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Soil respiration in a subtropical montane cloud forest in Taiwan

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ABSTRACT

Little is known about carbon budgets for tropical and subtropical montane cloud forest (TMCF) ecosystems. Information about the soil CO_2 efflux from these ecosystems is particularly scarce, although they have been shown to have special hydrological regimes which might be important in controlling soil respiration. In this study, we used an automatic chamber system to measure soil respiration rates at the Chi-Lan Mountain forest site. The half-hourly dataset was used for analyzing the controlling factors and mechanisms of soil respiration. A manipulation experiment was conducted in the field by applying 3-fold and 1-fold aboveground litter to the soil surface and measuring the respective soil respiration rates using the static alkali chamber method. The results showed that soil respiration rates have a positive exponential correlation with soil temperature and a negative exponential correlation with soil water content. An empirical model relating soil respiration (R_s) to soil temperature (T) and soil water content (θ) is $R_s = -0.095 + e^{0.88+0.10T-6.99\theta}$ with $R^2 = 0.83$. The annual soil respiration rate calculated using this model was 176 g C m^{-2} y^{-1}. This extremely low value might be caused by the permanently high soil moisture and the relative lower mean annual temperature compared to other sites that receive similar amounts of precipitation. The 3-fold and 1-fold litter treatments resulted in significantly higher soil CO_2 efflux compared to the chambers with no litter. The magnitude of difference diminished to negligible levels 6 months after treatment. About 10% of the annual soil respiration was contributed by the mineralization of fresh aboveground litter. The carbon mass loss of the decomposing litter during the first 6 months was mainly due to leaching of dissolved organic carbon (75%) and secondarily due to mineralization of CO_2. From the results of this study, we hypothesized that the TMCFs may be vulnerable to global warming since the drying of the soil may change the soil from being a carbon sink to being a carbon source, thereby releasing soil organic carbon that had been stored for a long period of time.

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1. Introduction

Carbon dioxide efflux from soil to the atmosphere, generally defined as soil respiration, is the key part of the carbon cycle in terrestrial ecosystems (Raich and Schlesinger, 1992). A model estimation of the global soil respiration rate of 76.5 Pg C y^{-1} (Raich and Potter, 1995) indicates its central role in the issue of global warming since its magnitude is about 10 times that of

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fossil fuel burning and cement manufacturing combined (ca. 7.8 Pg C y^{-1} in 2005) (Forster et al., 2007). Field measurement of soil respiration has been intensively carried out in recent decades with much effort being devoted to temperate ecosystems (synthesis for temperate forests, e.g. in Hibbard et al., 2005; global synthesis, e.g. in Raich and Schlesinger, 1992). Although for some vegetation types the data is limited, it has been reported that soil respiration rates vary significantly between the main vegetation types with the highest values measured in tropical moist forests and the lowest in tundra ecosystems (Raich and Schlesinger, 1992). At such a large spatial scale, mean annual soil respiration rates are controlled mainly by annual mean air temperature and annual precipitation and less by soil C, soil N, or soil C/N ratio (Raich and Potter, 1995).

The tropical and subtropical forests that Raich and Schlesinger (1992) used in their global synthesis are those mainly located in lowland areas, and ecosystems located in tropical mountains were not taken into account. Tropical montane cloud forests (TMCFs) are ecosystems that are frequently immersed in fog, which may bring extra water and nutrients through the so called ''occult deposition'' (Chang et al., 2006; Dawson, 1998; Eugster et al., 2006), but may also greatly reduce solar radiation (Bruijnzeel and Proctor, 1994). The resulting low vapor pressure deficit limits the evapotranspiration rate that would otherwise be as high as in the lowland forests located at the same latitude. Soil water content would therefore be permanently high, especially for those cloud forests receiving high precipitation. Decomposition of aboveground litter in TMCFs is limited in this climate, and thus a higher content of organic matter can be found compared to tropical lowland ecosystems (Bruijnzeel and Veneklaas, 1998; Kitayama and Aiba, 2002). Schuur and Matson (2001) showed decreasing net primary productivity along a gradient of increasing annual precipitation rate in the Hawaiian montane forest. The higher precipitation rate was responsible for the increasing soil water content and thus the retarded gas exchange and decomposition rate in the soil. In a model estimation of primary production in the Luquillo Mountains of Puerto Rico, Wang et al. (2003) demonstrated a decreasing trend of GPP and respiration with increasing elevation. Although some evidence shows that TMCFs have low primary productivity (Bruijnzeel and Veneklaas, 1998; Waide et al., 1998), little is known about carbon pools and budgets in these ecosystems, and even less information is available about soil respiration in TMCFs (Campos, 2006; Cavelier and Peñuela, 1990; Priess and Fölster, 2001).

