soil microbial competition for nutrients, however, is likely to drive the microbial community structure and corresponding alteration in nutrient mineralization (Yang et al., 2017). Our study showed that the level of CO_2 emissions due to soil respiration increased rapidly after cultivation for 7 days. Soil microbes were the most active and decomposed soil organic matter when soil moisture was adjusted to 60% water-holding capacity (Lu et al., 2012b). Soil carbon emissions slowly increased after cultivation for 7 days. The difference in soil CO_2 emissions with altitude was not obvious (Bai et al., 2008). However, soil CO_2 emissions were related to vegetation. Soil respiration of coniferous broadleaf forest was significantly stronger than that of meadow grassland and broad-leaved forest ($P < 0.01$), probably due to the microbial activity. There was no obvious influence of soil moisture on soil respiratory. Soil respiratory rate suggested the ability to release CO_2. The soil respiratory rate decreased with altitude (Lu et al., 2011; Gao et al., 2011). Soil respiratory rate decreased sharply within 7 days, and slowed down or remained steady, which was consistent with previous findings (Zhou et al., 2012). Soil respiration rate in meadow grassland was the lowest, while that of the subalpine elfin forest was the highest. Soil respiratory rate of broad-leaved and coniferous broadleaf forests decreased rapidly after cultivation for 14 days. The soil respiratory rate decreased as follows: subalpine elfin forest > coniferous broadleaf forest > needle forest > meadow grassland. The soil respiratory rate of subalpine elfin forest was significantly higher than that of meadow grassland ($P < 0.01$). No significant effect of soil moisture on the respiratory rate was observed, which was inconsistent with previous findings (Liu et al., 2009). These results suggest the combined effect of plant types, microbes and soil moisture. The change of soil moisture was minimal in plant growth, with less effect of soil moisture on the respiratory rate (Fang et al., 2001).

Soluble organic matter had an important effect on soil physicochemical and biological characteristics (Lu et al., 2012b). Soil organic matter is mostly composed of DOC from plant litter (Shen et al., 2015). The ground vegetation types were closely related to decomposition of humus, microbial biomass and root secretion. Our results suggest that soil DOC ranged from 1.693 to 2.196 mg g^{-1}, and gradually increased with increase in altitude, with a small amplitude. Our results were consistent with previous findings in that soil carbon of biological communities was high at low temperature and humidity. Soil organic matter accumulated at high altitude, low temperature and humidity. The organic type, quantity and quality of the soil influenced the properties of MBC. Meadows improved soil granular structure and activity to increase MBC (Wang et al., 2007). Our studies suggest that MBC increases with altitude, resulting in a significant positive correlation between soil organic carbon and MBC. The soil MBC was the highest in meadow grassland and the lowest in coniferous broadleaf forest. NO_3^--N decreased with increased altitude, and the change of NH_4^+-N was not obvious with altitude. DOC and MBC did not show similar correlation, which was consistent

with Liu's finding (Liu et al., 2012) and inconsistent with Han Lin's results (Han et al., 2010). Plants absorb nutrients from the soil organic matter by microbial decomposition. MBC reflects soil nutrient condition and activity of microorganisms. MBC was an effective index of evaluation of soil fertility and soil quality.

The differences and similarities in vegetation type and soil nutrient comprehensive status were analyzed by PCA of soil physicochemical properties at different altitudes (Wu et al., 2014). In our studies, the difference of soil physicochemical properties varied with altitude. The first and second principal components explain 40.95% and 20.27% of the variation, respectively.

Soil CO_2 emissions were positively correlated with TC, C:N ($P < 0.05$) by PCA (Liu et al., 2009), but not with MBC. There was no significant difference between DOC and MBC. The pH was negatively correlated with TC, TN and NO_3^--N. TC, TN. Crown density had a significant impact on soil respiration, and was used as a regulatory factor of soil respiration. Soil respiration showed significant negative correlation with organic matter and the correlation coefficient was 0.871 ($P < 0.05$) (Zhang et al., 2012). Soil moisture was low, and its effect on soil microbial activity reduced the soil organic carbon mineralization at low altitudes.

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