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Inorganic and organic carbon dynamics in a limed acid soil are mediated by plants

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ABSTRACT

Lime is commonly used to overcome soil acidification in agricultural production systems; however, its impact on inorganic and organic soil carbon dynamics remains largely unknown. In a column experiment, we monitored rhizosphere effects on lime dissolution, CO_2 effluxes, and the concentrations of dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) in leachate from an acidic Kandosol. The experiment consisted of four treatments viz: soil only (control), soil + lime, soil + wheat, and soil + lime + wheat. We measured CO_2-C effluxes at 7, 43 and 98 days after planting (DAP) and leachate was collected at 56 and 101 DAP. The soil CO_2-C efflux rate increased significantly with lime addition at 7 and 43 DAP compared to control. At 43 DAP, the largest increase in CO_2-C effluxes was observed in the lime + wheat treatment. However, at 98 DAP similar CO_2-C effluxes were observed from wheat and lime + wheat treatments, suggesting that most of the lime was dissolved in the lime + wheat treatment. Both DOC and DIC concentrations in the leachate increased significantly with lime and wheat only treatments (cf. control). In contrast to DOC, there was an increase in the DIC concentration in the soil leachate from lime + wheat treatment columns at 101 DAP (significant wheat × lime interaction), thus, accentuating the pronounced role of wheat roots. We conclude that plant mediated dissolution of lime increased the concentration of DIC in the soil leachate, while both liming and presence of plants enhanced DOC leaching.

1. Introduction

Carbon efflux from terrestrial ecosystems is a significant component of the global carbon (C) cycle, and plant and soil respirations are the major pathways of the C efflux. The soil organic C pool is about double the size of the atmospheric C pool (1500 Pg C), with an estimated global efflux from soil respiration of 73 Pg C yr^{-1} (Schlesinger and Andrews, 2000). The soil CO_2 can directly emanate from plant roots, microbial breakdown of soil organic matter (SOM), from the dissolution of carbonates in calcareous soils and lime applied to acidic soils in agricultural production systems (Rustad et al., 2000; Bertrand et al., 2007; Page et al., 2009; Tamir et al., 2011). Agricultural production systems are vulnerable to soil acidification that is further accentuated through plant biomass harvesting. The acidification is not only localized to topsoil but also propagates into the subsoil (Goulding and Annis, 1998).

Liming is a common practice to overcome the adverse impacts of soil acidification on field crops. With the worldwide expansion of agricultural production, the magnitude of lime application has dramatically increased in acidic soils (Fisher and Bowden, 2003; Helyar and Porter, 1989). Lime contributes to the CO_2 emission upon dissolution in these soils, but can also enhance soil biological processes and subsequent release of organically derived CO_2 (Biasi et al., 2008; Tamir et al., 2011). Because of the large area under agriculture that is continuously limed, even small changes in the C dynamics of limed soils can have significant impacts on the global atmospheric C efflux.

Root-induced biological, chemical and physical processes occur in the rhizosphere and are responsible for the release of root exudates and protons (H^+). Thus, the rhizosphere has direct acidifying effects through the release of H^+ during the excess uptake of cations over anions. Lime is solubilized through H^+ release from plant roots (Mubarak and Nortcliff, 2010), and this acidification may enhance lime dissolution rate and dissolved inorganic C (DIC) leaching. Root exudation of labile organic compounds and enhanced microbial activity may also stimulate the decomposition of native SOM, which has been referred to as rhizosphere priming (Cheng, 2009). Because soil acidity often limits both bacterial (Haynes and Naidu, 1998) and plant root growth (Bruce et al., 1988), liming may enhance rhizosphere priming, resulting in greater C losses through soil respiration (Hinsinger et al., 2003).

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Here we examined the effects of liming and presence of growing plants on soil inorganic and organic C dynamics. We monitored CO_2-C effluxes and changes in the leachate chemistry under wheat (*Triticum aestivum* L.) grown with and/or without lime in an acidic Kandosol. We hypothesized that 1) rhizosphere effects would enhance lime dissolution and subsequent CO_2 effluxes, and 2) liming would increase the mobility of DIC and dissolved organic C (DOC) in the presence of growing wheat plants than without plants.

2. Materials and methods

2.1. Soil sampling and characterization

Subsurface soil (10–20 cm) of a red Kandosol developed under C_3 vegetation, was collected from a long-term acidification trial site at the Agricultural Institute at Wagga Wagga in NSW (147°20′E, 35°05′S). The soil was air-dried, sieved through a 2 mm sieve, and analyzed for pH, electrical conductivity (EC), particle size distribution, total exchangeable acidity, cation exchange capacity (silver thiourea method) and exchangeable cations (Rayment and Lyons, 2010). Lime requirement (LR) of the soil to raise the soil pH to 6.0 was estimated using the method of Shoemaker et al. (1961). Total carbon (TC) and nitrogen (N) were measured on a Variomax CNS Analyser. In the highly acidic soil used in the study, the TC represents the organic carbon (OC) content of the soil. The soil physical and chemical properties are given in Table 1.

2.2. Plant growth

Treatments consisted of soil only (control), soil + lime, soil + wheat and soil + lime + wheat, with four replicates for each treatment. Lime was thoroughly mixed into the soil at a rate of 2.04 t ha^{-1}, about double the amount of lime (11.4 g $column^{-1}$) required to raise the pH up to 6.0. The soil (2800 g) was packed into 16 columns (diam. 11 cm, height 30 cm). These columns were made up of polyvinyl chloride (PVC) with a tap at the bottom. The following basal nutrients (mg kg^{-1}) dissolved in deionized (DI) water were added at the start of the experiment: N (30.3); P (91); K (114.9); B (0.1); Cu (1.2); Zn (1.7); Mn (0.8); Mo (0.1). Initially N was applied as ammonium [$(NH_4)_2SO_4$].

