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Freezing and Thawing of Agricultural Soils: Implications for Soil, Water, and Air Quality

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Freezing and Thawing of Agricultural Soils: Implications for Soil, Water, and Air Quality[†]

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Abstract

Most agricultural lands in the USA are subject to subfreezing temperatures. Soil freezing and thawing affects both biotic and abiotic interactions and processes which vary with weather, soil type, land management, and topography. Soil fauna generally undergo physiological changes or rely on locomotion as a means of adapting to frozen soils. Managing faunal populations using soil management may be achievable with a better understanding of winter ecological processes. Many of the thermal, hydraulic, mechanical, and physical properties of soils are altered by freezing and thawing. Soil erosion may be accentuated by soil freezing and thawing as a result of changes in aggregate stability and shear strength. Soil processes such as heat, water, solute, and gas flux are affected by the freezing process, although simulation of solute and gas flux in frozen soils is not well documented. Solute and gas flux affect water and air quality owing to the loss of chemicals to surface and ground water systems and gaseous emissions to the atmosphere, respectively. Information about biotic and abiotic characteristics of frozen soils, presented at a national workshop in March 1994 in Minnesota, aids in the development of sound management strategies for agricultural lands to preserve our soil, water, and air resources.

Introduction

The dynamic process of soil freezing and thawing can have a profound influence on our environment and ability to manage agricultural lands. Perhaps these impacts are best illustrated by the demise of manmade and natural structures resulting from thaw consolidation of permafrost in the Subarctic and by the spring resurgence of rocks to the surface of agricultural soils in the northern United States. The freeze-thaw process, which occurs as a result of the phase change in water, not only affects plant and animal life, but also the quality of our soil, water, and air.

Freezing and thawing often results in subtle, and at times irreversible, changes to soils. The subtle changes may alter the long term productivity of agricultural lands. For example, soil creep results in a loss of topsoil near ridge tops owing to the downslope movement of soil (1). Mechanical weathering is also a subtle, but irreversible process accelerated with more frequent freezing and thawing (2).

Some of the most productive soils in the world lie within the corn belt of the USA (3), a region subject to subfreezing temperatures. Soil freezing and thawing contribute to the quality of the soil resource within this region by influencing the physical, biological, and chemical processes of soils. Physical processes such as soil formation and structural development are accelerated with freezing and thawing (1). In addition, soil drainage and aeration are improved by the creation of macropores as soil fauna burrow below an advancing freezing front. Chemical processes such as the release of non-exchangeable ammonium as soils freeze and thaw (4) may allow improved access to nutrients by plants.

Soil freezing and thawing depends not only on weather, but also on land management, soil type, and topography. An understanding of weather and management practices which influence the distribution of frozen soils as well as the effect of freezing and thawing on soil properties and processes will aid in developing management strategies for improving the quality of our soil, water, and air. The following sections, which were topics addressed at a national frozen soils workshop in March 1994 in Minnesota, discuss the occurrence of frozen soils and impacts of freezing and thawing on soil, water, and air resources.

Distribution of Frozen Soils

Soil freezing and thawing is mainly confined to latitudes above the 40th parallel (Fig. 1). Rarely are frozen soils encountered in the Subtropical and Tropical regions, except in highland areas. The latitudinal zone of ephemeral frost (Fig. 1) encompasses an area of seasonally frozen soils. These soils remain unfrozen below the annual depth of freezing (perhaps several meters), are frozen from one to more than 180 days per year, and go through a single or as many as 100 freeze-thaw cycles. Ephemeral frost

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occurs in regions typified by Continental, Marine West Coast, and Highland climates (5).

first frost in fall (0°C) and the last frost in spring (Fig. 2). This time span is often considered a quiescent

