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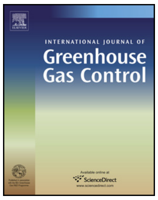

The impacts of introduced CO_2 flux on maize/alfalfa and soil

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ABSTRACT

Carbon capture and storage (CCS) is a technology of strategic importance to global carbon reduction. However, studies indicate that CCS may likely lead to CO_2 leakage in the long term. In the present study, the potential impacts of introduced CO_2 fluxes on the growth and development of selected crops and soil are described. Plants were grown in restructured pots with platform bottoms to simulate stored and introduced CO_2. In the initial growth stages, pure CO_2 gas was continuously injected into maize and alfalfa root zones at five different fluxes, ranging between 0 g/(m^2 d) and 2000 g/(m^2 d), for a minimum of 30 days. The results showed inhibition of plant growth and development, and soil modification, based on introduced CO_2 and control (absence of CO_2) scenarios. Maize and alfalfa showed decreased height, leaf number, leaf area, and root length trends as the introduced CO_2 flux increased. Photosynthesis and transpiration rates decreased, accumulated dry matter was significantly reduced, and soil pH and O_2 concentrations were reduced. The results indicated alfalfa was less tolerant than maize. The relationship between soil O_2 concentration and injected CO_2 flux was expressed as a linear equation. Most plant indicators did not change significantly when introduced CO_2 was within a flux of 500 g/(m^2 d), but when introduced CO_2 was between 500 g/(m^2 d) and 2000 g/(m^2 d) all indicators exhibited notably decreased values. Maize and alfalfa exposed to a 2000 g/(m^2 d) flux rapidly approached zero (0) in terms of all physiological indicators, and plant growth and development ceased, i.e. Maize and alfalfa showed a tolerance threshold of 500–2000 g/(m^2 d) flux for introduced CO_2. This provided the tolerance thresholds for maize and alfalfa under different scenarios of introduced CO_2, and clarified how the simulated introduction of CO_2 interfered with plant growth and development. The results of this study can inform future preventative and remedial actions in response to potential CCS leakage.

1. Introduction

Carbon capture and storage (CCS) is an emerging technology that is considered to have the potential to substantially reduce carbon emissions (IPCC, 2005). CCS was explicitly listed as one of the primary future global carbon reduction practices, together with the CDM (Clean Development Mechanism), and the Carbon Tax at the Durban Conference on Climate Change (South Africa, December 2011). However, CCS projects are at risk of leakage (Abood et al., 2009; Hawkins, 2003), with the greatest potential effects to human health and safety, ecology, and the environment at local levels if leaks occur (Heinrich et al., 2003; Saripalli et al., 2003). Consequently, it is essential to complete the following: a quantitative assessment of the impacts of introduced CO_2 on plants to determine tolerable CO_2 thresholds; define principles and elucidate CCS risk assessment processes; develop appropriate emission reduction policies, public awareness guidance, and monitoring and avoidance of accidental leakage in production practices. Two experimental approaches are available in simulating the impacts of leaked CO_2 on ecosystems. The first is based on a natural field site with a geological CO_2 emission source, e.g. geothermal steam (Beaubien et al., 2008), volcanoes (Biondi and Fessenden, 1999; Pfanz et al., 2007; Stephens and Hering, 2002, 2004), or geothermal hot springs (Macek et al., 2005). However, natural experimental sites exhibit highly homogenous impacts that fail to simulate the effects of an industrial CCS pool. Moreover, near-surface ecosystems have long been exposed to highly concentrated CO_2 levels prior to any experiment, and the organisms are well adapted to surface conditions (Beaubien et al., 2008). Therefore, a natural geological CO_2 emission source is not representative of CCS. The second approach is an artificial experimental leakage simulation platform

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that determines introduced CO_2 scenarios – an approach that is presently popular in studying surface ecological impacts in relation to CCS leakage. Most reported studies on the effects of CCS leakage on crop growth and development (such as increasing root-zone CO_2 concentration based on an aeroponics culture system) neglect the interaction of soil attributes, i.e. mechanical resistance, chemical properties, and microbes (Gao et al., 2006; Liu et al., 2010a; Sun et al., 2005), and the importance of soils that are depleted of O_2 (Boru et al., 2005). Furthermore, Patil et al. (2010) reported that various CO_2 leakage scenarios differentially influenced the growth and development of various crops: pasture and winter beans were markedly inhibited in emergence, growth, and development when the leakage rate was 1 L/min. West et al. (2009) showed that, under field conditions, uninterrupted leakage for 19 weeks at a rate of 3 L/min led to significant perturbations of alterations in surface ecology at a depth of between 50 and 100 cm below ground level. The mechanisms by which the geologically stored CO_2 affects surface ecology remain to be discussed at national and international levels, particularly for maize (National Bureau of Statistics of China, 2011; Zhao et al., 2008) and alfalfa (Zhang, 2004; Zhang et al., 2011), two major food and feed crops in China. Furthermore, studies based on natural and homogeneous leaked CO_2, or artificial and constantly introduced CO_2 sources lack data simulated under different scenarios (Hepple, 2005; West et al., 2005). In light of the necessity to manage the future potential for CCS leakage and to generate baseline data to elucidate the effects of CO_2 leakage on surface ecosystems, we employed a manually controlled simulation platform to examine the impacts of introduced CO_2 on soil attributes and on the growth and development of maize and alfalfa at different CO_2 fluxes. Our primary objectives were to determine an ecological tolerance threshold to can serve as a model for terrestrial plants; to further clarify how introduced CO_2 interferes with ecosystem functions; and, based on our results, to recommend preventative and remedial actions under future CCS leakage conditions.

