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Effects of elevated soil CO_2 concentration on growth and competition in a grass-clover mix☆

Karon L. Smith[a], Janice A. Lake[b,1], Michael D. Steven[a], Barry H. Lomax[b,*]

[a] School of Geography, University of Nottingham, University Park, Nottingham, NG7 2RD, UK
[b] The School of Biosciences, The University of Nottingham, Sutton Bonington Campus, Sutton Bonington, Leicestershire, LE12 5RD, UK

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ABSTRACT

To investigate potential environmental affects in the context of carbon dioxide (CO_2) leakage from Carbon Capture and Storage (CCS) schemes. The ASGARD (Artificial Soil Gassing and Response Detection) facility was established, where CO_2 can be injected into the soil in replicated open-air field plots. Eight plots were sown with a grass-clover mix, with four selected for CO_2 treatment while four were left as controls. Observations of sward productivity throughout the study allowed three effects to be distinguished: a direct stress response to soil gassing, limiting productivity in both species but with a greater effect on the clover; competition between the grass and clover affected by their differential stress responses; and an overall temporal trend from dominance by clover to dominance by grass in CO_2 treatments. The direct effect of soil CO_2 (or associated oxygen (O_2) deprivation due to the high levels of CO_2 in the soil) gave estimated reductions in productivity of 42% and 41% in grass, compared to 66% and 32% for clover in the high and low CO_2 gassed zones respectively. Canopy CO_2 increased by 70 parts per million (ppm) for every 1% increase in soil CO_2 and a significant positive response of stomatal conductance in clover was observed; although carbon acquisition by the plants should not therefore be impeded, the reduction in productivity of the gassed plants is indicative of carbon-based metabolic costs probably related to soil CO_2 affecting root physiology. Biomass measurements made after gassing has ceased indicated that recovery of vegetation was close to complete after 12 months.

1. Introduction

Carbon Capture and Storage (CCS) has been advocated as a means of reducing rising levels of atmospheric carbon dioxide (CO_2) to help mitigate climate change. Captured CO_2 is compressed and transported via pipeline to storage sites in deep geological reservoirs (depleted oil or gas reservoirs or deep saline aquifers). Geological evidence from oil and gas fields indicate that gases can remain trapped in suitable formations for millions of years. Although the risks of leakage from well-chosen sites are regarded as extremely small and protocols for leak detection have been developed (Leuning et al., 2008; Jenkins et al., 2016), it is nevertheless a regulatory requirement to demonstrate that the impacts of any possible leaks from CCS infrastructure, (including transportation pipelines) have been investigated and understood. In the unlikely event of captured CO_2 reaching the surface, CO_2 in the soil would rise, possibly to values approaching 100%; diffusion from the soil would lead to increased atmospheric CO_2, but to a much lesser extent due to rapid air mixing. CO_2 may also dissolve in soil water leading to changes in the pH level and possible uptake by plants in the transpiration stream (Steven et al., 2010). Atmospheric CO_2 may stimulate plant photosynthesis, but high soil concentrations are usually detrimental (IPCC, 2005). While much research in the context of global environmental change has been carried out to determine the effects of elevated atmospheric CO_2 on vegetation (Kimball et al., 1993; Van Noordwijk et al., 1998; Ghannoum et al., 2000; Moscatelli et al., 2001), much less is known about the potential effects of elevated soil CO_2.

Previous laboratory studies have reported significant plant stress responses to soil CO_2, with some suggestion of greater sensitivity in dicotyledons compared to monocotyledons (Noyes, 1914; Stolwijk and Thimann, 1957; Williamson, 1968; Glinski and Stepniewski, 1985; Bunnell et al., 2002; Rodriguez et al., 2005).

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* Corresponding author.
E-mail address: barry.lomax@nottingham.ac.uk (B.H. Lomax).
[1] Present address: Department of Animal and Plant Sciences, University of Sheffield, Sheffield, S10 2TN, UK.

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However, many of these studies were at relatively low CO_2 (ca. 2–6%) concentrations, similar to background soil CO_2 in agricultural systems (0.15 and 2.5% in the surface layers; Stolwijk and Thimann 1957; Russell 1973), with occasional large excursions in soil CO_2 being recorded (10 and 12% recorded (Chang and Loomis 1945; Stolwijk and Thimann 1957; Russell 1973; Glinski and Stepniewski 1985)). Natural CO_2 vents have been proposed as CCS leakage analogues, for example at Staveščinci, Slovenia, where plant height corresponded inversely with soil CO_2 (Vodnik et al., 2006) and Latera, Italy, where Beaubien et al. (2008) found an ecological gradient, with acid-tolerant grasses outcompeting clover near a CO_2 vent, consistent with the suggestion of differential sensitivities of plants. However, these seeps have been leaking CO_2 for extended periods so that the vegetation growing in the vicinity may have become adapted to the high soil CO_2 conditions. Moreover, at natural analogue sites, smaller concentrations of methane and trace amounts of more toxic gases, such as hydrogen sulphide (H_2S) or sulphur dioxide (SO_2) may also be present (Pfanz et al., 2004) making it difficult to attribute direct CO_2 effects.

Assessment of the potential impact posed in the unlikely event of leakage of CO_2 from CCS pipelines and storage infrastructure requires the application of realistic environmental scenarios (West et al., 2015). Here we describe a fully-replicated experimental open-air facility where pure CO_2 gas was injected into previously undisturbed soil to determine specific effects on the growth and health of vegetation. Within this experimental framework a mixture of pasture grass and clover were sown to investigate the effects of differential sensitivities on interspecies competition.

