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TOPSOIL AND SNOW: A CONTINUUM SYSTEM

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Abstract

Snow cover plays a fundamental role in terrestrial ecosystems, because it influences the Earth's climate, water quantity and quality, global biogeochemical cycles and soil properties. In particular, snow helps to create and maintain a specific pedo-environment through its influence on pedogenesis and topsoil characteristics, such as the thermal and water regimes and soil biogeochemistry. Importantly, seasonally snow covered regions are particularly susceptible to climate change, which could alter the timing and the quality of snow cover, with consequences on ecosystems and pedo-environments.

Keywords: soil temperature; carbon; nitrogen; ski runs; snow gliding.

1. Introduction

Seasonal snow cover and soil frost affect about 60% of the terrestrial earth surface, ranging from high latitude tundra and forest biomes to mid-latitude forests and grasslands biomes, and includes many mountain regions (Zhang et al. 2004; Brooks et al. 2011). Seasonal snow cover is an important part of Earth's climate system, and in fact helps regulate the temperature of the Earth's surface because of its high albedo. The insulating properties of snow influence the underlying soil temperature regime and the extent to which soil is directly exposed to freezing and thawing episodes (Edwards et al., 2007). In forest and tundra greater snow depth insulates soils from cold air temperatures and allows higher levels of microbial nitrogen immobilization under snow, as well as decreases soil N_2O efflux (Li et al. 2016), while shallower snowpacks are associated with higher hydrologic nitrogen export (Brooks et al., 2011). Both CO_2 and CH_4 flux studies during winter demonstrate active carbon (C) cycling under seasonal snowpacks in different ecosystems (Brooks et al., 2011). Snow also accumulates significant amounts of particulates and solutes due to atmospheric deposition, which can be rapidly released during spring melt in the form of an ionic pulse (Filippa et al., 2010). Therefore, the seasonal snowpack has the potential to exert a significant impact not only on terrestrial but also on aquatic ecosystems (Edwards et al., 2007; Williams et al., 2009). Brooks and Williams (1999) reported that more than half of the annual inorganic nitrogen (N) deposition can be stored in the snowpack and released during snowmelt episodes. Nitrogen is flushed through the snowpack at the beginning of snowmelt and, in combination with that released from soil mineralization, results in a pulse of inorganic N under the snowpack (Edwards et al., 2007). The soil may function either as a source or sink of nutrients depending on the species involved and the extent to which snowmelt infiltrates (Brooks and Williams, 1999).

The seasonally snow covered regions are particularly susceptible to climate change, because small changes in temperature or precipitation may result in large changes in the amount and timing of snow cover (Brooks et al. 2011). Climate change may affect the seasonal snow cover in several ways: higher temperatures result in a higher percentage of the precipitation falling as rain instead of snow, causing snow covers to be thinner and to melt earlier, a phenomenon already visible in many mountain ranges (e.g. Laternser and Schneebeli, 2003; Viglietti et al., 2014). Snow density is likely to increase in a warmer climate, as higher temperatures may cause wetter snow and increase the frequency of wet-snow avalanches which exert considerably erosive forces on soils (e.g. Rasmus et al., 2004; Ceaglio et al., 2012). Interestingly, a warmer climate will not necessarily result in warmer soils: a thinner and denser snow cover will reduce the insulation of the soil (Rixen et al., 2008a). Consequently, alpine ecosystems might face the counterintuitive situation that soils could become colder in winter in a warmer climate (Groffman et al., 2001). Give that soil and snow are obviously connected, they could be considered a continuous system, therefore an interdisciplinary approach is required, with competences from snow and soil scientists (Guymon G.L., 1978).

