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Frozen Soils: A Perspective on Past and Future Research for Promoting Sustainable Agricultural Systems†

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Abstract

Frozen soils impact many industries which rely on soil, water, and air resources in developing and manufacturing products. Most noteworthy is the agricultural industry in the northern United States where soils, which sustain food and fiber production, are subjected to frequent freezing and thawing. Soil freezing and thawing influences soil erodibility, surface and ground water quality, air quality, and biological activity. Many strides toward understanding frozen soil processes and managing lands to minimize the adverse effects of freezing and thawing have been made over the last two decades. Yet, further efforts to identify frozen soil processes which influence wind and water erosion, soil faunal adaptation, soil quality, movement of agricultural chemicals, and rural and urban water supplies will aid industry and society in meeting future needs for food and water.

Introduction

Freezing and thawing is a common occurrence across much of the United States. Frozen soils impact the quality and management of our natural resources, yet those impacts are not fully understood in sustaining agricultural production systems.

Weather plays a significant role in determining the depth and duration of frost in soils. We cannot manage, however, the vagaries of weather to alter soil freezing processes. There are opportunities in agricultural production systems to manage soil, snow, and crop cover which control movement of heat into and out of the soil and consequently influence soil freezing and thawing. Management strategies aimed at minimizing the adverse effects of freezing on crops, soil properties, and soil fauna, and on the movement of water and chemicals in the soil profile affect the quality of the soil, water, and air resources. Development and evaluation of these strategies by simulation and experimentation are an integral part of many research programs.

Many strides toward understanding the impacts of freezing on the biological, chemical, and physical processes of frozen soils have been made in the past two decades. The fate of plants exposed to freezing and thawing is well understood, but comparatively little is known concerning the mechanisms of plant adaptation and how to best manage plant residues during winter to optimize the soil environment in spring. Complexities of plant and soil mechanisms and management and dynamics of the freezing and thawing process require a combined monitoring and simulation approach toward managing agricultural systems.

Biological Processes

Insects have developed specialized mechanisms to survive the harsh winter environment of the northern United States. These mechanisms can lower the critical temperature threshold, below which irreversible physiological processes result in death to the insect. Some mechanisms of adaptation to subfreezing temperatures include: dehydration, glycerol formation, diapause, supercooling, and freezing tolerance. Cooling or chilling causes physiological change which prepares insects for overwintering. Mechanisms of adaptation observed in the laboratory, are difficult to observe in the field.

Nonsteady-state soil processes, characteristic of the field environment, influence the survival and adaptation of insects. Yet, the complexity of these processes within a freezing soil are not fully understood in interpreting the responses of insects. Nevertheless, soil management can often influence the degree of insect survival adaptation by altering the thermal and moisture regime of the soil environment.

Annelids have adapted to survive the winters of northern latitudes. Some species of worms undoubtedly overwinter beneath the frozen zone, yet many species hibernate within the frozen soil layer. The overwinter environment of worms is poorly understood, but opportunities exist for managing worm populations by altering the winter soil temperature regimes using different tillage, crop, and residue systems.

Earthworm burrows play an important role in water and chemical movement in soils (1). Burrows may be primarily vertical or horizontal, depending on

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earthworm species and both influence soil structure and macro-porosity. Vertical burrowers have a greater influence on infiltration and permeability as a result of forming preferential flow paths. Little is known about the effect of freezing and thawing on the stability of burrows and therefore preferential flow. Experimental evidence suggests that preferential flow paths in soil are altered by freezing and thawing (2). Similarly, freezing and thawing is thought to disrupt structural components of soil not unlike tillage (3).

Soil microbes decompose organic matter and influence the transformation of many chemicals and compounds. Microbial activity is closely correlated with soil water content and temperature. Generally, the activity of microbes increases with temperature with some activity reported at temperatures well below 0°C (4). In frozen soils, possible sites of microbial activity may include the liquid water films surrounding soil particles (5). Other sites of microbial activity are possible within the soil-residue complex, such as those occupied by snowmold fungi which thrive in the cool and moist environment below a snowpack.

