Soil Freezing Dynamics in a Changing Climate: Implications for Agriculture

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Introduction

Soil freezing can directly damage the overwintering shoots and root systems of winter cereals, perennial crops and pasture and turfgrasses, increasing mortality, and decreasing yield (Ouellet 1976; Fowler 2008). However, it can also have numerous indirect effects on crop yield via changes in abiotic factors such as soil moisture (Iwata et al. 2010), nutrients (Elliott and Henry 2009), bulk density, and aggregates (Oztas and Fayetorbay 2003) or biotic factors such as weeds, insects, microfauna, or microbes (Fig. 1). These indirect effects can either be positive for crops, as in the cases of decreased soil bulk density or damage to weeds and insect pests, or negative, as in the cases of damage to beneficial microorganisms or losses of soil nutrients. In addition, organisms can benefit from a given intensity of freezing yet suffer from another; for example, although insect pests can be killed by extreme soil freezing, they can also benefit from reduced energy expenditure at mild-to-moderate freezing relative to overwintering at above-freezing temperatures (Irwin and Lee 2003).

Overall, the biological effects of soil freezing on crops are a function not only of freezing intensity, but of soil freezing frequency, timing, rate, and depth (Henry 2007), which depend largely on air temperature and solar radiation. Precipitation can also play a large role by affecting snow cover, soil moisture and cloud cover, and live plant and litter cover can modulate the effects of air temperature and solar radiation on soil freezing (Fig. 2). In soil, the freezing point is an important threshold because it represents a shift in liquid water availability, with plants often becoming inactive and microbial activity decreasing sharply (Schimel and Mikan 2005; Fig. 3a). However, winter cereals and pasture grasses grown in cold regions can typically endure temperatures much lower than 0 °C before succumbing to lethal cold (Malyshev and Henry 2012), and thin water films remain around soil particles

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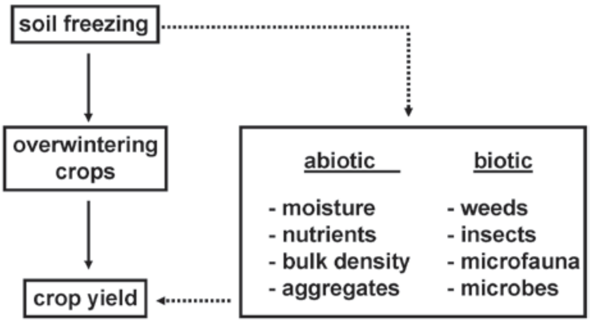

Fig. 1 Summary of direct (*solid lines*) and indirect (*dotted lines*) effects of soil freezing on crop yield

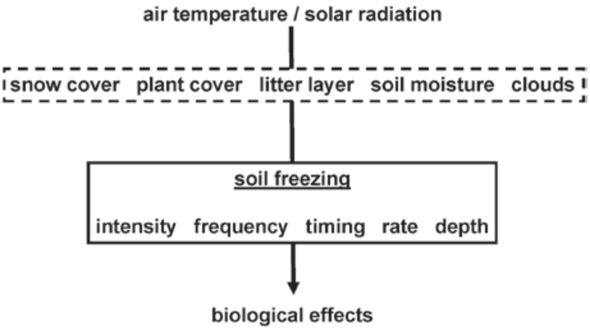

Fig. 2 Summary of factors modulating the effects of air temperature and solar radiation on solar freezing, and the facets of soil freezing that ultimately determine biological effects

below 0 °C, allowing microbial activity to continue until lethal temperatures are reached. Nevertheless, in between 0 °C and the threshold of lethal cold (Fig. 3b) sublethal damage to plants can occur. The dynamics of soil freezing (Fig. 3c) can also be important for determining biological effects. For example, in Fig. 3, panels (a) and (c) exhibit the same mean temperature, yet in (c) soil organisms are exposed to repeated cycles of freezing and thawing, which can be destructive to cells.

The objectives of this synthesis are to (1) summarize the observed and predicted responses of soil freezing dynamics to climate change, (2) assess the potential effects of climate change on freezing severity, and (3) explore options for the management of snow and plant cover to modulate the effects of climate on soil freezing. As a starting point, I briefly discuss the findings of Henry (2008), where soil freezing responses to variation in winter temperature and precipitation were examined for a large range of sites across Canada. I then examine the extent to which the findings of this chapter can be generalized and extrapolated more broadly to other regions. I draw from examples from the forestry and ecology literature in addition to the agriculture literature, based on the expectation that soil freezing across all of these systems is governed by some common principles, despite potential differences in ground cover.

