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SOIL FREEZE-THAW PROCESSES: IMPLICATIONS FOR NUTRIENT CYCLING[†]

C. WAYNE HONEYCUTT

ABSTRACT

Soil freeze-thaw processes can regulate nutrient availability to plants by influencing nutrient leakage from plant tissues, nutrient release from soil organisms, mineral weathering, various inorganic nutrient transformations, and nutrient transport in both soil solution and sediment. These aspects of freeze-thaw processes are given in this review. A frequently reported observation is that soil water content controls the extent of freeze-thaw impacts on several chemical, physical, and biological processes and components important for nutrient cycling. Practices affecting soil water content, such as tillage and crop residue management, may therefore provide opportunities for managing freeze-thaw impacts on nutrient use efficiency in crop production.

INTRODUCTION

Research is underway to link the dynamics of N availability from mineralized organic sources with the dynamics of plant N demand during a given growing season (1). An important component of this approach involves predicting available N at the time of spring tillage or planting. Soil freeze-thaw (FT) processes can greatly impact nutrient availability through their control on nutrient release from plant materials, nutrient release from soil organic components, mineral weathering, cation exchange, and soil physical properties influencing nutrient transport in soil solution and sediment. These aspects of FT processes are briefly reviewed in the following, with identification of common themes and generalizations provided where deemed appropriate.

NUTRIENT INPUTS FROM PLANT MATERIAL

Plant material is an important nutrient source in both natural (e.g. litterfall) and agricultural (e.g. crop residue) ecosystems. Susceptibility to freeze-injury with subsequent nutrient release varies among plant species. A wide range of freeze-killing temperatures exists even within a given plant species, depending on the physiological state at the time of freezing (2). For example, killing temperature for *Pinus mugo* ranged from –6°C when unhardened to –40°C when hardened. Injury may also increase with faster thaw rates, a phenomenon possibly related to cell rehydration rate (2).

Hurst et al. (3) reported no affect of FT (–5 to 5°C) on "leakage" of reducing sugars, K^+, or PO_4^{-3} in senescent leaves of two plant species. However, Hurst et al. (3) cited Tukey (4) as reporting increased rates of nutrient leakage induced by FT damage in active leaves. Thus nutrient leakage related to FT is probably more important in active leaves.

SOIL INORGANIC NUTRIENT TRANSFORMATIONS

Mineralogy may be expected to influence the importance of FT processes on inorganic nutrient transformations in soils. Freeze-thaw may be speculated to have more dramatic impacts on weathering of expanding lattice clay minerals such as montmorillonite, nontronite, and vermiculite than on non-expanding lattice clays such as kaolinite, illite, and biotite.

Fine et al. (5) studied the influence of FT on exchangeable K^+ in several soils and clay minerals. Soil FT treatments consisted of H_2O-saturated soils subjected to 10 FT cycles with freezing temperatures ranging from –10 to –16°C and with thawing apparently conducted at room temperature. A complete FT cycle was completed within 2 to 4 days. Freeze-thaw decreased exchangeable K^+ (increased fixation) by as much as 190 kg ha^{-1} in some soils and increased exchangeable K^+ by as much as 174 kg ha^{-1} in others. Addition of $CaCO_3$ inhibited release of fixed K^+ upon freezing.

Fine et al. (5) also examined FT effects on K^+ exchange in several clays. Freeze-thaw increased exchangeable K^+ from bentonite, nontronite, and montmorillonite. These minerals are all characterized by an expanding lattice. Freeze-thaw induced a net decline in exchangeable K^+ from illite (non-expanding lattice). Exchangeable K^+ levels in illite control samples exceeded those subjected to FT by 580 mg kg^{-1}.

Graham and Lopez (6) investigated the role of FT in K^+ release from 25 Missouri soils covering a range

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in parent materials, weathering stages, and inherent K fertility levels. Freeze-thaw increased K^+ release from crystal lattice (non-exchangeable) positions into the labile pool for all 25 soils. More K^+ was released from Ca-saturated soils than NH_4^+-saturated soils, suggesting the NH_4^+ ions partially blocked exchange sites in the lattice positions.

Summerfield and Rieley (7) subjected three peats to 20 FT cycles, each consisting of –16°C for 8 hr and 20°C for 12 hr. Exchangeable Ca^{+2}, Na^+, K^+, Mg^{+2}, and Fe^{+3} all increased as a result of the FT treatment.

