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Effects of simulated acid rain on soil CO_2 emission in a secondary forest in subtropical China

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ABSTRACT

Acid rain, which is caused mainly by dissolution of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) in the atmosphere, has been reported to have negative effects on ecosystems. However, few investigations have focused on the impacts of acid rain on soil CO_2 emission in forest. In this study, the effects of simulated acid rain (SAR) on soil respiration (R_s) and its heterotrophic component (R_h) in a secondary forest in subtropical China were investigated. Soil CO_2 efflux was measured by using a Li-8100 infrared gas analyzer with attached chamber. Measurements were generally made once a week from 21 March 2010 to 16 May 2011 in order to investigate the seasonal variations of R_s and R_h under different SAR treatments. Soil temperature and moisture at the depth of 5 cm were measured at the time of soil CO_2 efflux measurements. Results indicated that different SAR treatments exhibited similar seasonal patterns of R_s and R_h. Seasonal mean R_s rates for the CK (deionized water), A1 (pH 4.0), A2 (pH 3.0) and A3 (pH 2.0) treatments were 2.63, 1.92, 1.89 and 2.16 μmol m^{-2} s^{-1}, respectively, while mean R_h rates for the four treatments were 1.80, 1.64, 1.76 and 1.79 μmol m^{-2} s^{-1}, respectively. Two-factor analysis (respiration components and SAR) of variance implied that SAR had significant ($p = 0.031$) effects on soil CO_2 emissions, but this was contingent on the specific respiration components. SAR showed significant inhibition effects on R_s (autotrophic + heterotrophic components) rather than R_h. The ratio of R_h to R_s was significantly higher in the CK than in the acid rain treatments (A1, A2 and A3). Soil temperature and moisture were two controlling factors regulating the seasonal patterns of R_s and R_h for each of the SAR treatment. Soil temperature and moisture accounted for more than 80% of the seasonal variations observed in R_s and R_h. This work highlights that the effects of SAR are important to consider in assessing the annual soil CO_2 emission, particularly under the scenario of increasing acid rain pollution.

1. Introduction

Acid rain is one of the foremost examples of regional air pollution and has received worldwide attention because acidification damages are often the result of atmospheric transport of sulfur and nitrogen emissions across state and/or national boundaries (Menz and Seip, 2004). Regions that have been most affected by acidic deposition include Europe, eastern North America, and Southeast Asia, especially central and southern China (Kuylenstierna et al., 2001; Menz and Seip, 2004). Acid rain is caused mainly by dissolution of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) in the atmosphere. These pollutants mainly originate from human activity such as the combustion of fossil fuels within thermal power plants and automobiles (Francisco Sant'Anna-Santos et al., 2006; Kita et al., 2004; Zhang et al., 2007). Because of the difficulty and cost in disposing these gases in many countries, they are often emitted into the atmosphere with no effective treatments. The nationwide monitoring data provided by China Meteorological Administration in 2007 demonstrate that most areas in southern China were registered acid rain with pH values below 5.0 (Hou and Zhao, 2009). Zhang and Jiang (2012) reviewed that most ecosystems in southern China had received large quantities of acidic inputs.

Second to gross photosynthesis, CO_2 emissions from soils (i.e., soil respiration) exceed all other terrestrial–atmospheric carbon exchanges (Raich and Schlesinger, 1992). Over two thirds of terrestrial carbon is stored belowground and a significant amount of the atmospheric CO_2 assimilated by plants is respired by roots and microbes in terrestrial soils (Hibbard et al., 2005). Soil respiration is therefore a key process that underlies our understanding of the terrestrial carbon cycle (Davidson et al., 2006). Increases in soil CO_2 emissions have the potential to exacerbate increasing atmospheric CO_2 levels and to provide a positive feedback to global warming (Raich and Tufekcioglu, 2000). Generally, soil respiration (R_s) is separated into two components: root (autotrophic) respiration

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(R_a) and microorganism (heterotrophic) respiration (R_h) (Kuzyakov, 2006; Kuzyakov and Larionova, 2005).

Impacts of acid rain on forest ecosystem are an increasing environmental concern. Reich et al. (1988) and Wright et al. (1990) found that simulated acid rain (SAR) application changed foliar N content. Some investigations suggest that SAR can accelerate leaching of nutrients from plant foliage and soil (Reddy et al., 1991; Turner and Tingey, 1990; Zhang et al., 2007). Acid rain is thought to be responsible for elevated levels of toxic aluminum in soil, leaching of plant nutrients (particularly magnesium) from soils, or reduced availability of phosphorus (Menz and Seip, 2004). Schaedle et al. (1989) found that acid rain increased Al^{3+} in soil solution, which is toxic to fine roots. Fan and Wang (2000) reported that high H^+ load in SAR inhibited seedling growth. Since acid rain application changes roots and soil conditions which are thought to influence CO_2 emissions from roots and organic matter decomposition (Boone et al., 1998; Kuzyakov, 2006; Kuzyakov and Larionova, 2005), acid rain has the potential to affect R_s. Fritze (1992), for example, has found that acidic loads applied during a short time period, sometimes even in a single load, demonstrated the toxic effects of acid on R_s.

Many efforts have been devoted to study the impacts of acid rain on plant and soil traits in forest in southern China (e.g. Fan and Wang, 2000; Wang et al., 2009; Zhang et al., 2007). Unfortunately, few investigations have focused on the impacts of acid rain on soil CO_2 emission in forest; particularly lacking, to our knowledge, is the long-term *in situ* measurements. Also, the information about the dependences of soil respiration on temperature and moisture under different SAR pH levels is also rare.