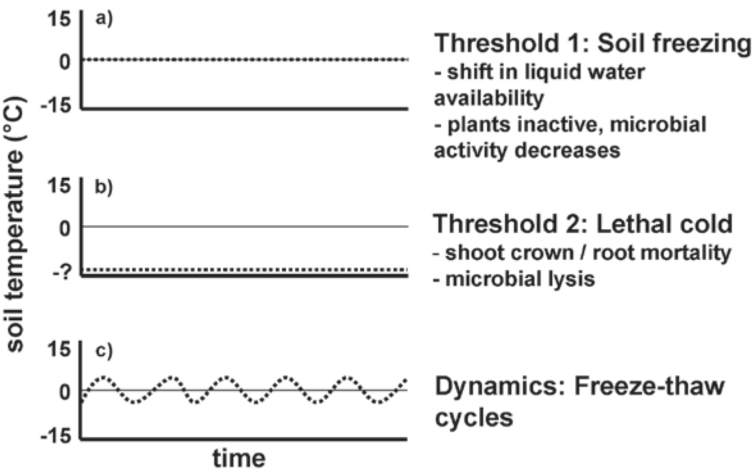

Fig. 3 Important thresholds and dynamics of soil freezing

Freeze-Thaw Cycles (FTC) in Air Versus Soil

In the late fall and early spring, when snow cover is absent or intermittent, soil temperatures often track air temperatures, exhibiting diel FTC; however, soil temperatures can be decoupled substantially from air temperatures over winter when snow cover is present (Sharratt et al. 1992). Therefore, the months of the year that feature the coldest air temperatures often feature relatively mild and stable soil temperatures. Warmer and more variable air temperatures over winter could reduce snow cover and expose soil to cold air overnight or during cold spells, leading to the prediction that in some regions we may observe "colder soils in a warmer world" (Groffman et al. 2001). It is anticipated that increased soil freezing may intensify microbial cell lysis and root mortality, increasing soil hydrological and gaseous fluxes of nitrogen in the spring (Henry 2007). Although there is some ambiguity as to whether it is the freeze or the thaw that is most stressful for soil organisms (Jefferies et al. 2010), or whether increased soluble nitrogen availability over winter results from increased mineralization, FTC can indeed increase soluble nitrogen concentrations in soil (Elliott and Henry 2009).

Frequency of Soil Freeze-Thaw in Canadian Soils

Henry (2008) examined historical weather and soil temperature data for 31 sites in Canada to explore whether there was indeed a relationship between warmer (or drier) winters and increased soil FTC. The sites in the study ranged from arctic to temperate regions, and the weather records spanned up to 40 years. Data were collected from well-kept grass turf on a level surface remote from trees or buildings, and a soil depth of 5 cm was chosen based on the assumption that it best represents the core depth of rooting and soil biological activity.

As predicted, the number of days with snow on the ground decreased in both warm and dry winters, and the effect of warming on snow cover was particularly strong in the warmest sites. The latter trend was explained by the location of the warmest sites along a snow ecotone (i.e., the transition zone between sites that experience much snow over winter and those that experience very little), where the snow pack often melts multiple times in response to warm spells over winter. A decreasing number of days of frozen soil in warm winters was also observed, indicating that soils will not remain frozen as long in a colder world, a result consistent with those of Jylha et al. (2008), based on climate model projections for Europe. However, as predicted, the number of FTC experienced per winter increased in both warm and dry winters. Projected temperature and precipitation increases were then applied to the regression equations derived from the historical data. With respect to days of frozen soil, the northern temperate sites were predicted to experience the greatest changes, despite projected warming being mild at these latitudes relative to arctic regions. Among all sites, more than 80 % were projected to experience an increased frequency of soil FTC with climate warming.

Regional Patterns in the Frequency of Soil FTC

Kreyling and Henry (2011) conducted a follow-up study of 177 soil stations in Germany, and surprisingly, an opposite trend of a decreasing number of FTC with warming was observed for recent decades. However, many of these sites experienced warmer winters than the warmest Canadian sites, such that the German data were an extrapolation of the Canadian data to warmer sites, rather than a contradiction. A number of these German sites are expected to experience vanishing winters, where snow cover and soil freezing will become mostly absent. Beyond these two studies, the question arises as to whether this trend of increased FTC in cold temperate regions (e.g., Canada) and decreased FTC in warmer temperate regions (e.g., Germany) with climate warming can be generalized. The answer appears to be yes, with Decker et al. (2003), Mellander et al. (2007), Campbell et al. (2010), and Fortin (2010), all conducted in relatively cold regions, showing a trend of increased FTC with warming (Table 1). Sinha and Cherkauer (2008) observed a similar trend for the northernmost sites in their study, but similar to Kreyling and Henry (2011), they observed a decreased frequency of FTC with warming in their southernmost sites. With respect to precipitation, Isard and Schaetzl (1998) observed a similar trend as Henry (2008), with an increased number of FTC in dry years.

