Agriculture, Ecosystems and Environment 258 (2018) 91–103

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Changes in snow cover alter nitrogen cycling and gaseous emissions in agricultural soils

Lindsay D. Brin[a], Claudia Goyer[a,*], Bernie J. Zebarth[a], David L. Burton[b], Martin H. Chantigny[c]

[a] Fredericton Research and Development Centre, Agriculture and Agri-Food Canada, 850 Lincoln Road, Fredericton, NB, Canada
[b] Department of Environmental Sciences, Dalhousie University, Agricultural Campus, PO Box 550, Truro, NS, Canada
[c] Québec Research and Development Centre, Agriculture and Agri-Food Canada, 2560 Hochelaga Boulevard, Québec, QC, G1V 2J3, Canada

ARTICLE INFO

Keywords:
Nitrous oxide
Carbon dioxide
Snow cover
Climate change
Denitrification
Nitrification

ABSTRACT

Climate change-related increases in winter temperatures and precipitation, as predicted for eastern Canada, may alter snow cover, with consequences for soil temperature and moisture, nitrogen cycling, and greenhouse gas fluxes. To assess the effects of snow depth in a humid temperate agricultural ecosystem, we conducted a two-year field study with (1) snow removal, (2) passive snow accumulation (via snow fence), and (3) ambient snow treatments. We measured in situ N_2O and CO_2 fluxes and belowground soil gas concentration, and conducted denitrification and potential nitrification laboratory assays, from November through May. Snow manipulation significantly affected winter N_2O dynamics. In the first winter, spring thaw N_2O fluxes in snow removal plots were 31 and 48 times greater than from ambient snow and snow accumulation plots respectively. Mid-winter soil N_2O concentration was also highest in snow removal plots. These effects may have been due to increased substrate availability due to greater soil frost, along with moderate gas diffusivities facilitating N_2O production, in snow removal plots. In the second winter, spring thaw N_2O fluxes and soil N_2O concentration were greatest for ambient snow plots. Peak fluxes in ambient snow plots were 19 and 24 times greater than in snow accumulation and snow removal plots, respectively. Greater soil moisture in ambient snow plots overwinter could have facilitated denitrification both through decreased O_2 availability and increased disruption of soil aggregates during freeze-thaw cycles. Overall, results suggest that effects of changing snow cover on N cycling and N_2O fluxes were not solely a direct effect of snow depth; rather, effects were mediated by both soil water content and temperature. Furthermore, the fact that treatments with greatest mid-winter belowground N_2O accumulation also had greatest spring thaw N_2O fluxes in both years suggests the hypothesis that high spring thaw fluxes were due not only to spring soil conditions, but also to an effect of soil conditions in frozen soils that had facilitated N_2O production throughout winter.

1. Introduction

Humans have greatly increased fluxes to the atmosphere of the potent greenhouse gas nitrous oxide (N_2O), and approximately 66% of anthropogenic fluxes are due to agricultural activities (Davidson and Kanter, 2014). These fluxes continue in winter, even when soils are frozen (Dorland and Beauchamp, 1991; Teepe et al., 2001), with winter emissions making up 45–80% of annual emissions in agricultural systems (Röver et al., 1998; Teepe et al., 2000; van Bochove et al., 2000). Emissions are often greatest during freeze-thaw cycles and at spring thaw (Goodroad and Keeney, 1984; Cates and Keeney, 1987; Nyborg et al., 1997).

Climate-related increases in annual temperature and precipitation as predicted for eastern Canada and the northeast United States could greatly alter the amount, timing, and continuity of winter snow cover (Huntington et al., 2004; Hayhoe et al., 2006; Brooks et al., 2011). It is unclear whether changes in snow cover will increase or decrease greenhouse gas emissions throughout winter and during thaws. A meta-analysis of snow manipulation experiments found that the strength and direction of the effect of decreasing snow depth varied by latitude and climate: snow removal caused greater increases in spring N_2O flux at lower latitudes with greater annual precipitation and less variable soil temperatures (Blankinship and Hart, 2012). A few studies have employed snow removal experiments in agricultural fields. These studies found that winter N_2O production and spring thaw emissions often increased along with the greater soil frost and decreased soil O_2 in soils associated with snow removal (Maljanen et al., 2007, 2009, Yanai et al., 2011, 2014). However, whether fluxes were greater from snow removal