2. Snow cover and subnivean soil properties

2.1. Soil temperature and microbial activity

Snow is an excellent thermal insulator and consistent seasonal snow cover effectively decouples soil temperature from the air temperature (Edwards and Cresser, 1992) (Fig. 1). Soils typically experience freezing conditions during early winter, sometimes before a deep snow cover accumulates to protect the soils from low air temperatures, remaining in a partially unfrozen condition (+1 to −3°C) (Jones, 1999): biological activity is surprisingly high at temperatures approaching subzero, which are typical of these subnivean conditions (Federer et al. 1990; Mikan et al., 2002; Panikov et al., 2006). The presence of liquid water has been identified as an essential prerequisite for physiological activity of microbes in any environment, including soils at near or subzero temperatures (Coxson and Parkinson, 1987; Mikan et al., 2002). In addition microbial activity is strongly affected by the supply of labile organic carbon (Boddy et al., 2008; Brooks et al., 2005; Buckeridge and Grogan 2008) which during winter could be influenced by the effects of snow depth and soil thermal status on litter decomposition rates (Hobbie and Chapin, 1996; Sulkava and Huhta, 2003).

2.2. Snowmelt and soil nutrient cycling

The mountain snowpack represents an important source of nutrients and water for soils, because it can accumulate significant amounts of wet and dry atmospheric deposition which may be held in storage until release during a melt period

(Filippa et al., 2010). In high-elevation areas, more than half of the year's N deposition is periodically stored in the snowpack (Hiltbrunner et al., 2005). Filippa et al. (2010) reported that in the NW Italian Alps dissolved inorganic N (ammonium and nitrate) stored in snow was comparable to concentrations found in other sites of the Alps, and corresponding to about 2–6% of the over-winter N mineralization in alpine soils. The melting of the snow cover defines the start and length of the growing season, and water and nutrients released from the snowpack influence soil moisture and nutrient status until later in the summer. Field and laboratory experiments have demonstrated that initial stages of snowmelt often have ionic concentrations many times higher than averages for the whole snowpack, referred to as an ionic pulse (Johannessen and Henriksen, 1978). Therefore, during snowmelt soluble inorganic N compounds and other N sources such as dust particles, are released into the soil in a relatively short time period, favouring the plant species which take up nutrients during snowmelt (Bilbrough and Welker 2000; Hiltbrunner et al., 2005).

2.3. Soil gas fluxes

The interaction between snow cover and soil is also important for gaseous emission, because there is evidence that microbial activity and consequent emission of gaseous C and N continue in the relatively warm conditions that may occur in soils under a continuous snowpack (Sommerfeld et al. 1993; Brooks et al. 1996;). For example, Filippa et al. (2009) at Niwot Ridge, Colorado, found that during winter, the relatively well-developed soils together with prolonged deep snow cover, result in subnivean N_2O production that might account for between 19 and 28% of the annual flux. In summer N_2O fluxes followed a decreasing trend during the dry-out period after snowmelt, interrupted by higher values related to precipitation events which were identified as the main factors controlling N_2O flux. Both CO_2 and CH_4 flux studies during winter demonstrate active carbon cycling under seasonal snowpacks in different ecosystems, with a high sensitivity of fluxes to small changes in seasonal snow cover (Brooks et al., 2011).

3. Snow distribution, pedogenesis and soil properties

Wind redistribution of snow involves erosion of snow cover by the shear force of the wind, transport of blowing snow in transit, and deposition of snow to sites with higher aerodynamic roughness or less exposure to wind. In open environments, vegetation and terrain features can produce dramatic variations in snow accumulation by trapping wind-transported snow (Jones et al. 2001). The topographically defined snowpack distribution produces a spatial gradient in soil water availability, soil temperature and in the timing of soil dry-down following snowmelt (Taylor and Seastedt, 1994). The spatial variation of snow accumulation affects litter decomposition rates (O'Lear and Seastedt 1994), plant communities distribution (Fisk et al. 1998) and productivity (Walker et al. 1994), and organic matter accumulation (Burns and Tonkin 1982).