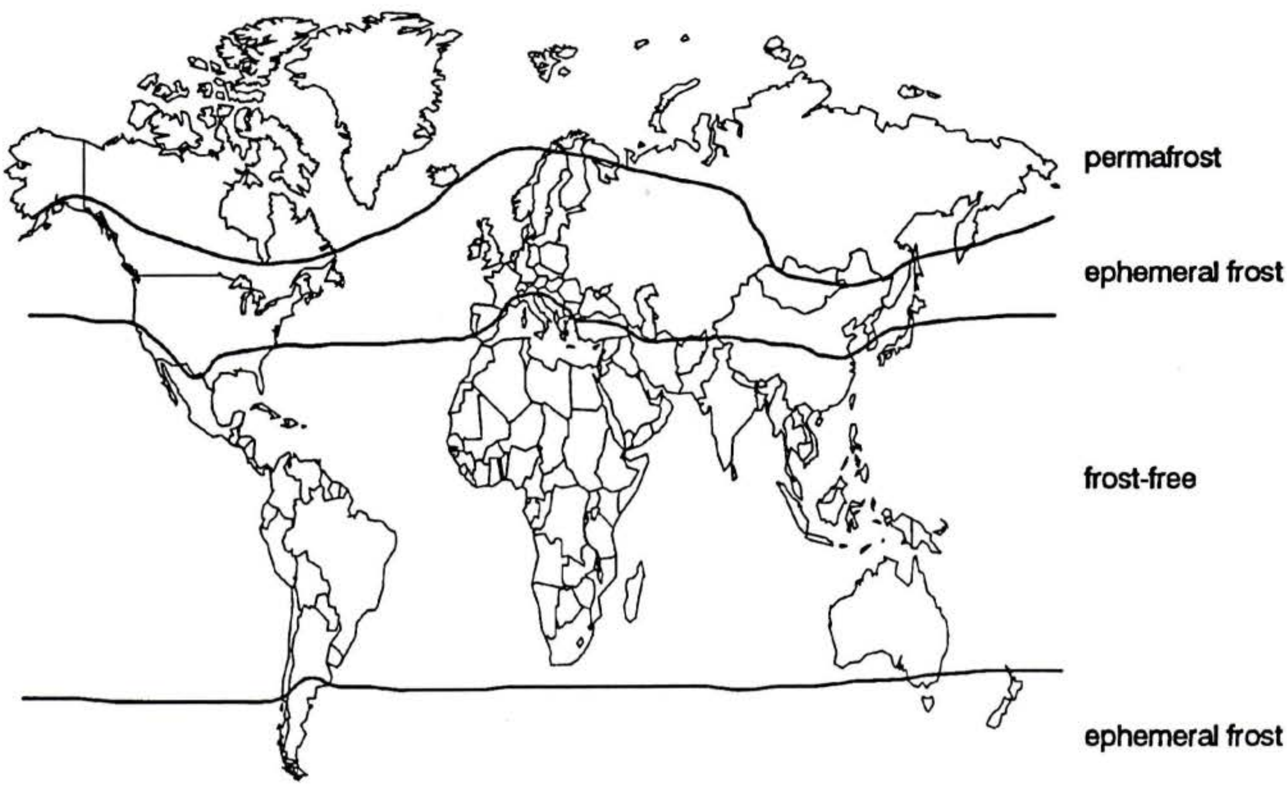

Fig. 1. World distribution of permafrost and ephemeral soil frost. Latitudinal zones were constructed using climatic regions of Heintzelman and Highsmith (5) and data of Nekrasov (14).

The latitudinal zone of permafrost, occupying the Subarctic and Arctic climatic regions, denotes soils that are permanently frozen below the annual depth of freezing and thawing. Agricultural soils of these regions typically freeze to a greater depth and remain frozen longer than soils of more temperate regions. These soils are some of the least productive in the world owing to such factors as low fertility and poor profile development (3). In addition, frequent diurnal freezing and thawing and low winter temperatures contribute to an unfavorable soil environment for winter crops (6).

Seasonally and permanently frozen agricultural soils are encountered throughout much of the USA except along the west coast, southern humid subtropics of the conterminous USA (7), and in Hawaii. Nearly 90% of the USA is subject to freezing and thawing based upon data by Visher (7) and the United States Department of Commerce (8). Formanek et al. (9) estimated that about 50% of the crop, timber, and range lands in the USA are impacted by freezing and thawing.

In the northern region of the USA, agricultural soils are typically idle (i.e. do not support a growing crop) for greater than one-half of the year. This is exemplified by the more than 200 days between the period marked by subtle changes within the soil profile. Management of agricultural soils from harvest in the fall to planting in the spring is critical to the quality of our soil and water resource. Indeed, management influences mass and energy exchange processes at the soil surface which in turn governs the physics, chemistry, and biology of the soil ecosystem.