---

[*] Corresponding author.
E-mail address: claudia.goyer@agr.gc.ca (C. Goyer).

https://doi.org/10.1016/j.agee.2018.01.033
Received 25 July 2017; Received in revised form 22 January 2018; Accepted 28 January 2018
0167-8809/

plots than control plots depended on soil type (sand, mull, or peat) and the timing and extent of snow removal (Maljanen et al., 2009).

Winter soil processes and N_2O fluxes are directly affected by the timing and extent of precipitation, and establishment of a consistent seasonal snow cover (Jones, 1999; Wipf and Rixen, 2010; Brooks et al., 2011). Snow acts as an insulator, eventually decoupling soil temperatures from those of the air, and moderating the depth and extent of winter soil frost and the occurrence of freeze-thaw events (Sharratt et al., 1992). Soil frost, in turn, affects gaseous diffusion, the availability of water, and transport of substrates, and ice formation disrupts organic compounds and microbial cells, increasing available soil organic carbon (C) and nitrogen (N) (Christensen and Tiedje, 1990; Christensen and Christensen, 1991; Brooks et al., 2011). This could increase N_2O fluxes, particularly during subsequent thawing (Maljanen et al., 2007, 2009, Yanai et al., 2011, 2014). Snow depth also affects the infiltration of water into soil during mid-winter and spring thaws, and contributes to soil N availability through addition of inorganic N contained in the snow (van Bochove et al., 2000).

Denitrification, the anaerobic, microbially-mediated reduction of NO_3^- to N_2, has been demonstrated to be the main source of N_2O in laboratory and field experiments with frozen and thawing soils (Öquist et al., 2004; Mørkved et al., 2006; Wagner-Riddle et al., 2008). The rates and end products of denitrification (i.e., N_2O vs. N_2) are controlled by aspects of the soil environment that are affected by snow depth, such as soil temperature, moisture, and frost. Low temperatures may favor N_2O production due to low functioning of N_2O reductase at temperatures below ~5 °C (Sahrawat and Keeney, 1986; Holtan-Hartwig et al., 2002; Dörsch and Bakken, 2004), although the effect of low temperatures on N_2O production versus reduction has been shown to vary by soil source, presumably due to variation in microbial communities (Dörsch and Bakken, 2004). The restriction of gas diffusion by soil frost can directly promote denitrification by decreasing O_2 availability. However, restricted gas diffusion and low O_2 availability could also indirectly limit N_2O production, via two routes. First, evidence from unfrozen soils indicates that a lack of O_2 limits the production of NO_3^- by aerobic nitrification, suggesting that denitrification could become NO_3^--limited (Firestone et al., 1980). Second, N_2O is more likely to be reduced to N_2 when its diffusion out of the soil is limited (Sahrawat and Keeney, 1986; Davidson et al., 2000). Therefore, greatest production of N_2O may occur at moderate gas diffusivities (e.g. if frost layers are permeable or discontinuous, or at field capacity for thawed soils), when oxic zones and anoxic microsites exist, facilitating both denitrification and nitrification (Davidson et al., 2000). However, it is unclear how changes in soil temperature, frost, and moisture in response to altered snow depth will interact to affect N_2O production over winter and during thawing.

To assess the effects of snow depth on soil N cycling and gaseous emissions in humid temperate agricultural ecosystems, we conducted a two-year field study with snow removal, passive snow accumulation, and ambient snow treatments. We hypothesized that soil temperature and moisture, and frost intensity and duration, would differ between soil removal, ambient snow, or snow accumulation treatments, resulting in differences in the pattern and intensity of N_2O fluxes.