2. Methods and materials

The experimental procedures were conducted at a demonstration garden (40°32′ N, 116°03′ E, 536 m a.s.l.) owned by an organic agriculture company based in Yanqing, Beijing from August through October 2011. The experimental plot spanned an area of approximately 50 m^2, and was covered to prevent pots from receiving uncontrolled water via precipitation. Dicotyledonous and monocotyledonous crops were chosen for the experiments on an alfalfa (*Medicago sativa* L.) 'Zhongmu No 1' and a maize (*Zea mays* L.) hybrid 'Zhongnuo No 2'. Topsoil, classified as cinnamon type (depth 0–20 cm, weight 162 kg) was obtained from local farmland. The soil was loaded into cultivation pots and compacted to a thickness of 50 cm. Prior to the experiment the soil was a medium texture loam with pH 7.32, volumetric mass of 1.30 g/cm^3, and volumetric water content of 22.67%.

2.1. Simulation platform for introduced CO_2

The experiment was conducted under self-made manually controlled simulation platforms that were used to inject CO_2 into the bottoms of the plant pots (Fig. 1). The platform simulated a simple ecosystem, and consisted of a controlled CO_2 release device, a monitoring/recording and management system, different simulation scenarios used to introduce CO_2 through construction of a set of mutually independent, simple farmland-based ecosystems, and manual control of CO_2 release from deep soil at different rates and fluxes.

2.1.1. Controlled CO_2 release

The device for controlled release of CO_2 consisted of a special cultivation pot (50 cm in length and width, 80 cm in height), a gas flow meter with a valve, a gas conduit with a shunt, and a CO_2 cylinder. The special cultivation pot was partitioned with a permeable shim and 0.5 cm aperture leading into an upper soil chamber (60 cm in height) for crop growth, and a lower gas chamber (20 cm in height) for homogeneous CO_2 release, to ensure that CO_2 entering the gas chamber from the cylinder evenly re-entered the soil chamber. The shim was covered with a double layer of nylon gauze. An intake pipe was installed 10 cm below the shim on the outer wall of the pot, below which a drainage valve was installed.

2.1.2. Planting and management

Maize and alfalfa were seeded on 18 August 2011. Maize seedlings were singled out at the three-leaf stage, leaving one seedling per pot. Plants were fertilized once with urea on 14 September at an application rate of 3 g/pot. Plants were watered once every ±10 d with 5 L of water. CO_2 introduction in the maize section of the experimental plot began on 18 September and on 26 September in the alfalfa section, and lasted until the end of the experimental period in October 2011.

2.1.3. CO_2 introduction scenario setting

Based on relevant international findings (Beaubien et al., 2008; West et al., 2009) and an upper limit (2000 $g/(m^2\,d)$) for maize tolerance threshold limit that we previously determined (Wu et al., 2012), five CO_2 introduction scenarios were established in this experiment: one control (absence of CO_2) and four CO_2 introduction scenarios (Table 1). The CO_2 injection flux was used as a key CO_2 indicator (Saripalli et al., 2003) as follows: CK (0 $g/(m^2\,d)$), G_{500} (500 $g/(m^2\,d)$), G_{1000} (1000 $g/(m^2\,d)$), G_{1500} (1500 $g/(m^2\,d)$), and G_{2000} (2000 $g/(m^2\,d)$). Each scenario was repeated three times.

The different CO_2 injection fluxes were established to control the CO_2 flow rate. The control scenario (absence of CO_2) was not connected to a gas conduit, and therefore CO_2 was not injected. The four leakage scenarios were connected to four gas shunts, and the CO_2 from the cylinders traveled via 3 mm stainless steel gas conduits. Gas flow meters controlled the amounts of CO_2 that entered the cultivation pots. By readjusting the valve pressure and pot flow meter injection rate, the CO_2 flux introduced to the lower plant parts was maintained within relevant ranges, namely: CK (0 mL/min), G_{500} (44 mL/min), G_{1000} (88 mL/min), G_{1500} (132 mL/min), and G_{2000} (176 mL/min). The CO_2 injection flux and rate conversion formula (1) is as follows:

$$F = v \times \frac{\rho}{s} \tag{1}$$

where F represents the CO_2 injection flux, $g/(m^2\,d)$; v the CO_2 injection rate, mL/min; ρ represents CO_2 density under normal pressure, approximately 1.977 g/L; and s the pot cross-sectional area, approximately 0.25 m^2.

2.2. Measurement indicators and methods

The monitoring and recording system included the following measures: crop morphology, leaf photosynthesis and transpiration, soil pH, soil CO_2 emission flux, soil O_2/CO_2 concentration, and soil moisture and temperature. Specifically, maize and alfalfa heights were directly measured with a ruler, while maize leaf number was calculated conventionally. Maize leaf area was estimated using the length and width coefficient method, i.e. leaf area = length × width × k. The lengths and widths of ear leaves were measured using a ruler; leaf length was measured from the leaf tip to the leaf sheath, and leaf width was measured at the widest point. In the CK, G_{500}, and G_{1000} scenarios, the value of k was 0.75, while in