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The emissions of nitrous oxide and methane from natural soil temperature gradients in a volcanic area in southwest Iceland

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Nitrous oxide (N_2O) and methane (CH_4) emissions were measured along three natural geothermal soil temperature (T_s) gradients in freely drained upland soils in a volcanic area in Iceland. Two of the T_s gradients (underneath a grassland (GN) and a forest site (FN), respectively) were recently formed (in May 2008) and thus subjected to relatively short-term warming. The third T_s gradient, underneath another grassland site (GO), had been subjected to long-term soil warming (over at least 45 years). The N_2O and CH_4 emissions were measured using the static chamber method. In addition, subsurface soil gas concentrations (5–20 cm) were studied. N_2O emissions from GN were slightly higher than those from GO in the temperature elevation range up to +5 °C, while CH_4 uptake rates were similar. Under moderate soil warming (<+5 °C) there were no significant increases in gas flux rates within any of the sites, but when soil warming exceeded +20 °C, both N_2O and CH_4 emissions increased significantly at all sites. While net uptake of CH_4 (up to −0.15 mg CH_4 m^{-2} h^{-1}) and occasional N_2O uptake (up to −12 μg N_2O m^{-2} h^{-1}) were measured in the unwarmed plots at all sites, net emissions were only measured from the warmest plots (up to 2600 μg N_2O m^{-2} h^{-1} and up to 1.3 mg CH_4 m^{-2} h^{-1}). The subsurface soil N_2O concentrations increased with soil warming, indicating enhanced N-turnover. Subsurface soil CH_4 concentrations initially decreased under moderate soil warming (up to +5 °C), but above that threshold they also increased significantly. A portion of the N_2O and CH_4 emitted from the warmest plots may, however, be geothermally derived, this should be further confirmed with isotope studies. In conclusion, our research suggests that moderate increases in soil temperature (up to +5 °C) may not significantly increase N_2O and CH_4 emissions at these upland soils, both in the short and longer term. However, warming trends exceeding +5 °C as predicted for 2100 in pessimistic scenarios may cause increased trace gas emissions and thus significant positive feedbacks to climate change.

1. Introduction

Nitrous oxide (N_2O) and methane (CH_4) are important greenhouse gases (GHGs). With a 100-year time horizon, the global warming potential (GWP) of N_2O is 265 times that of carbon dioxide (CO_2) (IPCC, 2014). N_2O is mainly produced in soils as a consequence of two microbial activities; aerobic nitrification and anaerobic denitrification (Priemé and Christensen, 2001). The processes forming N_2O as an intermediate product are controlled by several factors such as temperature, moisture, pH and N-availability (Barnard et al., 2005; Brown et al., 2012). This implies that the emissions of N_2O are sensitive to changing environmental conditions. Upland forest soils in the Nordic countries are usually negligible sources of N_2O, whereas N-fertilized agricultural soils

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and drained peat soils are major sources (Maljanen et al., 2010a).

Methane has 28 times the GWP of CO_2 over a 100-year time horizon (IPCC, 2014) and is formed in soils by anaerobic methanogenesis (Le Mer and Roger, 2001; Serrano-Silva et al., 2014). The production of CH_4 is primarily controlled by oxygen content, but is additionally controlled by soil temperature, pH, moisture and salinity (Le Mer and Roger, 2001; Serrano-Silva et al., 2014). Methane that is produced in deeper soils layers can be transported to the atmosphere via ebullition through wet soils, via diffusion, or via the aerenchyma of vascular plants (Marushchak et al., 2016; Serrano-Silva et al., 2014). Methane can be oxidized in the soil by methanotrophic microbes, both under aerobic and anaerobic conditions (Knittel and Boetius, 2009). The optimum conditions for this process include neutral soil pH, a soil temperature of ~25 °C and low salinity (Serrano-Silva et al., 2014). As a consequence, the CH_4 efflux from the soil is the net result of both methane production and methane oxidation. As both processes are controlled by several environmental factors, any change therein can affect this efflux (Le Mer and Roger, 2001). Upland mineral soils are usually small sinks for atmospheric CH_4, whereas waterlogged wetlands are the major sources of CH_4 at northern latitudes (Maljanen et al., 2010a).

To study the effects of climate change on N_2O and CH_4 fluxes, warming experiments are often employed. However, short-term manipulative warming treatments can be impacted by several confounding factors and can be considered as over-simplistic (De Boeck et al., 2015). Natural temperature gradients (e.g. thermal gradients as a result of geothermal activity) on the other hand offer a number of benefits that makes them suitable “field laboratories” for research on GHG responses to soil warming (Kayler et al., 2015; O'Gorman et al., 2014). Geothermal activity can remain stable for many years, making it possible to investigate long-term warming effects, but major tectonic events can also create new hotspots, exposing previously unwarmed ecosystems to higher temperatures and enabling studies of recent (short-term) temperature responses (O'Gorman et al., 2014).