Freppaz et al. (2012) reported that after 16 years of snow distribution manipulation at Niwot Ridge (Colorado) under moderate snow cover the total soil organic carbon (TOC) and total nitrogen (TN) were significantly greater than either under deep or shallow snow cover. Depth and duration of the snow cover as well as vegetation influence site factors such as soil moisture and soil temperature that are important to soil-forming processes (Holtmeier and Broll, 1992) (Fig. 2). Studies conducted by Holtmeier and Broll (1992) provide evidence for distinct differences in pedogenesis and soil properties due to microtopography and scattered tree islands, because their influence on windflow near the soil surface, which in turn affects the distribution pattern of the winter snow cover. Schaetzl (1990) found a different degree of soil development under pit and mound originated by tree uprooting. Pit exhibits a stronger pedogenesis than undisturbed and mound soils explained by: a) the greater water content, which may facilitate weathering processes; b) thicker O horizons, which may lead to increased production of organic acids; c) greater insulation by thick litter and snow cover, which reduces the incidence of soil freezing. In addition, as reported by Pintaldi et al. (2016), differences in snow cover distribution due to hummock microtopography could also contribute to create specific pedoclimatic conditions, enhancing selective plant species distribution, variations on topsoil properties and different soil development under hummocks and interhummocks.

4. Seasonally snow-covered soils under a changing climate

Increased air temperature due to climate change likely will result in shorter snow covered seasons due to later accumulation and earlier melt (Brooks et al. 2011), with a general decrease in the spatial extent of spring snow cover in the Northern Hemisphere (IPCC 2014), readily observable in an increase in elevation of the rain–snow line (Lundquist et al. 2008). The reduction in snow cover, as well as its variations in density and thickness (Rixen et al. 2008a), reduces the degree of insulation and results in cold soil temperatures, extensive soil freezing and an increase in freeze/thaw cycles (Edwards and Cresser, 1992; Groffman et al., 1999) (Tab. 1). Several researchers reported the effects of freeze/thaw cycles on soil processes such as an increase in fine root mortality (Tierney et al., 2001), a change in soil structure (Kværnø and Øygarden, 2006), an influence on microbial activity (Grogan et al., 2004) and nutrient loss (Matzner and Borken, 2008). Freppaz et al. (2008) (LTER site Mont Mars) reported how a reduction in snowpack depth caused a significant increase in soil net ammonification and net nitrification but did not affect microbial biomass N, revealing how soil freezing could enhance soil-aggregate disruption, releasing physically protected soil organic matter and fragmentation of organic matter itself (Tab. 1). Freeze-thaw events are known to release labile, readily utilizable, organic carbon compounds. The effects of this increase in carbon substrate have been observed in the field when fluxes of CO_2 from seasonal snowpacks increased exponentially following a severe, early winter freeze before the development of a consistent snowpack (e.g. LTER site Niwot Ridge) (Brooks et al., 1997).

5. Snow movements and soil properties

Mountain areas are widely affected by soil erosion, which is generally linked to water runoff processes (Ceaglio et al. 2012). However, snowmelt runoff and snow movement related processes may also be important factors that can enhance soil erosion (Konz et al., 2009; Ceaglio et al. 2012). The snow movements which effect soils are mainly snow gliding and full-depth snow avalanches (Ceaglio et al. 2012). Additionally, the snowmelt period can contribute significantly to the total annual runoff and sediment yield in streams and rivers. (Lana-Renault et al., 2011). These phenomena can exert considerable erosive forces on soils; in particular avalanches can transport consistent amounts of debris, especially when they involve the whole depth of snow or run onto snow-free areas (Freppaz et al., 2006, 2010; Confortola et al., 2011). Deposits of debris from snow avalanches are common in mountain environments indicating the importance of avalanches as specific geomorphic agents (Fig. 2). For example, Ceaglio et al., (2012), in the Aosta Valley of Italy, reported snow related soil deposition rates of 161.0 ± 34.8 $Mg ha^{-1}$ for a single snow avalanche event, with a soil erosion rate of 20.8 ± 4.5 $Mg ha^{-1}$ $event^{-1}$, corresponding to a soil layer of 1.73 ± 0.37 mm.