2. Materials and methods

2.1. Study site and experimental design

This study was conducted over two years at the Fredericton Research and Development Centre, Agriculture and Agri-Food Canada, Fredericton, New Brunswick, Canada. Fields were in a potato (*Solanum tuberosum*)-barley (*Hordeum vulgare*) rotation. In each winter, the study was conducted in a field following the harvest of the potato crop, so that any potential crop effects would be consistent. To achieve this, two different, adjacent plot areas were used in the two winters.

Fredericton, NB, has an average winter (November through April) temperature of −3.0 °C and receives an average of 215 cm snow per year, with winter monthly average snow depths from 1 to 17 cm (1981–2010, Fredericton CDA station, Environment Canada). However, variability in snow depth can be substantial; the greatest recorded snow depth at this station was 112 cm in March 1963. Soils at this site are Orthic Humo-Ferric Podzols according to the Canadian system of soil classification. Soil properties were determined in the surface soil (0–7.5 cm) from three samples of each treatment from each year's plot area. Soil pH was 6.0 and consistent across plot areas. Soil textures varied between the two adjacent plot areas. In the first year, soil texture was a loam with 45% sand and 12% clay, as determined by the pipette method. In the second year, soil had significantly greater sand and significantly lower silt and clay content; soil texture was a sandy loam with 68% sand and 6.6% clay. Total soil C and N, as determined by the dry combustion method, were significantly greater in the field used in the first year than in the second, but did not differ significantly by treatment. In the first year, soil N and C contents were $1.6 \pm 0.04\ \text{g kg}^{-1}$ N and $16.7 \pm 0.5\ \text{g kg}^{-1}$ C respectively, and in the second year, soils were $1.2 \pm 0.09\ \text{g kg}^{-1}$ N and $10.3 \pm 0.09\ \text{g kg}^{-1}$ C respectively.

Experimental manipulations consisted of snow removal, snow accumulation, and ambient snow treatments. Due to the logistics involved in removing or accumulating snow, a random block design could not be used, and replicate plots were located within larger treatment areas. In snow removal plots, snow was removed when it accumulated to greater than 10 cm depth. Removal typically occurred within 48 h after snow had ceased falling, but this time period was occasionally increased due to consecutive heavy snowstorms. Snow was removed with shovels, or with a snow blower when soils were frozen. A thin (1–4 cm) layer of snow was left to maintain albedo. In snow accumulation plots, snow was passively accumulated using a snow fence (Home Depot Model #3407). The snow fence was oriented perpendicular to the northeast, the predominant wind direction during snowfall. Replicate plots were located along the peak of the snow drift, in a line parallel to the snow fence, approximately 4 m downwind from the fence. Due to space constraints related to the length and orientation of the snow fence, three replicate plots were used for the snow addition treatment while four replicate plots were used for the snow removal and ambient treatments. Measurements of soil analytes, N cycling processes (denitrification and nitrification rates), and gas concentrations were done using three replicates per treatment, whereas gas fluxes were measured in three replicates plots in the snow accumulation treatment and four replicate plots in snow removal and ambient treatments.

All treatment areas and replicate plot sizes were decreased the second year due to space restrictions to avoid wetter parts of the field where potatoes had grown poorly the previous growing season. The sizes of full treatment areas were as follows: in winter 2013–2014, snow removal: 14 m × 44 m; snow addition: 30 m × 52 m; ambient snow: 20 m × 30 m; in winter 2014–2015, snow removal: 12 m × 25 m; snow addition: 30 m × 43 m; ambient snow: 14 m x 34 m. Replicate plots for gas flux measurements, located within each treatment area, were 4 m × 6 m the first year and 3 m × 6 m or 4 m × 4 m the second year. Replicate plots for soil sampling, also located within each treatment area, were a minimum of 6 m × 7 m the first year and 4 m × 4 m the second year.

2.2. Environmental measurements

Snow depth was measured manually with a meter stick at each gas flux collar on each gas sampling date in both winters. In the second winter, snow depth was also measured at hourly intervals using a snow sensor (SR50AT with CR200X data logger, Campbell Scientific) installed in each of the three treatment plots.

Soil temperature and volumetric (liquid) water content were monitored at one hour intervals at 5 cm depth from November through May using one Decagon EM50 data logger equipped with 5TE sensors in