Both types of natural soil temperature gradients can be found in the Hellisheiði geothermal systems in southwest Iceland. In May 2008, a major earthquake in southern Iceland affected the geothermal systems close to its epicenter (Halldorsson and Sigbjornsson, 2009). A part of this geothermal system moved from its previous location to a new and previously unwarmed area, creating a natural soil warming experiment. This offers a unique opportunity to study how various ecosystem processes, including N_2O and CH_4 dynamics, are affected by short-term temperature changes. Other geothermal systems in the area were not affected by the earthquake, providing natural soil temperature gradients that can be used to study long-term soil temperature effects on N_2O and CH_4 dynamics.

The “ForHot“ research network was established in 2012 to bring European scientists together to study how changes in soil temperature affect various ecosystem processes in both natural grasslands and a planted 45-year old Sitka spruce forest in southern Iceland. The large range in temperature elevations at the ForHot sites offers both conditions similar to the predicted climate change during the next century as well as more extreme temperatures that can yield new insights into stress physiology (Kayler et al., 2015; O'Gorman et al., 2014).

The major aim of this study within the ForHot project was to investigate changes in N_2O and CH_4 flux rates along soil temperature gradients to better predict the impacts of future soil warming on atmospheric impacts of terrestrial ecosystems. Our hypothesis was that a significant increase in soil temperature will accelerate microbial processes and turn these sites from N_2O and CH_4 sinks to sources.

2. Methods

2.1. Study site

The ForHot study sites are located in southwest Iceland, in the surroundings of the village Hveragerdi (64.008°N, 21.178°W), on land owned by the Agricultural University of Iceland (Fig. 1). In 2004–2014, the area had a mean annual air temperature of 5.2 °C and a mean annual precipitation of 1431 mm (Icelandic Met Office, IMO). The growing season normally starts in May and ends in late August. The soil type at the study sites is Brown Andosol (Arnalds, 2015), with relatively high pH (5.5–7.0) and large soil water retention capacity (O'Gorman et al., 2014).

On the 29th of May 2008, a major earthquake (magnitude 6.3 on the Richter scale) occurred in southwest Iceland (Halldorsson and Sigbjornsson, 2009), where ca. 70–100 years pass between such large earthquake episodes in this region. The 2008 earthquake caused large structural damages to infrastructures and affected geothermal systems close to its epicenter. One such geothermal system moved from its previous location to a new and previously unwarmed area (Þorbjörnsson et al., 2009), and the new belowground geothermal channels within the bedrock resulted in soil temperature increases in the soil above. The soil temperature elevation measured at 10 cm soil depth reaches >50 °C where the channels are closest to the surface (O'Gorman et al., 2014). The recently warmed area is covered by two different ecosystem types: a) a planted 45 year old Sitka spruce (*Picea sitchensis*) forest (Forest New, FN) and b) a natural, unmanaged treeless grassland (Grassland New, GN) dominated by *Festuca* sp., *Agrostis* sp. and moss (Fig. 1).

The third study site (Grassland Old, GO) is located 2.5 km NW from GN and FN on an older temperature gradient in Grændalur (the ‘green valley’) allowing to study the long-term effects of warming. It is covered by the same grassland type as GN. At the GO site the earliest survey of geothermal hot-spots was made in 1963–1965 (45 years prior to the 2008 earthquake) (Kristján Sæmundsson, pers. comm.). In autumn 2008, the locations of the new and old geothermal hot-spots in the area were mapped and published (Þorbjörnsson et al., 2009). This survey was used to select the GO and GN sites for the ForHot study. Further, the existence of some of the hot-spots prior to the 2008 earthquake at GO is also supported by regular field measurements of soil temperature since 2005 in a previous study in Grændalur (Daebeler, 2014). The geothermal activity has most likely been persistent in Grændalur for centuries, however, as according to local knowledge its name is derived from the subarctic grasslands staying green during most of the winter on the warmest hot-spots. The oldest historical document that mentions this place name was published in 1708 (Magnússon and Vídalín, 1918-1921). Additional evidence for persistent geothermal warming at the GO site are geothermal clay layers found at various depths in the soil profile (Leblans, pers. communication). This indicates that over longer time periods, the warming may have fluctuated somewhat, as was observed at other nearby, older hot-spots following the 2008 earthquake (Daebeler, 2014).

2.2. Chamber measurements

The gas fluxes (N_2O and CH_4) were measured using the static chamber method (e.g. Maljanen et al., 2010b). The flux measurements were made along temperature gradients in FN, GN and GO during years 2012–2014 in several campaigns during the growing season (May-August) and in GN additionally during one winter campaign in February 2015. There were five to six gas flux sampling points on each gradient. The sampling points were covering