Soils can be eroded in different ways, depending on the avalanche type (Confortola et al., 2011). If full-depth avalanches predominate, and the avalanche flows interact directly with the soil surface, the soils can be stripped off in the track zone and can be fragmented and/or highly degraded (Freppaz et al., 2006, 2010) (Fig. 3). Complex soil profile morphologies may occur along an avalanche path, with both buried or truncated horizons (King and Brewster, 1978; Stanchi et al., 2014). If surface avalanches predominate, then soils in the transition zone are better preserved and the avalanche channels can be completely grass-covered (Bozhinskiy and Losev, 1998). Also snow gliding phenomena can contribute significantly to soil erosion at the snow–soil interface as shown by Meusburger et al. (2014), who identified snow gliding as a relevant driver for winter soil erosion in the Swiss Alps. Changes in snow distribution due to snow avalanches help shape plant and animal distribution, particularly in the deposition zone where the deeper snow represents a non-flowing water storage during the winter, with specific chemical properties, which is released when the temperature increases during the summer growing season (Luckman, 1977; Freppaz et al., 2010).

6. Snow and soil characteristics in ski runs

In the last decades in mountain regions the surface area converted to recreational activities has increased due to the increasing demand of tourists for winter sports. To guarantee skiing despite unfavourable weather conditions, snowmaking facilities have been installed in many ski resorts (Rixen et al. 2008a). To enhance ice crystal formation under warmer temperatures, additives to enhance ice nucleation are increasingly used in snowmaking (Rixen et al., 2003). Therefore, ski-run construction and management have a great influence on the chemical and physical properties of underlying soils. For example, as reported by Rixen and Freppaz (2015), the average amounts of nutrient salts and ions in the melting water is, on average, eight times higher on pistes with artificial snow. In addition, as well as additives, the water used for artificial snow, such as calcium-rich water from down-elevation rivers, may have long term consequences on soil and vegetation (Rixen et al., 2008b; Wipf et al., 2005). Freppaz et al. (2013) reported that soils in ski-runs have an almost complete lack of structure, with subsequent problems of soil compaction and reduction of water and air permeability, which enhances erosion on ski-runs. Snow plays an important role on ski-run soil processes, because groomed snow is denser and thin compared to natural snow. These characteristics may result in reduced insulation capacity of the snowpack and thus, the underlying ground may become much colder with subsequent effects on soil nutrient dynamics and plant development (Freppaz et al. 2013). The soils of ski runs are thus subjected to more intense freezing, higher CO_2 fluxes, and changes in pH and nitrogen fixation (Freppaz et al. 2013). Rixen et al. (2008a) found that a denser and thinner snow cover reduced soil insulation and lowered soil temperatures, with a consequent increase in net N mineralization (Tab. 1). Furthermore, a denser snow cover resulted in a delay in plant phenology of up to five weeks after melt-out., therefore changes in snow properties linked to ski run management, can cause significant changes in soil and vegetation processes (Rixen et al. 2008a).

7. Conclusion

Given the high number of studies, the effects of snow cover on mountain ecosystems in general, and in particular on soil biogeochemistry is remarkable, especially in the perspective of climate change. This contribution revealed how in mountain areas soil and snow should be considered a continuum, because of a strong and effective mutual interaction, which is primarily reflected in the topsoil properties.

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Figure Captions

Fig. 1. Mean daily topsoil temperature (10 cm depth, °C) at site 1 (snowbed site, 2840 m a.s.l.) and site 3 (windblown snow site, 2770 m a.s.l.) registered from Fall 2008 to Summer 2016 at the LTER site Istituto Mosso (Piemonte Region, NW-Italian Alps).