Carbon budgets are not as well understood in the forest ecosystems of Taiwan, especially in forests located at higher elevations. It is often a challenge to perform field studies in the mountainous forests since the slopes are usually high and the land surfaces are less homogeneous, which makes the quantification of nutrient and energy fluxes difficult. The Chi-Lan Mountain (CLM) site is one of the most accessible sites since its slope is 'only' 14° and the even-aged forest stand has homogeneous canopy structure. We started forest ecosystem research in 2002 and focused mainly on the nutrient cycling and fog deposition problems (Chang et al., 2006). After a preliminary test had shown that the site might be feasible for micrometeorological measurements (Klemm et al., 2006), a carbon budget program including flux tower measurements and chamber methods was initiated in 2005. Here we report the results of the soil respiration measurements using the chamber method. The objectives of this study were to measure soil respiration and to analyze the controlling factors at this montane cloud forest site. The study was also aimed at evaluating the contribution of aboveground litterfall on soil respiration.

2. Materials and methods

2.1. Site description

Field work was conducted at the Chi-Lan Mountain (CLM) site (24°35′N, 121°25′E). Chi-Lan Mountain is one of the most important habitats of *Chamaecyparis obtusa* var. *formosana* and *Chamaecyparis formosensis* in northern Taiwan. Both of these tree species were intensively harvested around the island from the 1940s to the 1990s due to their high wood quality. Although little is known about the ecophysiological characteristics of these species, it is well documented that they usually occur within the cloud belt zone (Su, 1984). At Chi-Lan Mountain, large areas of old-growth *Chamaecyparis* forests up to ca. 2000 years old still exist along with *Chamaecyparis* plantations of different ages. The study of the *Chamaecyparis* forest ecosystem started in 1984 in the Yuan-Yang Lake Nature Reserve (YYL), which is a 374 ha watershed composed of old-growth forests and lake ecosystems. Kao et al. (2003) made a carbon-related measurement at the YYL site and found a significant vertical gradient of CO_2 concentration within the canopy. Imberger and Chiu (2002) investigated heterotrophic respiration of soils taken from the YYL site and from a regenerated *Chamaecyparis* forest nearby. The laboratory incubations showed an equal contribution of fungal and bacterial respirations to overall soil respiration.

In 2002, an ecosystem research program was initiated at the 300 ha CLM site, which is 2.5 km away from the YYL site and is mainly composed of *C. obtusa* var. *formosana* that was naturally regenerated after clear-cutting in the 1960s. The tree density of *C. obtusa* var. *formosana* was 1820 ha^{-1} and this species occupied about 83% of the total basal area. The other 32 tree species were angiosperms dominated by *Illicium anisatum* and *Dendropanax dentiger*. Biomass and nutrient stocks of *C. obtusa* var. *formosana* were investigated in 2003 and 2004 by applying destructive methods to 19 *C. obtusa* var. *formosana* trees for aboveground biomass, by digging 3 trees for coarse root biomass and by digging 10 soil cores (30 cm × 30 cm area, 40 cm in depth) for fine root biomass. Carbon stocks in *C. obtusa* var. *formosana* were estimated to be 43.8 and 37.2 t C ha^{-1} for above- and below-ground biomasses, respectively (Chang, unpublished data). The soil of the site was classified as Lithic Leptosol (WRB, 1998) of loamy texture. The poorly developed soil profile contained about 90% coarse material of metamorphic slate and quartzite. Due to the high precipitation of up to 5000 mm annually, the soil is extremely acidic and contains few base cations below the O horizon (Chang et al., 2007). Soil carbon stocks sum to 27.3 t C ha^{-1}, of which 32% is stored in the O horizon and 48% in the A horizon (Chang, unpublished data). The topography of this mountai-

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