Cheng et al. (8) demonstrated that the influence of FT on Mn and Fe release depends on both soil particle size and soil H_2O content. Manganese and Fe release was greater following three FT cycles than following either freezing or thawing alone in a flooded soil (wetted to 200% of field capacity). However, Mn and Fe release from unflooded soil (wetted to 80% of field capacity) was unchanged to slightly less following the three FT cycles. Exchangeable Mn and Fe extracted from flooded soil also increased with decreasing soil particle size. Freeze-thaw treatments decreased both exchangeable Ca and K. Mineralogy of the soil used in that experiment was not given.

The influence of long-term freezing on soil P availability has also been investigated. Mack and Barber (9) froze a soil for nine months at –20.5°C and then leached it for 80 hr at 16°C. About 8 mg P kg^{-1} was leached from previously frozen soil compared to 5 mg P kg^{-1} leached from soil stored at 2.7°C. Mack and Barber (9) felt that temperature may affect either the type of P compound or its surface area.

A subzero optimum temperature for chemodenitrification was reported by Christianson and Cho (10). Chemodenitrification rates of a NO_2^--treated soil decreased with incubation temperature from 20°C to –1.8°C. Further reduction in temperature coincided with a dramatic rise in N_2 production, with greater N_2 production rates at –3.5°C than at 20°C. Further temperature decreases below –3.5°C resulted in decreased chemodenitrification. Christianson and Cho (10) proposed that salt exclusion associated with freezing water increased NO_2^- concentration in the film of unfrozen water adjacent to soil particles. This explanation is compatible with the subzero optimum temperature observed because chemodenitrification rates are quite dependent upon NO_2^- concentration.

NUTRIENT RELEASE FROM ORGANIC SOIL COMPONENTS

Freeze-thaw effects on survival at the cellular level can provide insight into nutrient release from soil organisms subjected to FT. Mazur (11) felt that the conditions of initial cooling and return to physiological temperatures impact cell survival more strongly than the actual temperature reached. Maximum cell survival was reported at some intermediate cooling rate, with cooling at either slower or faster rates resulting in greater injury.

Most cells remain unfrozen at –10 to –15°C, although ice is present in the extracellular medium. Mazur (11) hypothesized that the cell membrane can block passage of extracellular ice at temperatures above about –15°C, thereby preventing nucleation of supercooled water within the cell. Mazur (11) reasoned that the greater vapor pressure of supercooled water within the cell compared to extracellular ice results in water movement out of the cell where it is frozen externally. The remaining intracellular solution becomes more concentrated and the activity of intracellular water is reduced. Slow cooling reduces intracellular freezing because the progressive dehydration promotes equilibrium between the activity of intracellular water and the activity of external ice and the external solution. Conversely, a rapid cooling rate may prevent intracellular water loss at a rate sufficient to reduce its activity to the equilibrium value, thereby leading to intracellular freezing and death.

A slow freezing rate can also lead to cell injury. This effect is often termed the "solution-effect" because it is related to changes in the composition and properties of aqueous solutions produced by extracellular ice (11). Progressive freezing increases solute concentration in the remaining unfrozen solution. Because the primary solutes in and around cells are electrolytes, the increased salt concentration may lead to cell death (11).

Freeze-thaw effects on survival at the organism level also provide insight into nutrient release from soil organisms subjected to FT. Nelson and Parkinson (12) isolated species of *Pseudomonas, Bacillus,* and *Arthrobacter* from an arctic soil at Devon Island, Canada. Cultures of each isolate were added to sterilized soil and successively subjected to 3, 0, –5, –15, and –22°C for 24 hours each. Soils were either subjected to a fast thaw at 3°C for 4 hr or a slow thaw achieved by reversing the freezing treatment. A common observation for all three isolates and for the mixed indigenous soil bacteria was that survival after FT was dramatically greater at low soil water contents.

Different organisms responded differently to other treatments investigated. A slow rate of thaw was more deleterious to species of *Pseudomonas* and *Bacillus* but did not affect survival of *Arthrobacter* or the indigenous soil bacteria. The influence of nutrient supply and temperature before FT were also examined. *Pseudomonas* M216 was less viable under N-limiting conditions than under C-limiting conditions. *Arthrobacter* M51 survival was high and unaffected by either nutrient-limited or growing temperature conditions. Differential effects of FT on soil microorganisms were also reported by Morley et al. (13). In that study, FT cycles desynchronized predator-prey population cycles, resulting in increased prey (amoeba) populations.