Bioremediation is commonly used to restore contaminated lands such as those impacted by oil spills or toxic wastes. Landfarming and bio-piles are two forms of bioremediation used to restore polluted landscapes. Many contaminated landscapes are located in fragile and frigid environments. Cold or frozen soils slow the bioremediation process by slowing microbial activity. However, freezing soil is a means of containing toxic spills.

PHYSICAL PROCESSES

The freezing process in soils generates intense pore ice pressures (6). Soil heaving caused by pore ice pressure is detrimental to plant survival, destructive to building foundations and roads, and a causative factor for changes in soil aggregation and structure. Silt loam soils are most susceptible to frost heave. These soils are characterized by a surface adsorption and capillary conductivity which permit rapid rates of water movement to the freezing front, but little open pore space for the growth of ice crystals.

Unfrozen water content within a frozen soil matrix progressively declines with falling temperatures. The decline in matric potential with the onset of soil freezing results in water flow from unfrozen layers to the freezing front. Salts are preferentially excluded from the pore ice, thus forming a briny liquid with a low freezing point (7). Temperatures lower than -40°C are required to freeze the water films adsorbed on soil particles (8). The amount of unfrozen water in frozen soils is dependent on such factors as temperature, total water content, solute concentration, and soil specific surface area.

Measurement of unfrozen soil water content is accomplished using such methods as Time Domain Reflectometry (TDR) and Nuclear Magnetic Resonance. The TDR technique is for *in situ* measurements of water content, yet accuracy of the measurements is questionable because the dielectric character, generally assumed to remain constant across temperatures, actually changes with temperature (9).

Water movement occurs in frozen soil, especially in dry soils with continuous macropores, cracks, or voids. Substantial infiltration rates have been observed under such conditions (10). Infiltration rates, however, are slower for a soil subjected to nocturnal freezing owing to ice-filled pores restricting water movement (11). Indeed, rates of water movement into soil are influenced by the type of soil frost. For example, infiltration rates are slower in soils with concrete frost than with granular frost (12). Most agricultural soils freeze in a massive concrete state while granular frost is associated with forested soils (13). Infiltration into frozen soils is enhanced by frost tillage, a technique that rips through the frozen layer with a chisel-type implement (14,15).

Some studies show greater than expected infiltration rates into frozen soil, suggesting that there is a mechanism for liquid water movement other than through unfrozen water films lining the soil matrix (16). Flow paths for water movement in soils are affected by the freezing and thawing process. Schnabel et al. (2) found enhanced leaching of nitrate through soil columns after one freeze-thaw cycle and attributed the greater leachate concentration to changes in preferential flow paths. Little is known concerning environmental conditions and soil properties which alter flow paths under freezing conditions.

In the past 20 years attempts have been made to simulate the combined movement of heat, water, and solutes in porous materials. Only a few researchers have considered these processes in frozen soils, possibly because of the complexities involved in estimating soil parameters as soils freeze (17). The SHAW (18) and SOIL (19) models are examples of detailed models that can predict soil properties and processes under freezing and thawing conditions. Such models aid in understanding the complexities of interactions in frost-susceptible field soils.

Tillage has a major effect on overwinter soil processes (20). Tillage results in a change in soil surface properties which affects runoff, infiltration, and energy exchange processes. Several studies show entrapment of more snow by standing stubble reduces the depth of freezing and thereby results in earlier melting of ice in the soil. However, fall tillage is favored in northern regions with short growing seasons because soil surfaces that are denuded warm faster in the spring than surfaces with crop residue cover. Minimum- and conservation-tillage is desirable, however, to minimize erosion of agricultural lands. In many areas of the northern United States, blowing soil from adjacent bare fields darkens snow (21) resulting in an accelerated rate of snowmelt owing to increased absorption of solar energy.

