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Soil organic carbon depletion and degradation in surface soil after long-term non-growing season warming in High Arctic Svalbard

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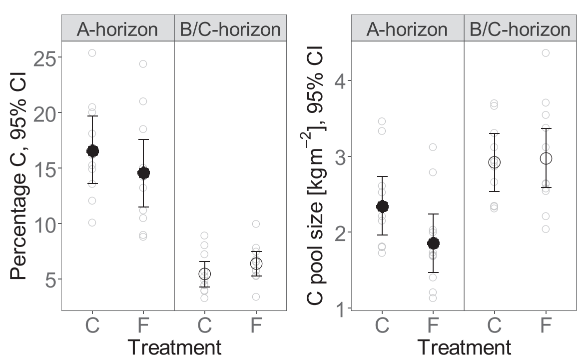
HIGHLIGHTS

- Soil was warmed in situ for nine consecutive non-growing seasons (NGS) in Svalbard.
- NGS warming depleted soil organic carbon (SOC) pool of the soil's shallow A-horizon.
- NGS warming transitioned the A-horizon SOC to an advanced state of decomposition.
- The underlying B/C-horizon's SOC pool and state was not affected.
- NGS warming mineralizes more C in shallow than in deep soil.

GRAPHICAL ABSTRACT



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ABSTRACT

Arctic tundra active-layer soils are at risk of soil organic carbon (SOC) depletion and degradation upon global climate warming because they are in a stage of relatively early decomposition. Non-growing season (NGS) warming is particularly pronounced, and observed increases of CO_2 emissions during experimentally warmed NGSs give concern for great SOC losses to the atmosphere. Here, we used snow fences in Arctic Spitsbergen dwarf shrub tundra to simulate 1.86 °C NGS warming for 9 consecutive years, while growing season temperatures remained unchanged. In the snow fence treatment, the 4-11 cm thick A-horizon had a 2% lower SOC concentration and a 0.48 kg C m^{-2} smaller pool size than the controls, indicating SOC pool depletion. The snow fence treatment's A-horizon's alkyl/O-alkyl ratio was also significantly increased, indicating an advance of SOC degradation. The underlying 5 cm of B/C-horizon did not show these effects. Our results support the hypothesis that SOC depletion and degradation are connected to the long-term transience of observed ecosystem respiration (ER) increases upon soil warming. We suggest that the bulk of warming induced ER increases may originate from surface and not deep active layer or permafrost horizons. The observed losses of SOC might be significant for the ecosystem in question, but are in magnitude comparatively small relative to anthropogenic greenhouse gas enrichment of the atmosphere. We conclude that a positive feedback of carbon losses from surface soils of Arctic dwarf shrub tundra to anthropogenic forcing will be minor, but not negligible.

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1. Introduction

Temperature is one of the main limiting factors for decomposition in Arctic soils (Wallenstein et al., 2009), leading to vast soil organic carbon (SOC) pools exceeding Earth's atmosphere's C stock (Hugelius et al., 2014; Tarnocai et al., 2009). In the face of climate warming, temperature limitations on decomposition processes might be alleviated, putting the biologically degradable part of this SOC pool at risk of being released to the atmosphere (Kleber, 2010; Schmidt et al., 2011). In Arctic regions, climate warming is especially pronounced during the non-growing season (NGS) (Stocker et al., 2014). As the NGS is the predominant part of the year, changes in its climate can have a disproportionally large effect on decomposition processes: relatively low decomposer activities at low temperatures can be offset by the long duration of the NGS and lead to long-term SOC loss. Soil organic C in the Arctic dwarf shrub tundra's active layer consists of a large proportion of readily decomposable compounds (Pautler et al., 2010; Pedersen et al., 2011; Sjögersten et al., 2003), and here we test if long-term in situ NGS warming could not only have an effect on its SOC pool size, but also on its bulk chemical composition.

Soils from cold dominated ecosystems appear to be in early stages of decomposition and at risk for rapid SOC loss with increasing temperature. Warming may specifically accelerate the degradation of readily decomposable compounds and thereby progress its decomposition stage. As an indicator for the relative degree of a given soil's SOC decomposition stage, the alkyl/O-alkyl ratio has been used (Feng and Simpson, 2008; Pautler et al., 2010; Pedersen et al., 2011; Simpson et al., 2008; Sjögersten et al., 2003). For instance, Sjögersten et al. (2003) observed higher alkyl/O-alkyl ratios in more decomposed forest soils as compared to soils in less decomposed stages from nearby tundra soils in northern Scandinavia for which they attributed to higher decomposer activities in forest soils due to higher soil temperatures in the more sheltered microclimate. Further, an extreme-event induced active layer detachment in northern Canada where sub-surface active layer soil was exposed to air temperatures via soil movements after extensive rain-fall accelerated SOC decomposition and increased its alkyl/O-alkyl ratio (Pautler et al., 2010). Similar effects can be expected in response to NGS warming through climate change of Arctic dwarf shrub tundra ecosystems.