Impacts of Freezing and Thawing

The quality of our soil, water and air resources can be altered by soil freezing and thawing. Soil quality is dependent on the physical, biological, and chemical properties and processes of soils acting in concert. Surficial and ground water quality, as impacted by agriculture, are influenced by the release of chemicals from the soil system via leaching or runoff. Air quality is influenced by agricultural practices through efflux and influx of gases at the soil surface.

Soil resource

Soil properties and processes important in engineering and producing food and fiber are affected by freezing and thawing. For example, frost heave of roadways and building foundations as well as soil subsidence caused by thawing permafrost are visual

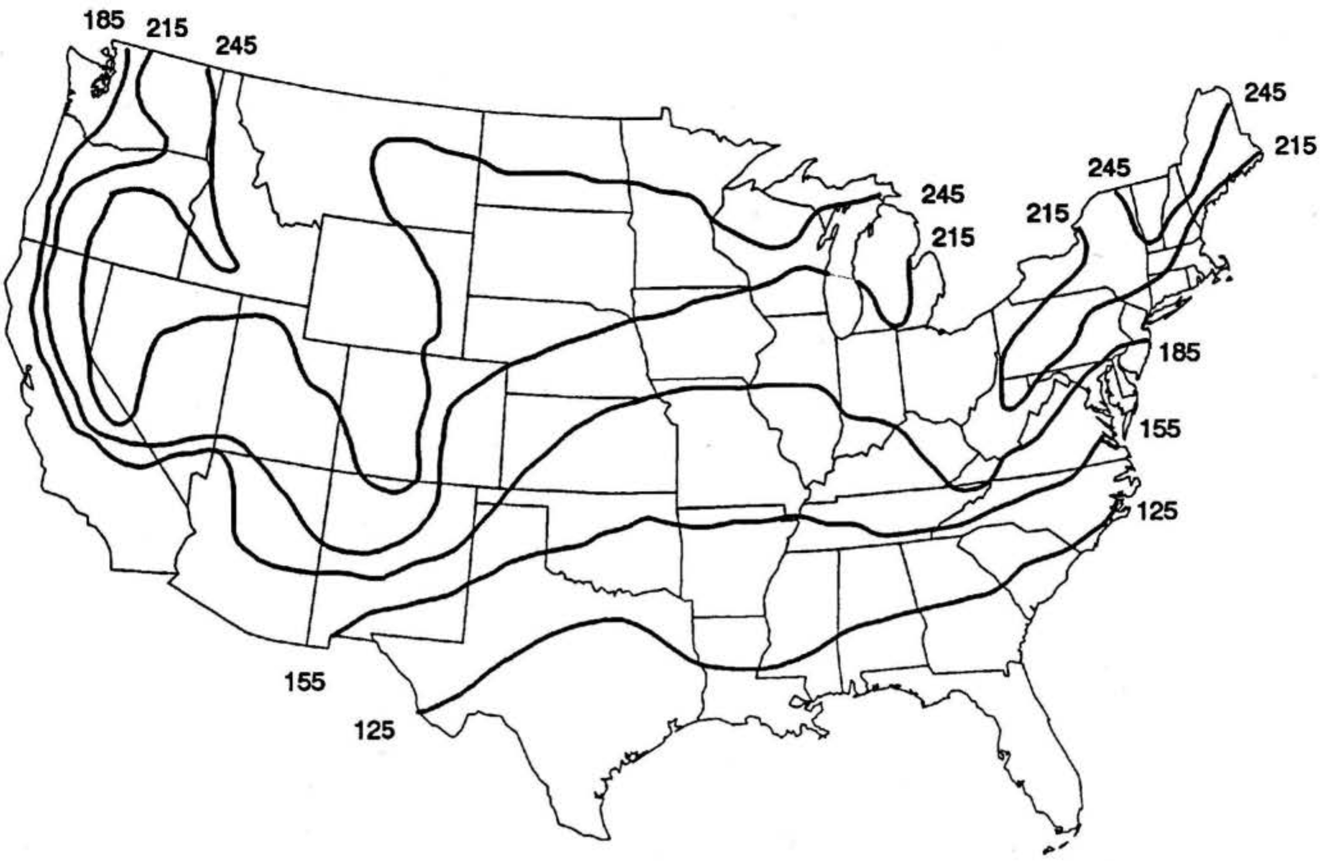

Fig. 2. Isolines of the number of days between the first freeze (air temperature below 0°C) in fall and the last freeze in spring. Adapted from (8).

manifestations and concerns in engineering designs. Wind and water erosion are threats to the sustainability and productivity of our soils and are commonly observed on agricultural lands when soils are frozen. Freeze-drying of soil aggregates and a decrease in soil shear strength caused by freezing and thawing accentuate these erosion processes.