Wind and water erosion in the northern United States is influenced by soil freezing and thawing. Soil aggregates often lose their cohesion when freezing breaks them apart. At temperatures above 0°C the surface tension of water pulls these particles back together as the soil dries and some degree of cohesion is re-established. However, if sublimation removes the ice, the particles are not pulled together, the bonding agents are not deposited at the points of contact, and the loose particles are very susceptible to transport by wind or water. Water erosion is often visible on landscapes after the onset of spring thaw. During thaw, disruption of thawed and often saturated topsoil may result in downslope movement of sediment over frozen subsoil. Multiple freeze-thaw cycles exacerbate the situation in areas like the Pacific Northwest.

Chemical Processes

Movement of solutes in soil affects our ability to optimize placement of plant nutrients and to protect water resources from contamination (22). Solute transport is of primary concern during the growing season when fertilizer applications and root growth provide large sources of and sinks for nutrients. Yet, relatively little is known concerning how far and in what amounts solutes are transported during winter. Water movement toward an advancing freezing front and formation of ice crystals in soil pores affect solute movement during winter. Solutes, excluded from ice crystals, are concentrated in the thin liquid layer surrounding soil particles (7). Consequently, movement of a relatively small amount of water results in relatively long distance movement of water and its solutes in frozen soils. Movement of solutes is likely to be enhanced during spring thaw. Lack of vegetation and wetter soil at this time contribute to the likelihood of leaching and runoff losses of solutes.

Mineralization of organic N and atmospheric deposition of N continue during the winter (23). Mineralization, is caused by microbial decomposition and by the dehydration of organic matter which is caused by alternate freezing and thawing (24). Formation of nitrate and nitrous oxide is enhanced under alternate freezing and thawing (24, 25). Loss of N associated with fall-application of fertilizer is of concern in maintaining water quality and optimizing the efficiency of production systems. Loss of fertilizer-N typically does not occur when the soil is frozen, but occurs during the fall and spring (26). Some loss of N in spring is due to volatilization (27).

Information concerning pesticide transport in frozen soils is sparse, owing to the complexity of the pesticide compounds and soil interactions.

Depression-focused recharge of soil water in the prairie pothole region of the north-central United States may contribute to ground water contamination. Surface and subsurface movement of soil water toward pothole depressions can carry chemicals. This process is accentuated during spring thaw when a frozen subsoil constrains vertical movement of soil water. Indeed, lateral movement of chemicals may be more significant than vertical movement in the soil profile during thaw. Another type of lateral movement of water and chemicals is illustrated by the saline seeps in part of the western United States (28).

Overwintering Crops

Survival of winter annual and perennial crops during winter depends on weather conditions, surface cover, crop physiological characteristics, and soil physical processes which govern heat and water flow. Winter crops are generally selected for their ability to survive winter temperatures and soil conditions. Frost heave damages plant stands by rupturing the root system and/or leaving vital parts of the plant exposed to the cold air. Ice sheeting may also injure or kill plants by rapidly cooling the soil below the plants' lethal temperature. Some plants (for example, winter lupins) are killed because their tops remain green and continue to transpire during the day while their roots, in the frozen soil, are unable to provide the water needed; the plants die of desiccation, even though they are able to survive freezing. Plant survival may be affected by restricted gaseous diffusion of toxicants through frozen soil. Frozen soil layers inhibit diffusion of carbon dioxide and nitrous oxide from the unfrozen subsoil to the atmosphere; maximal gas fluxes occurr after spring thaw (29).

Crop residues retard the exchange of heat and water between the soil surface and the atmosphere. Consequently, freeze-thaw events at the soil surface vary in time and space (30). Standing residue stubble is used as a means to trap blowing snow and to conserve both water and heat (31, 32, 33). Residues also diminish wind speeds at the soil surface and thus minimize sublimation from soil aggregates and transport of soil particles. Although crop residues are a means to modify heat and mass transfer at the soil surface, little is known about how residue placement and physical characteristics affect transfer processes and therefore freezing and thawing of soil. Residue orientation, amount, size, and composition (for example, color, density, porosity, surface roughness) are important attributes governing energy exchange processes.