Because the H^+ in the SAR is toxic to soil microorganisms and roots, it was assumed that soil respiration components might be affected by acid rain. In order to examine the potential effects of SAR on soil CO_2 emission, a field experiment with different SAR levels has been conducted. The specific questions addressed here were the following: (1) whether and how does SAR affect R_s and R_h in the subtropical forest? (2) How do soil temperature and moisture affect the variability of soil CO_2 emission under different SAR treatments?

2. Materials and methods

2.1. Site description

In 2010, experiments were performed at Longwang Mountain (32.20°N, 118.72°E) near Nanjing City, Jiangsu province, China. This study site is located on the north shore of lower reaches of Yangze River. The Longwang Mountain has a monsoon climate and falls into the northern edge of the humid subtropical climate zone. Annual average temperature of the experimental site is 15.6 °C and annual rainfall averages 1 100 mm. The broad leaf and needle leaf mixed hardwood forest is dominated by hackberry (*Celtis sinensis* L.), sweet gum (*Liquidambar formosana* L.), hardleaf oatchestnut (*Castanopsis sclerophylla* L.) and masson pine (*Pinus massoniana* L.), with some stands of Chinese pistache (*Pistacia chinensis* L.) and crape myrtle (*Lagerstroemia indica* L.). The stand has a density of 2000 trees ha^{-1}, which reaches canopy closure of 0.8 and presents rare herbaceous vegetations. The soil collected from the experimental site is classified as yellow-brown soil in Chinese taxonomy or Typic Paleudults in soil taxonomy. The soil in this experimental site is shallow; its depth varies from 35 to 50 cm and is underlain by quartzite bedrock. Soil properties of C and N content and pH are shown in Table 1.

Table 1
Soil C and N content and pH in the soil profile.

Depth (cm)	Soil C content (g kg^{-1})	Soil N content (g kg^{-1})	pH
0–4	62.7 ± 0.8	3.0 ± 0.2	6.8 ± 0.0
4–10	62.1 ± 1.1	2.7 ± 0.2	6.7 ± 0.1
10–20	60.2 ± 2.0	2.6 ± 0.2	6.6 ± 0.1
20–30	58.5 ± 2.5	2.4 ± 0.2	6.5 ± 0.1
30–40	53.8 ± 3.1	2.2 ± 0.2	6.5 ± 0.3
40–50	49.6 ± 3.7	2.0 ± 0.2	6.6 ± 0.2

2.2. SAR treatment

In February 2010, the experiment was arranged in a split-plot design, which was indicated in Fig. 1. There were four main blocks; each block was split into R_s and R_h treatments. Four simulated acid rain (SAR) treatments, which were CK (control), A1 (pH 4.0), A2 (pH 3.0) and A3 (pH 2.0), respectively, were randomly assigned in each of the R_s and R_h treatments. There were 32 micro-plots assigned in the field experiments, with each micro-plot area measuring 1 m × 1 m. Comparing soil CO_2 effluxes in small, trenched plots, where trenching excludes roots and nearby undisturbed locations, is one method for partitioning field-based estimates of annual R_s into its autotrophic and heterotrophic components (Bowden et al., 1993; Hanson et al., 2000; Kelting et al., 1998). The plots in R_h treatment were trenched with care to minimize soil disturbance. Trenches were cut (>30 cm) into the soil to sever roots entering the plot (Lavigne et al., 2003; Mäkiranta et al., 2010). To exclude also any C input from subcanopy herbs, where present, these were generally removed in trenched plots (Lavigne et al., 2003). In un-trenched plots where R_s was measured, only vegetation within the soil collar for measuring CO_2 efflux was eradicated by hand. The vegetation was removed about a month before the commencement of respiration measurement. Soil CO_2 effluxes measured in trenched and un-trenched plots were R_h and R_s, respectively.

The rain applied in the CK (control) treatment contained only deionized water with pH 6.7. In order to have the SAR reflecting the real mole ratio of H:S:N according to previous acid rain records (Hou and Zhao, 2009; Zhang et al., 2007), acidic solutions were prepared by adding a mixture of H_2SO_4 and HNO_3 (4.5:1 mole ratio) to deionized water (Zhang et al., 2007). SAR events were applied bi-weekly and the amount applied to each micro-plot was 1.25 L m^{-2} per application event. The simulated rainfall was applied to the treatments by means of a simulation apparatus capable of delivering droplet sizes in the range of 1.0 to 1.2 mm diameter. This study simulated an over 14-month exposure experiment in acid rain intensity. There is a several-day interval between SAR addition and soil CO_2 efflux measurements in order to avoid pulse CO_2 emission due to water sprinkling.

2.3. Soil CO_2 efflux measurement

Soil CO_2 efflux was measured by using a Li-8100 infrared gas analyzer (Li-Cor Inc., Lincoln, NE, USA) with attached chamber. The PVC soil collar (20 cm in diameter) was permanently installed (3 cm) into the soil in each SAR treatment for soil CO_2 efflux measurements. There was one collar in each plot. Aboveground vegetation within the soil collar was eradicated by hand prior to chamber placement and measurements to avoid canopy CO_2 exchange. Therefore, for soil CO_2 efflux measured, we did not include aboveground respiration from living plants. Measurements were generally made once a week from 21 March 2010 to 16 May 2011, in order to investigate the seasonal variations of R_s and R_h under different SAR treatments. During respiration measurements, a double-sealed gasket system seals the chamber both inside and outside of the soil collar to minimize CO_2 leaks and wind effects. Air flow generated by a rotary pump inside the analyzer control unit of Li-8100 provides a steady flow of air to the 20 cm chamber, with minimal pulsations. The analyzer optical bench measures CO_2 concentration; the concentration is then used to calculate flux rate.