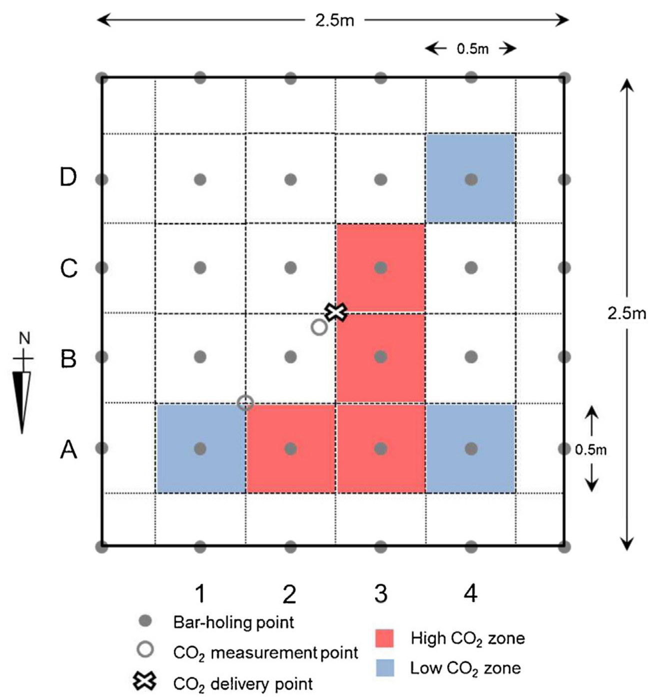

Fig. 1. Schematic showing plot layout, gas measurement, bar-holing points and sampling transects (A_1–A_4 and B_3–D_3) used in this study. Red squares mark areas of high soil CO_2 and blue low soil CO_2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Methods

2.1. Experimental plots

The ASGARD (Artificial Soil Gassing And Response Detection) facility was located in a field of permanent pasture at the Sutton Bonington campus of the University of Nottingham, UK (N 52.8°, W 1.2°). CO_2 was injected into the soil in 16 field plots (each 2.5 m × 2.5 m) via 20 mm (Inside Diameter (ID)) medium density polyethylene (MDPE) gas pipes. The pipes were inserted into the ground at an angle of 45° to the vertical and the CO_2 was delivered into the soil at a depth of 500–600 mm below the centre of each CO_2 gassed plot via perforations in the end of the pipes. This depth was chosen to limit lateral gas migration across the site. Food-grade, liquid CO_2 was stored in two 200 L cryogenic vessels (BOC, Derby, UK), the liquid CO_2 was converted to gaseous phase CO_2 and regulated down to a pressure of ~22 psi (152 kPa) before being delivered via a single inlet mass flow sensor (Alicat, Tucson, USA) to 16 individual mass flow controllers (Alicat, 0.1–10 L min^{-1}). CO_2 was delivered at a flow rate of 1 L min^{-1} to each experimental gassed plot. The mass flow controllers were operated, and the system data logged, by a PC-based control system (TVC, Great Yarmouth, UK). For a full site description and characterisation see Smith et al. (2013).

For this study eight experimental plots were used, each separated by a 1 m border. Four randomly selected plots were injected with CO_2 gas and four acted as untreated controls. Each experimental plot had a 0.25 m buffer zone around the edge, with the remaining area sub-divided into sixteen 0.5 × 0.5 m sampling sub-plots (Fig. 1). Above-ground biomass and plant physiological measurements were measured in two transects running East-West (subplots A_1–A_4) and North-South (A_3–D_3) crossing the zone of highest soil gas concentration; a single transect running East-West (A_1–A_4) was used in the control plots. Plots were hand dug and sown on 19th April, 2010 with 'POCHON' Persistent Long Term Grazing Ley, (Cotswold Seeds, Gloucestershire, UK), a mixture of 87.5% perennial rye grass (*Lolium perenne*) and 12.5% white clover (*Trifolium repens*), at a rate of 3 g m^{-2}. The plots were left to establish and weeded by hand throughout 2010 to ensure that only grass and clover remained. CO_2 was delivered to the centres of the four plots from 21st March, 2011 to 15th June, 2012.

2.2. Gas measurement

CO_2 in the soil was monitored by means of permanently-installed vertical tubes located 0.15 and 0.7 m from the centre of each gassed plot at a depth of 0.3 m. Holes made in the end of the tubes allowed air in the tube to equilibrate with the surrounding soil atmosphere. CO_2 and oxygen (O_2) were measured two to three times per week using a GA5000 landfill gas analyser (Geotech, Warwickshire, UK). Additional measurements to map soil gas concentrations at 0.3 m depth were taken on three occasions—27th June, 2011, 19th October, 2011 and 14th June, 2012 by bar-holing on a grid at 0.5 m intervals across each plot (Fig. 1), as described in Smith et al. (2005), giving a good overview of the horizontal distribution of CO_2 within the soil. However it is intrinsically prone to some underestimation of CO_2 concentration because of the possibility of air mixing with the sample.

The seasonal average of CO_2 measured in the permanently installed tube at 0.15 m from the centre of the plot, for the three months preceding each bar-holing measurement, was compared with the bar-hole estimate for the same location by averaging the values for the four closest bar-holes, inversely weighted according to their distance from the 0.15 m tube. A similar calculation was made for the tube permanently installed at 0.7 m from the centre. The CO_2 concentrations obtained by bar-holing were then scaled using the mean of the two ratios of permanent tube to bar-hole CO_2. This method assumes that any effects of air mixing are the same across the plot and that the spatial pattern represented by the bar-hole data is consistent throughout the season, even though individual values may vary. The scaled CO_2 gas distribution within the plot was mapped using Surfer 7 (Golden Software Inc., Golden,