Soil freezing may also result in a considerable flush of microbial activity and N mineralization. Freezing two soils at -14°C increased soil respiration at 15 to 30°C by 12 to 56% (14). However, lack of increased respiration in a third soil indicated the importance of other factors. Ivarson and Sowden (14) hypothesized this observation to reflect degree of humification, where the more humified soils displayed a greater response to freezing. Based on the premise that increased humification increases the hydrophilic properties of organic matter, Ivarson and Sowden (15) speculated that freezing in more humified soils may result in greater expansion, followed by "greater breakdown of soil organic gels." Soulides and Allison (16) also reported FT to increase CO_2 evolution. However, wetting-drying caused a much larger increase in CO_2, and drying was more destructive to bacteria than freezing at –22°C.

Freezing a soil at –14°C for 3 wk coincided with a 44-fold increase in water extractable free amino acids (15). Free sugar content also increased following a –14°C treatment (14). Four FT cycles from –14 to 4°C and a single 3-wk freeze at –14°C had similar effects for both free amino acid and free sugar contents.

Freeze-thaw may also result in significant increases in soil inorganic N. DeLuca et al. (17) subjected 18 soil by land-use treatment combinations to –20°C for 1 wk. Freeze-thaw increased N mineralization rate and total N mineralized. The flush of mineral N was highly correlated (r^2 = 0.84) with the release of ninhydrin-reactive N, and ninhydrin-reactive N was closely related to microbial biomass N (r^2 = 0.80). Consequently, DeLuca et al. (17) concluded that soil microbial biomass was the source of increased inorganic N following FT.

An important question is 'What is the magnitude of nutrient mineralization resulting from soil freeze-thaw processes?'. Many factors would undoubtedly contribute to variable answers to this question. However, Morley et al. (13) attempted to answer the question based on their experimental results. In their study more than 45% of mixed soil bacterial species survived 10 FT cycles from –27 to 23°C. Using Van Veen and Paul's (18) conversion factors, Morley et al. (13) calculated that a population of 5×10^8 bacterial cells g^{-1} soil with FT-induced death and lysis of 40% would translate into nearly 9 mg N mineralized kg^{-1} soil. This means about 22 kg N ha^{-1} would be mineralized as a result of FT if this soil had a bulk density of 1.2 Mg m^{-3} in the surface 20 cm. Using the same bulk density and surface thickness values for DeLuca et al.'s (17) study indicates inorganic N increased by about 1 to 16 kg N ha^{-1} 10 days after the freezing treatment.

Another important question is 'Which is more important for soil organism survival: the conditions of the FT cycle (e.g. number and rates of cycles, soil water content) or the actual temperature reached?'. Morley et al. (13) concluded that for bacterial survival, freezing rate was not as important as the final low temperature reached. In direct contrast, Mazur (11) reported that FT rates impact cell survival more strongly than the actual temperature attained. A unifying hypothesis is that for temperatures greater than about –15 to –10°C, the conditions of the FT cycle are more important for microorganism survival. However, at temperatures less than –15 to – 10°C, the actual temperature reached becomes more important because cell survival is dramatically reduced below this temperature range. This hypothesis is substantiated by reports of no effect of freezing at –10°C on inorganic N content (19), a dramatic increase in inorganic N derived from microbial biomass following freezing at –20°C (17), and from observations that most cells remain unfrozen at –10 to –15°C (11).

Freeze-thaw processes may also influence N losses in gaseous forms. Rates of both denitrification and NH_3 volatilization decreased on the first day following a 12-hr treatment at –8°C (20). However, the following days at 15°C showed greater denitrification and NH_3 volatilization rates than for soils not subjected to FT. Freeze-thaw induced increases in NH_3 volatilization were short-lived (1 day) and shortened the period during which NH_3 volatilization was detectable. This led Edwards and Killham (20) to conclude that FT only altered volatilization rate, but not the pool size of volatilized N. By contrast, denitrification rates remained greater after FT for the entire 8 day incubation period, suggesting the amount of N denitrified was increased as a result of FT.

Several other studies have focused on FT relations with denitrification. Christensen and Tiedje (21) added KNO_3 and H_2O to field cores and monitored N_2O production. A modest N_2O flux (2 g N ha^{-1} d^{-1}) was measured in a January thaw of 1°C, but a flux of 486 g N ha^{-1} d^{-1} was measured in a March thaw of 4°C.

Dorland and Beauchamp (22) studied N transformations under anaerobic conditions at temperatures ranging from –2 to 25°C. Nitrous oxide production peaked at 110 mg N kg^{-1} soil just one day after alfalfa addition at 25°C. Although it took 26 days to reach 110 mg N kg^{-1} soil, N_2O production also reached this level in soils incubated at –2°C. It is interesting to note that the thermal unit requirement for reaching 110 mg N kg^{-1} was similar for both treatments (27 and 26 degree days, respectively) if one uses a baseline of –3°C for calculating thermal units (23).

