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Effects of elevated atmospheric CO_2, prolonged summer drought and temperature increase on N_2O and CH_4 fluxes in a temperate heathland

Mette S. Carter [a,*], Per Ambus [a], Kristian R. Albert [a], Klaus S. Larsen [a], Michael Andersson [a,1], Anders Priemé [b], Leon van der Linden [a], Claus Beier [a]

[a] Biosystems Division, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, P.O. Box 49, DK-4000 Roskilde, Denmark
[b] Department of Biology, University of Copenhagen, Sølvgade 83H, DK-1307 Copenhagen K, Denmark

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ABSTRACT

In temperate regions, climate change is predicted to increase annual mean temperature and intensify the duration and frequency of summer droughts, which together with elevated atmospheric carbon dioxide (CO_2) concentrations, may affect the exchange of nitrous oxide (N_2O) and methane (CH_4) between terrestrial ecosystems and the atmosphere. We report results from the CLIMAITE experiment, where the effects of these three climate change parameters were investigated solely and in all combinations in a temperate heathland. Field measurements of N_2O and CH_4 fluxes took place 1–2 years after the climate change manipulations were initiated. The soil was generally a net sink for atmospheric CH_4. Elevated temperature (T) increased the CH_4 uptake by on average 10 μg C m^{-2} h^{-1}, corresponding to a rise in the uptake rate of about 20%. However, during winter elevated CO_2 (CO_2) reduced the CH_4 uptake, which outweighed the positive effect of warming when analyzed across the study period. Emissions of N_2O were generally low (<10 μg N m^{-2} h^{-1}). As single experimental factors, elevated CO_2, temperature and summer drought (D) had no major effect on the N_2O fluxes, but the combination of CO_2 and warming (TCO_2) stimulated N_2O emission, whereas the N_2O emission ceased when CO_2 was combined with drought (DCO_2). We suggest that these N_2O responses are related to increased rhizodeposition under elevated CO_2 combined with increased and reduced nitrogen turnover rates caused by warming and drought, respectively. The N_2O flux in the multifactor treatment $TDCO_2$ was not different from the ambient control treatment. Overall, our study suggests that in the future, CH_4 uptake may increase slightly, while N_2O emission will remain unchanged in temperate ecosystems on well-aerated soils. However, we propose that continued exposure to altered climate could potentially change the greenhouse gas flux pattern in the investigated heathland.

1. Introduction

Nitrous oxide (N_2O) and methane (CH_4) are important greenhouse gases (IPCC, 2007), and N_2O is the dominant substance responsible for depletion of the stratospheric ozone layer (Ravishankara et al., 2009). On a global scale, N_2O emissions from unfertilized grassland/steppe, including heathlands, is estimated to be 0.4 Tg N_2O–N y^{-1} (Stehfest and Bouwman, 2006), which corresponds to about 2% of the total annual N_2O emissions (Fowler et al., 2009). Methane uptake by aerobic soils worldwide is estimated to be 30 Tg CH_4 y^{-1}, counteracting 6% of the total emission of CH_4 from natural and anthropogenic sources (Wuebbles and Hayhoe, 2002).

Nitrous oxide emitted from soil primarily originates from the two microbial processes nitrification and denitrification, which occur under aerobic and anaerobic soil conditions, respectively (Wrage et al., 2001). Thus, both processes are controlled by soil moisture that regulates oxygen (O_2) availability and by supply of substrates, ammonium (NH_4^+) or nitrate (NO_3^-). In addition, denitrifying bacteria need labile carbon (C) compounds as an energy source. Soils may act as a sink for atmospheric N_2O, which has been observed at low mineral nitrogen (N) availability and the responsible organisms could be denitrifying bacteria, but are probably also nitrifying organisms (Chapuis-Lardy et al., 2007).

The CH_4 flux between soil and atmosphere is the net result of CH_4 production by methanogenic archaea and CH_4 oxidation by methanotrophic bacteria (Le Mer and Roger, 2001). In aerobic soils,

* Corresponding author. Tel.: +45 2133 1383.
E-mail address: mthy@risoe.dtu.dk (M.S. Carter).
[1] Not present affiliation.

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CH_4 oxidation typically proceeds at a greater rate than CH_4 production, resulting in net uptake of atmospheric CH_4. Maximum CH_4 oxidation usually occurs in deeper soil layers. Thus, CH_4 uptake is strongly controlled by the physical diffusion of atmospheric CH_4 through the soil profile, which is mainly regulated by the soil texture and water content (King, 1997), as molecular diffusion in water is four orders of magnitude slower than in air.

The effect of drought on fluxes of CH_4 and N_2O has only been investigated in a limited number of studies in temperate ecosystems on aerobic soils. In a temperate spruce forest, Borken et al. (2000) found that prolonged summer drought increased the annual CH_4 uptake by more than 40%. However, in a deciduous forest on well-drained soil, the CH_4 uptake was only increased by 7% because soil in the control plots already had a low water content due to effective drainage (Borken et al., 2006). Goldberg and Gebauer (2009) reported that summer drought reduced the N_2O emission from a spruce forest.

Elevated atmospheric carbon dioxide (CO_2) concentrations affect soil properties via plant-mediated processes, and thereby potentially the fluxes of N_2O and CH_4. It is well known that plants growing under elevated CO_2 may reduce their transpiration, leading to increased water use efficiency and soil moisture contents (Morgan et al., 2004; Robredo et al., 2007). Furthermore, a common plant response to elevated CO_2 is increased deposition of root-derived C into the rhizosphere (Allard et al., 2006; Pendall et al., 2004).