Decker (2003) observed an increased frequency of FTC in warm years, but commented that many of these FTC occurred under the snow and were of a very small amplitude. This observation raises the question of whether changes in the number

Table 1 Regional summary of changes in freeze-thaw cycle frequency, severity and depth in response to warming (or changes in precipitation, shown in parentheses)

Reference	Location	Latitude and longitude	Sites	Cover	Freeze-thaw cycle		
					Frequency	Severity	Depth
Isard and Schaetzl (1998)	Michigan, USA	43.7, −85.5	10	Forest	↑ (Dry)		↑
Venalainen et al. (2001)	Finland	60.2–68.6, 25.0–27.4	13	Bare soil			↓
Decker et al. (2003)	Vermont, USA	44.5, −72.5	1	Forest	↑	↑	
Hirota et al. (2006)	Hokkaido, Japan	42.8 N, 143.0	11	Agricultural			↓Wet
Isard et al. (2007)	Michigan, USA	43.8–45.3, −83.7 to −86.4	39	Forest		↑	
Mellander et al. (2007)	Northern Sweden	64.2, 19.7	8	Forest	↑		
Henry (2008)	Canada	42.0–74.7, −52.8 to −128.8	31	Grass	↑	–	
Sinha and Cherkauer (2008)	Indiana, USA	38.5–41.4, −86.4 to −86.7	3	Agricultural	↑(N), ↓(S)	↓	
Wang et al. (2009)	Qinghai-Tibet, China	34.7–34.8, 92.8–93.1	2	Alpine meadow			↑
Campbell et al. (2010)	New Hampshire, USA	43.9, −71.8	5	Forest	↑		
Fortin (2010)	Quebec, Canada	46.5–46.8, −71.1 to −71.9	4	Grass	↑		
Sinha et al. (2010)	Midwestern USA	38.5–45.5, −85.5 to −95.0	15	Grass/bare soil			↓
Kreyling and Henry (2011)	Germany	47–55 N, 5–16	177	Bare soil	↓	↓	

↑ increase, ↓ decrease, – no change, *N* northern sites, *S* southern sites, *dry* in dry years, *wet* in wet years of FTC are biologically relevant if the FTC are mild. In some cases multiple FTC have increased losses of soil N (Joseph and Henry 2008), although in other cases the pool of FTC-sensitive materials appears to have become exhausted, with subsequent FTC having less of an effect than the initial FTC (Henry 2007). Large amplitude soil FTC have usually produced stronger effects than small amplitude FTC (Henry 2007), and freezing depth can also be an important factor (Groffman et al. 2001). Therefore, it is clear that other facets of FTC other than frequency must be considered in order to assess possible effects on crops.

Changes in Soil FTC Severity and Depth

In Henry (2008), although the minimum annual soil temperature decreased in dry winters, there was only a marginally significant effect of warm winters on the minimum annual soil temperature ($P=0.07$). The coupling of minimum annual soil surface temperature to mean winter air temperature may be weaker than FTC frequency because extreme freezing can be driven by episodic events (i.e., a cold snap with no snow), whereas FTC frequency is a measure that is cumulative over the whole winter, and thus more representative of mean winter temperature. Nevertheless, increases in the severity of soil freezing with warming have been observed in some northern temperate regions (i.e., Decker et al. 2003; Isard et al. 2007; Table 1). Much like trends in FTC frequency, this trend reverses to one of less severe soil freezing in sites that currently experience mild winters (Sinha and Cherkauer 2008; Kreyling and Henry 2011).

An alternative method to assess soil freezing severity is to measure frost depth. There is a long lag time between changes in air temperature and temperature responses deep in the soil. Therefore, frost depth is a more balanced function of both the severity of air temperatures and the duration of cold over the course of winter. The responses of frost depth to climate change have been highly regional, with decreased frost depth in response to warming in Venalainen et al. (2001) and Sinha et al. (2010), but increased frost depth noted by Isard and Schaetzl (1998) and Wang et al. (2009), and no change noted by Campbell et al. (2010;Table 1).