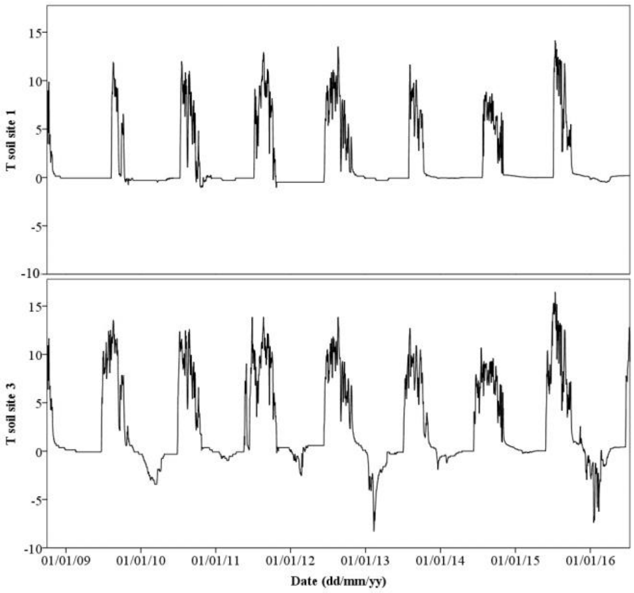

Fig. 2. A podzol under a thick snow cover in the LTER site Mont Mars (1840 m a.s.l., Valle d'Aosta Region, NW-Italian Alps) (Photo M. Freppaz).

Fig. 3. A Topsoil deposited in the run-out area of a glide-snow avalanche (Valle d'Aosta Region, NW-Italian Alps)

(Photo M. Freppaz).

Country/Bioma	Elevation (m a.s.l.)	Topsoil C and N in the study area (ranges)	> snow depth	< snow depth	> snow density	Authors
Lys Valley (Aosta Valley-Italy)/Subalpine-Alpine forest-meadow	1450	TOC (g Kg^{-1}) 12-39 TN (g Kg^{-1}) 0. 5-3.1 DOC (mg Kg^{-1}) 207.0-289.0 DON (mg Kg^{-1}) 115.0-138.5	> T soil Net ammonification ↓ Net nitrification ↓	< T soil Net ammonification ↑ Net nitrification ↑		Freppaz et al. 2008
Niwot Ridge LTER site (Colorado-USA)/ Alpine tundra	3528	TOC (g Kg^{-1}): 120-130 TN (g Kg^{-1}): 8.0-9.0	TOC (g kg^{-1}): ~ 90-100 TN (g Kg^{-1}): ~ 8 pH: ~ 5.4 DOC (mg Kg^{-1}): ~ 170 DON (mg Kg^{-1}): ~13	TOC (g Kg^{-1}): < 90 TN (g Kg^{-1}): ~ 6 pH: ~ 5.6 DOC (mg Kg^{-1}): ~ 178 DON (mg Kg^{-1}): ~19		Freppaz et al. 2012
Bipenggou Nature Reserve of Lixian County (Sichuan-China)/ Alpine forest	3580	DOC (mg Kg^{-1}): 240-250 DON (mg Kg^{-1}): 50-55	DOC (mg Kg^{-1}): ~ 250 DON (mg Kg^{-1}): < 50	DOC (mg Kg^{-1}): ~ 550 DON (mg Kg^{-1}): ~ 100		Tan et al. 2014
Western Alps (Piedmont-Italy)/Subalpine forest	2030	TOC (g Kg^{-1}): 59.3 TN (g Kg^{-1}): 4.2 DOC (mg Kg^{-1}): 250-331 DON (mg Kg^{-1}): 9.2- 14.2	T soil: > 0° C DOC (mg Kg^{-1}): < 400 DON (mg Kg^{-1}): < 40	T soil: < 0° C DOC (mg Kg^{-1}): > 400 DON (mg Kg^{-1}):> 40		Viglietti et al. 2014
Rhaetian Alps, (Davos-Switzerland)/Subalpine meadow	1530				T soil: < 0° C > Net ammonification > Net N mineralization	Rixen et al. 2008a

Table 1.Examples of changes in topsoil C and N forms and temperature (Tsoil during winter) in different biomes due to changes in snow characteristics (increase in snow depth: > snow depth; decrease in snow depth: < snow depth; increase in snow density: > snow density).