The effect of elevated atmospheric CO_2 on N_2O fluxes has been investigated intensively through the last decade in a variety of ecosystems. Long-term studies ($\geq$1 year) in natural or semi-natural ecosystems on well-aerated soils with low N availability show either no response in annual N_2O emissions rates to atmospheric CO_2 levels (Baggs et al., 2003; Mosier et al., 2002; Phillips et al., 2001b) or increased N_2O emissions from soil under elevated CO_2 (Kammann et al., 2008). The positive effect of elevated CO_2 on the N_2O emission was explained by increased rhizodeposition of labile C substrates stimulating denitrification. In an N-limited pine forest, Phillips et al. (2001b) observed seasonal variability in the N_2O response to elevated atmospheric CO_2 compared to an ambient control. This included reduced N_2O emissions during the growing season due to high plant-microbial competition for N, and enhanced N_2O emissions during winter possibly because denitrification was stimulated by greater soil moisture and labile C sources under elevated CO_2. In a short-term study during autumn, Arnone and Bohlen (1998) also found that elevated atmospheric CO_2 increased N_2O emission, which they ascribed to improved soil moisture conditions in a relatively dry grassland favouring the microbial transformation of N.

Reduced CH_4 consumption under elevated atmospheric CO_2 has been observed in several ecosystems on undisturbed aerobic soils (Ambus and Robertson, 1999; Baggs and Blum, 2004; Dubbs and Whalen, 2010; Ineson et al., 1998; Phillips et al., 2001a), but the exact mechanism is not well known and may vary between ecosystems. Two possible mechanisms have been suggested for the reducing effect of elevated CO_2 on net CH_4 consumption: i) decreased CH_4 oxidation due to higher soil water content and thereby reduced diffusion of CH_4 (Ambus and Robertson, 1999; Baggs and Blum, 2004) and ii) increased CH_4 production due to anaerobic microsites caused by reduced O_2 diffusion and increased respiration (McLain and Ahmann, 2008).

Effects of elevated temperature on N_2O and CH_4 fluxes have only been investigated in a few field-scale warming experiments located in temperate ecosystems on well-aerated soils (McHale et al., 1998; Peterjohn et al., 1994; Rustad and Fernandez, 1998). The artificial warming had either no effect on CH_4 flux or it increased CH_4 uptake, which could be related to the observed warming-induced declines in soil moisture in certain soil layers. Warming may reduce soil moisture by increasing the evapotranspiration (Dermody et al., 2007). No effect of warming on N_2O flux was observed (McHale et al., 1998; Peterjohn et al., 1994), although elevated temperature is known to increase net N mineralization (Rustad et al., 2001).

In the current study, the effects of future climatic and atmospheric conditions on the biosphere-atmosphere exchange of N_2O and CH_4 were investigated in a temperate heathland at the CLIMAITE experimental site (www.climaite.dk). CLIMAITE was initiated in 2005 to improve our understanding of how biological processes in natural terrestrial ecosystems may be affected under future environmental conditions involving elevated temperature, elevated concentration of atmospheric CO_2 and prolonged summer drought, simulating *in situ* the climatic scenario as predicted for Denmark in year 2075 (Mikkelsen et al., 2008). Previous studies have examined the effects on greenhouse gas fluxes of warming, elevated CO_2 and summer drought, but to our knowledge field studies combining all three factors in a full-factorial design have not been reported. We formulated four hypotheses for the responses in N_2O and CH_4 fluxes to the climate change parameters investigated in the experiment.

1) Prolonged summer drought will stimulate CH_4 uptake and reduce N_2O emissions.
2) Elevated CO_2 will reduce CH_4 uptake due to higher soil moisture caused by plant water saving mechanisms. Nitrous oxide emissions will remain unchanged under elevated CO_2 because the stimulating effects of increased soil moisture and availability of labile carbon compounds will be offset by increased plant-microbial competition for N.
3) Warming will increase CH_4 uptake because of reduced soil moisture. On an annual basis N_2O emission will be unaffected by warming, but this may include a reduction during spring and summer due to reduced soil moisture and an increased emission in autumn due to higher N turnover rates.
4) In the combinations of two or three treatments, the treatment effects will either counteract each other, if in opposite directions, or intensify each other, if in the same direction.

To address these hypotheses, we conducted a full-factorial study including all treatments. In addition, a more intense study involving a subset of five treatments was carried out to focus on treatment effects during the experimental summer drought and the subsequent rewetting period.

2. Materials and methods

2.1. Field site

The study took place at the CLIMAITE experimental site (Mikkelsen et al., 2008) situated at Brandbjerg (55°53′ N, 11°58′ E) about 50 km NW of Copenhagen, Denmark. The site is a dry, temperate heathland on a hilly nutrient-poor sandy podzol (FAO classification). The mineral soil consists of 20.5% coarse sand, 71.6% fine sand, 5.8% silt and 2.2% clay, and has a pH_{H_2O} of 4–5. Mean pore volume and field capacity of the upper 15 cm of the mineral soil is 42 and 17 vol%, respectively. The content of carbon and nitrogen decline sharply from 6.4% and 0.34% in the upper 2 cm of the mineral soil to 0.39% and 0.02% in the 10–30 cm layer, respectively. Above the mineral soil is an organic top layer of about 5 cm in depth containing approximately 23% carbon and 1.2% nitrogen. The vegetation is dominated by *Calluna vulgaris* (L.), *Deschampsia flexuosa* (L.) and various mosses. Annual mean temperature is 8.0 °C, annual mean precipitation is 613 mm (www.DMI.dk) and the N