Deceased snow cover is expected to have a particularly strong influence on frost depth, but with variable effects among continuous permafrost regions, discontinuous/sporadic permafrost regions, and seasonally frozen ground regions (Zhang 2005). Increased snow cover in localized regions can also have strong effect on soil frost depth, as demonstrated by the dramatic decreases in soil freezing depth observed in response to heavy snow brought about by changing air circulation patterns in Hokkaido, Japan, in recent decades (Hirota et al. 2006). Decreased frost depth in this region has increased the overwinter survival of unharvested potatoes that emerge as weeds in the year following planting (discussed further in the following sections, and elsewhere in this book). Similarly, on the Tibetan Plateau, increased snow cover over the last 50 years has retarded frost penetration at depth despite lower than normal air temperatures over this period, although the increased snow cover also delays the date of spring thaw (Yang et al. 2008).

Increased Variability in Air Temperatures and Precipitation

Although the discussion to this point has dealt with changes in mean climate, increased variability in air temperatures and precipitation is also predicted with climate change, which could further stress plants by exposing them to episodic frost events in early fall or late spring when plant cold acclimation is low (Rigby and Porporato 2008; Joseph and Henry 2009). Several studies have noted that the largest changes in the timing and duration of freezing have been occurring in the spring, rather than in the fall (Sharratt 1993; Han et al. 2010). Although these predictions call for fewer extreme frost events and an increase in warm extreme temperature events (Degaetano and Allen 2002; Kharin et al. 2007), early spring warming can promote deacclimation, leaving plants vulnerable if cold early spring conditions return (Gu et al. 2008). Similarly, extreme warming events in the middle of winter can cause plants to deacclimate, leaving them vulnerable to subsequent cold events (Bokhorst et al. 2011). Changes in atmospheric circulation can also counter the general trend of warming locally, resulting in increased extreme cold air temperature events in some regions (Vavrus et al. 2006).

Physical Effects of FTC

In addition to the effects of temperature fluctuations on crops, plants can be sensitive to changes in physical processes in response to climate change (Thorsen et al. 2010). For example, frost heave can damage root systems, and ice encasement can reduce gas exchange, leading to the accumulation of respiration products (Gudleifsson and Larsen 1993). The effects of low temperature on available soil moisture have long been appreciated in agricultural systems (Wilner 1955), and changes in snow depth and soil freezing are expected to interact to modify water infiltration and soil moisture (Hardy et al. 2001). Increased soil frost can reduce water infiltration into soil, increasing runoff and creating a greater potential for soil erosion (Zheng and Flerchinger 2001; Sinha and Cherkhauer 2008; Wang et al. 2009). However, freezing can also increase the quantity of water drawn from deeper layers into the topsoil (Iwata et al. 2010). In addition, episodic winter rain events followed by sudden temperature decreases can impede soil water infiltration substantially, independent of changes in soil frost depth (Iwata et al. 2011). Changes in soil water infiltration over winter are expected to interact with soil nitrogen losses (see elsewhere in this book).

Management of Snow and Plant Cover to Modulate Climate Change Effects on Soil Freezing

Models predicting soil temperatures have been used for decades to assess potential winter cereal mortality (Larsen et al. 1988), and for annual crops, the simplest response to climate change may be simply one of switching to more frost-tolerant cultivars or crops. Alternatively, frost-sensitive crops could still be maintained by modifying snow or litter cover to insulate soils (Fig. 3). For example, winter kill of wheat by frost can be reduced by increasing stubble height, which traps more snow (Malhi et al. 1992), and likewise, the addition of residues or mulch (Gusev and Yasitskiy 1991; Sharratt 2002; Chen et al. 2007) or tillage practices (Hay 1977; Larsen et al. 1987) can alter soil freezing. Commercially available protective covers have also been used for frost control in turf grasses for golf courses (Dionne et al. 1999). The tradeoff of these insulative layers can be one of the increased risk of snow mold infection (see elsewhere in this book). As described above, there are also situations where increased frost depth is desired to control weeds or pests. Increased frost depth can be achieved using snow removal techniques (Hirota et al. 2011), and dust can also be applied to snow to accelerate spring melt (Steltzer et al. 2009).

Conclusions

Overall, the prediction of "colder soils in a warmer world" (Groffman et al. 2001) appears to be likely for many northern temperate systems, although regional changes in the timing and thickness of snow cover will also play an important role in determining soil freezing dynamics independent of changes in air temperature. Similarly, increased climate variability may prove to have a more important influence than mean changes in temperature and precipitation, given that increased variability can result in frost events that occur when plants are not cold acclimated, and warm spells encourage plants to deacclimate prematurely. The trend of decreased soil freezing in southern temperate regions has important implications, both for releasing weeds and pests from frost pressure, and reducing germination of species that have overwinter chilling requirements. The management of soil frost via the modification of snow cover or other insulating materials presents a possible benefit in some cropping systems, but likely requires careful modeling and cost benefit analysis to optimize these benefits.

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