INSTRUMENTATION

Instruments used in monitoring the winter environment have greatly improved in recent years. Reliability of data loggers operating in harsh winter environments has improved. Accurate temperature measurements are feasible with the aid of data loggers for determining freezing point depressions and many of the constants and coefficients in simulation models. Measurement of some of the most basic parameters in frozen soils research, however, still eludes the investigator. Soil water content in the frozen and unfrozen state is difficult to determine spatially and temporally, and quantifying frozen and unfrozen water content generally requires using multiple sensors. For example, unfrozen water content is determined using Time Domain Reflectometry and total water content (frozen and unfrozen) is determined by neutron attenuation. Snow depth and density are difficult to measure on a continuous basis because of lack of development of instrumentation and because of soil variability over a landscape. Sensors are needed to monitor temporal changes in water vapor during winter which are needed for estimating water losses by evaporation and sublimation. Biological activity within the soil is very difficult to measure. For example, no instruments have been developed to adequately monitor earthworms in soil during winter.

MODELING

Several models have been developed to predict freeze-thaw effects on soil system processes and properties (34). Some simplistic models estimate frost depth and duration from air temperature measurements. More complex models, such as the SHAW model (18), simulate many of the processes involved in the freezing and thawing of agricultural soils. Several models describe solute transport in frozen soil. These models have been useful in predicting seed-bed water content and solute concentrations in arid environments (35), estimating frost heave (36), managing nutrients in cropping systems (37), and estimating nitrate leaching (38). No models have been developed for simulating pesticide transport in frozen soils.

Models are an important tool in understanding the complexities of the soil system. They allow us to improve our understanding of system interactions and processes, and also they are valuable in developing future management strategies that are sustainable, productive, and environmentally safe. Models, however, will be used in industry for managing agricultural systems only after extensive validation under a wide range of environmental conditions. Indeed, of the more than 30 models developed to simulate frozen soil processes, only one-third have been validated in the field or laboratory.

FUTURE RESEARCH NEEDS

The complexities of interactions within the atmosphere-snow-residue-frozen soil system must be understood to better manage our natural resources. Enhancing our knowledge concerning these complex interactions, however, is tempered by the finite amount of resources available for research. Few research projects that address frozen soil processes are fully funded through regional or national agencies. Many projects are funded along with more publicized research endeavors or thrusts. Research priorities must be established so that funds are available for those projects that have the greatest impact on our society. One priority for research might well be the impact of overwinter processes on crop growth and production. Other priorities might include the influence of freezing and thawing on soil quality, soil erosion, and rural and domestic water quality. In addition, research priorities must also consider the sustainability of agricultural production systems to preserve our natural resources and protect our environment.

Directions for future research in frozen soils must be sensitive to the needs of both the agricultural industry and society. Research priority areas in frozen soils that will aid in managing agricultural lands and our natural resources include:

- Soil structure and stability
- Soil fauna adaptation
- Gaseous emissions from soil
- Transport of nutrients and pesticides
- Soil water transport
- Crop residue management and physical properties
- Development of instrumentation
- Validation or development of transport models

Specific tools needed for future research include improved sensors and development that monitor and of mechanistic models that and simulate the physical, chemical, and biological processes of soils throughout the year. Frost models must be expanded to include a crop component to aid their utility in designing integrated production systems.

Current research efforts are often directed at a field scale. Future research, however, should be conducted on a range of scales from the microscale (clay platelets) to the mesoscale (watershed). Indeed, processes at the microscale often affect those at the field scale. For example, adsorption of pesticides to soil and organic matter affects the transport of these chemicals within and from the root zone. These efforts require a multidisciplinary approach in understanding the dynamics of an integrated frozen soil system.

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