The effects of warming on SOC pool depletion and its alkyl/O-alkyl ratio can be expected to be strongest in surface soil horizons of the active layer for several reasons. Arctic and alpine surface soils are reported to be richer in O-alkyl carbon (C) than deeper soil horizons, i.e. the alkyl/O-alkyl ratio increases with depth, indicating that the stage of decomposition advances with depth, an effect already visible in the upper few cm of soil profiles (Pedersen et al., 2011; Sjögersten et al., 2003). Further, environmental controls in deeper horizons may stabilize otherwise chemically readily decomposable compounds from microbial decomposition by e.g. sorption to the mineral phase (Kawahigashi et al., 2006; Kleber, 2010; Schmidt et al., 2011; Trumbore, 2009), which becomes more prominent in deeper horizons with a higher mineral proportion. Hence, total loss of SOC in deeper horizons upon warming could be lower than in surface near horizons. Increases in ecosystem respiration (ER) by experimental NGS warming in the Arctic (Björkman et al., 2010; Morgner et al., 2010; Nobrega and Grogan, 2007; Schimel et al., 2004; Semenchuk et al., 2016a; Webb et al., 2016) may thus be primarily (but not exclusively) driven by degradation and depletion of SOC substrates from surface rather than deep soil or thawed permafrost (cf. Schuur et al., 2009; Natali et al., 2014). This is supported by recent studies finding significantly higher soil CO_2 fluxes and stronger responses to warming in surface horizons up to 10 cm depth than in deeper soil horizons (Hicks Pries et al., 2017; Lee et al., 2010).

In the Arctic, significant ER increases have been shown to respond directly to in situ NGS warming in a variety of tundra ecosystems (Björkman et al., 2010; Morgner et al., 2010; Natali et al., 2014; Nobrega and Grogan, 2007; Schimel et al., 2004; Semenchuk et al., 2016a; Webb et al., 2016). Semenchuk et al. (2016a) demonstrated that these effects were followed by decreased growing season ER after eight years of NGS warming in Svalbard dwarf shrub tundra. Similarly, ER responses to experimental continuous in situ soil warming are shown to be transient and decrease after a few years of continuous warming in a mid-latitude forest site (Melillo et al., 2002, 2017). One explanation for these effects suggests that soil warming accelerates decomposition processes and alters SOC pool size and composition; soil OC is transformed from a relatively early stage to a later stage of decomposition, and thus provides a less favourable substrate for respiring decomposing organisms (Kirschbaum, 2004; Eliasson et al., 2005; Bradford et al., 2008). Here, we use the opportunity to collect soil and verify that hypothesis within the experiment used by Semenchuk et al. (2016a).

We test whether nine years of continuous in situ NGS warming (average 2° warming within a snow manipulation treatment) of relatively C poor (3–25% C) High Arctic dwarf shrub tundra surface soil (16 cm depth) (i) reduced SOC pool size and (ii) changed the SOC chemical composition towards a more advanced decomposition stage in a snow fence experiment in Adventdalen, Svalbard. In the same experiment, Semenchuk et al. (2016a) found that 8 years of continuous NGS warming and connected increased ER during the NGS lead to decreased growing season ER and suggested that changes in SOC pool size and composition could account for this. Based on these results, we test the following:

1.1. Hypotheses

(1) Carbon content is depleted in NGS warmed surface soils, i.e. long-term increased NGS ER decreased the C pool.
(2) Carbon compound composition is altered in NGS warmed soils. More specifically, we expect the alkyl/O-alkyl ratio to be higher in NGS warmed soils, i.e. that the relative degree of SOC decomposition is advanced.
(3) The effects from Hypotheses 1 and 2 are larger in the A-horizon than in the top 5 cm of the underlying, C poorer and mineral richer B/C-horizon, i.e. the combination of environmental conditions and initial SOC composition in the B/C-horizon render the bulk SOC there more resistant to warming.

2. Material and methods

2.1. Site description (location, soil, vegetation, climate, seasonality)

The study site is on the southern (left) riverbank in Adventdalen, a large valley about 12 km east of Longyearbyen on Spitsbergen, Svalbard (78°10′N, 16°04′E) with continuous permafrost with an active layer thickness/maximum thaw depth of about 75 to 90 cm at the study site (own data, Fig. S2). The cryoturbated gelisol soils at the study site (Semenchuk et al., 2016a) are dominated by fluvial and aeolian sedimentation and consist of a relatively thin and C poor, dark brown A-horizon of about 2–11 cm thickness with about 15–25% C content and an underlying, grey, silty B/C-horizon with about 3–9% C content, which extends to the permafrost table (see Strebel et al., 2010 and own data below).

Situated in the bioclimatic subzone C, the vegetation type is classified as Prostrate/hemiprostrate dwarf-shrub tundra (CAVM Team, 2003), dominated by the dwarf shrubs *Cassiope tetragona*, *Dryas octopetala* and *Salix polaris*.

Average air temperature 2000 to 2011 at Longyearbyen airport, about 20 km west of the study site, during the approximate NGS months October to April were −9 °C and during the approximate growing season months 3.4 °C (www.eklima.no). Average snow depth in the control area was about 40 cm (own data, Fig. S1).