Eight columns were planted with wheat seeds, and after seedling emergence, four plants were maintained in each column in a polyhouse with 12 h of light. The columns were watered daily with DI water, and 60% water holding capacity was maintained by weighing the columns before watering. At the time of acute deficiency (after 67 days of planting), the plants were supplied with Hoagland's no. 2 basalt salt mixture (SIGMA) at the rate of 3.2 g L^{-1}.

Table 1
Chemical and physical properties of the soil used in the experiment.

Total C (%)	1.4
Total N (%)	0.11
C:N	12.7
$\delta^{13}C$ (‰)	−25.2
pH (1:5 H_2O)	5.22
pH (1:5 $CaCl_2$)	4.11
Electrical conductivity (1:5, dS m^{-1})	0.05
Total exchangeable acidity ($mmol_c$ kg^{-1})	9.34
CEC ($mmol_c$ kg^{-1})	34.0
Exchangeable calcium ($mmol_c$ kg^{-1})	10.5
Exchangeable magnesium ($mmol_c$ kg^{-1})	3.89
Exchangeable potassium ($mmol_c$ kg^{-1})	5.10
Exchangeable sodium ($mmol_c$ kg^{-1})	2.25
Lime requirement (g kg^{-1})	2.28
Clay (%)	20
Silt (%)	8
Sand (%)	72

A total of 285 mL $column^{-1}$ of Hoagland solution was applied throughout the wheat growth period. The N added through Hoagland solution was in the form of nitrates [$Ca(NO_3)_2$ and KNO_3].

2.3. Sampling and measurements

We measured the soil CO_2-C efflux (mg C day^{-1} $column^{-1}$) at 7, 43 and 98 days after planting (DAP). The measurement at 7 DAP was done for the eight columns without wheat plants only. The second measurement was performed at 43 DAP, when wheat was still in the vegetative stage and the third at 98 DAP after post anthesis stage. The soil C efflux was measured using a modified method by Cheng et al. (2003). Before measurement, we sealed the top of the columns using silicone rubber with an air inlet. Using a closed circulation system, initial CO_2 from the root–soil system was removed by scrubbing with a soda lime and subsequent CO_2 evolved was trapped in a CO_2 trap (a PVC tube filled with 250 g burnt and acid-washed sand and 30 mL of 2.5 M NaOH) during a 48 h period. The total contents of the CO_2 trap were transferred to a 500 mL bottle, and sand was submerged by adding a known amount of DI water. Aliquot samples of the solution from the bottles were analyzed for inorganic carbon (IC) on a TOC analyzer (Shimadzu TOC-VCSH Analyser). We calculated cumulative amount of CO_2 evolved from the columns between 7 and 98 DAP by multiplying the average daily soil CO_2-C efflux rate between the two measuring dates by the time interval between two measuring dates, and by adding the preceding soil CO_2-C efflux. Because at 7 DAP plants were very small, we assumed that at that time soil CO_2-C efflux rates measured in columns without plants were the same as in columns with plants.

Leaching was induced after the second and third soil CO_2-C efflux measurements at 56 and 101 DAP by adding 150–250 mL and 250–300 mL of DI water respectively and draining the columns aided by an aquarium pump (Apollo AM-3, Apollo Enterprises, Ventura, CA). We added these variable amounts of DI water in order to obtain similar amounts of leachate ($\sim$50 mL). The leachate samples were collected in polypropylene tubes, ultracentrifuged and passed through syringe filter (<0.2 μm). The samples were stored in the dark at 4 °C until analysis. The leachate pH and EC were measured using a PHM 210 Standard pH meter and CDM 210 Conductivity meter respectively. All cations except ammonium (NH_4^+) were analyzed using a Varian SpectrAA-220FS atomic absorption spectrometer and anions with a high-performance liquid chromatography using a P680 HPLC Dionex pump. A UV–VIS spectrophotometer (UV mini 1240 Shimadzu) was used to determine the concentration of NH_4^+. The analyses of DIC and total dissolved C (TDC) were performed using a Shimadzu TOC-VCSH Analyser. The levels of DOC were determined by difference between the TDC and DIC levels in the leachate.

The wheat plants were harvested at 101 DAP. The wheat tops and roots were washed with DI water, blotted on a filter paper sheet, and dried to a constant weight at 65 °C in a forced-air oven. The dried tops and roots were ground in a Wiley mill fitted with stainless steel blades.

After the harvest, soil from all the columns was removed and divided into three depths i.e. 0–5 cm, 5–15 cm and 15–25 cm. Soil pH for each layer was measured in 1:5 soil solution ratio. Small amounts of soil were finely ground (<53 μm). The fine-ground soil samples from each layer and plant samples were analyzed for $\delta^{13}C$ using an isotope ratio mass spectrometer (IRMS; Thermo Finnigan Delta V, Bremen, Germany). The sub-samples were converted to ash for calculating ash alkalinity (Slattery et al., 1991).

2.4. Statistical analysis

Statistical analyses were conducted in JMP v. 9 (SAS Institute, Cary, NC, USA) statistical program. Homogeneity test was applied