Studies have also addressed the role of freezing temperature on survival of soil macrofauna. Forge and MacGuidwin (24) studied the independent and interactive effects of soil water and freezing temperature on *Meloidogyne hapla* (nematode) survival. For a given temperature, survival was greater at soil water potentials of –1.91 to –0.52 MPa than at wetter potentials. Dry water potentials were considered to increase survival directly by reducing the amount of ice-filled pore space and indirectly by promoting physiological changes that improved the nematode's ability to withstand freezing conditions. Temperature and soil water potential before freezing interactively affected nematode survival. The positive effect of low water potential became more pronounced as temperatures decreased from –1 to –4°C. However, the positive effect of drier water potential diminished with increasing freeze duration.

NUTRIENT TRANSPORT IN SEDIMENT AND SOIL SOLUTION

Soil loss through erosion can be substantial for frozen soils (25, 26). Just one FT cycle can reportedly reduce soil cohesion by 50% (27). This can lead to significant losses and landscape redistribution of soil-bound nutrients.

Freeze-thaw directly impacts aggregate stability, which in turn, strongly influences infiltration and erosion. The magnitude of change in aggregate stability is related to soil water content at the time of freezing. Aggregate stability generally decreases with increasing soil water content at freezing (28, 29, 30). Precipitation following FT also increases soil erodibility by promoting consolidation (reduced infiltration) of previously freeze-loosened soil (31).

Aggregate stability can also affect nutrient availability. Khonnolaynen and Reppo (32) reported that increased water stability of aggregates reduced the freeze-induced release of NH_4^+.

Water movement in frozen soils is a significant factor affecting nutrient distribution within the soil profile. Both Willis et al. (33) and Pikul and Allmaras (34) reported upward water movement within frozen soils. Willis et al. (33) hypothesized that warmer soil temperature deep in the profile result in greater vapor pressure than at cooler temperatures in the upper profile. The resultant vapor pressure gradient causes upward movement of water vapor. Pikul and Allmaras (34) described how water may also move upward in the liquid state. Thin unfrozen water films around soil particles in the frozen layer have a low matric potential. Subsoil water with a greater matric potential may move upward in response to the matric potential gradient. During one freezing night, Pikul and Allmaras (34) observed volumetric water content at 0.25 cm to increase from 0.31 $m^3\ m^{-3}$ at 1800 hr to 0.57 $m^3\ m^{-3}$ at 0600 hr in a bare soil. Water content in an unfrozen stubble-covered plot increased from 0.34 to 0.40 $m^3\ m^{-3}$ during the same time. Pikul and Allmaras (34) also noted this phenomenon to result in large evaporative water losses at the soil surface during daytime thaw. Such water losses concentrate nutrients in the zone of evaporation.

Many interactions associated with water movement and nutrient transport in frozen soils may exist. The wetting-drying related to evaporation at the soil surface may disrupt soil aggregates, leading to surface crusting, less infiltration, and more erosion of soil-bound nutrients (35). Surface crop residues or litter may also reduce soil freezing (36), leading to less water and solute movement upwards, less evaporative loss, less aggregate disruption, and less crusting and erosion. On an ecosystem level, different vegetative covers are associated with specific frost types, each having different infiltration characteristics (37, 38). For example, the relatively impermeable "concrete" frost type is reportedly most common in sod, and the more permeable types (e.g. "porous-concrete") occur more extensively in forested areas (38) .

SUMMARY

Soil FT impacts several processes regulating the content, availability, and profile distribution of nutrients. Factors such as climate, soil mineralogy, soil texture, tillage, and crop residue management may modify the importance of FT on cation exchange, microorganism survival, aggregate stability, infiltration, and erosion.

A common theme emerging from this review is that FT effects on many properties are very dependent upon soil water content. Exchangeable Mn and Fe increased in a saturated soil but either decreased or did not change in an unsaturated soil following FT (8). Soil microorganism survival after FT was dramatically greater at drier soil water contents (12). Nematode survival following FT was also greater at drier soil water contents (24).

Fundamental equations for heat and water flux predict faster rates of FT and deeper depths of frost penetration in drier soils (39). Such predictions are related to differences in the heat capacities of wet and dry soils and are verified by field observations (40, 41, 42, 43).

Freeze-thaw at wetter soil water contents generally results in the greatest reduction in aggregate stability (28, 29). Greater infiltration and percolation rates are observed in frozen soils with low water contents at the time of freezing (42). Thus soil water content is a key determinant regulating FT impacts on notable chemical, physical, and biological processes of nutrient cycling. Consequently, practices affecting soil water content such as tillage and crop residue management provide opportunities for managing FT impacts on nutrient use efficiency in crop production.

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