Freezing and thawing influence the productivity of soils by imposing changes to the physical and mechanical properties of soils (10). Soil properties modified by freezing and thawing include heat capacity, thermal conductivity, electrical conductivity, hydraulic conductivity, infiltration, density, shear strength, penetrability, porosity, aggregate stability, and structure. Changes in these soil properties affect both soil productivity and agricultural operations. For instance, trafficability in wet fields is improved as soils freeze owing to an increase in soil strength. Freeze-thaw also plays an important role in weathering and soil formation (2).

Soil biota

Soil freezing and thawing is a major abiotic stress for organisms. The ability of soil fauna to adapt to frozen soils results in part from changes in migratory patterns and residence times within the soil profile. Other forms of adaptation of soil fauna to subfreezing temperatures include their ability to supercool or to enter freeze-resistant stages (11). Very little is known about the physical environment of soil fauna during the winter and the role of soil management in regulating overwinter faunal populations. A better understanding of winter ecological processes will improve our ability to manage these populations to enhance soil quality.

Perennial plants rely solely on physiological changes to avoid low temperature injury. Indeed, plants such as alfalfa and winter wheat are well adapted to the northern USA where soil temperatures often drop below the lethal temperature of about –20°C. Plant death may result from exposure to critically low temperatures caused by ice sheets or frost heave. Suffocation is another cause of death associated with ice sheets. Thus changes in soil properties, such as infiltration and porosity, associated with freezing may affect plant productivity.

Water resource

The hydrology of soils is a principal consideration in assessing available water storage capacity, ground water recharge, and runoff. The availability of soil water for plants and soil organisms is influenced by freezing and thawing as a result of water redistribution within a soil profile and changes in the infiltration and permeability of soils. Rapid fluctuations in ground water level at the onset of freezing in the fall or thawing in the spring have been attributed to the upward movement of water to the freezing front and to overwinter changes in preferential flow paths in the soil. Runoff from frozen soils is of concern in quantifying sediment and nutrient loss and in flood forecasting.

Water quality is also affected by freezing and thawing owing to the movement of chemicals with soil water and to changes in the availability of soil minerals (12). Lateral movement may be of greater magnitude than vertical movement of chemicals in frozen soils and is largely governed by topography, soil water content, and the type and depth of frost. Therefore, management methods that minimize the development of soil frost are desired to improve infiltration and reduce runoff in the spring.

Air resource

Air quality can be altered by soil freezing and thawing as ice sheets or impervious frozen soil layers impede the movement of air between the soil and atmosphere. Consequently, changes occur in the composition of soil air. Upon thawing, carbon dioxide and nitrous oxide (two gases important in regulating the global climate) in the lower soil profile have been observed to diffuse through the overburden into the atmosphere (13).

Airborne soil particles have recently been identified as an important component of air quality. Indeed, transport of soil particles into the atmosphere, which contribute to poor air quality, may be enhanced by the degradation of soil aggregates caused by freeze-drying.

Technologies for Assessing Frozen Soil Impacts

Simulation and observation of frozen soil processes improves our ability to manage agricultural lands for preserving and improving our soil, water, and air resources. Simulations have been developed over the past two decades to ascertain the water and temperature profiles of a freezing and thawing soil. Yet, few simulations have been validated using field data and few include chemical transport processes as a means of assessing the fate of chemicals in frozen soils.

Techniques to monitor the soil physical environment and to collect and store field and laboratory data have improved during the past decade with the refinement of the data logger. New and improved instrumentation in monitoring fluxes of radiation, vapor, heat, solutes, and gas; frost depth; soil water potential; infiltration; density; and porosity enable more accurate measurements of processes in the soil environment. Also, better capabilities to characterize ice lenses, snow depth and density, crop residue properties (e.g. extent of cover), and migratory patterns and physiological changes in soil organisms aid in evaluating the ecology of management systems.

National Frozen Soils Workshop

In 1990, about 40 people participated in an International Symposium on Frozen Soil Impacts on Agricultural, Range, and Forest Lands at Spokane, Washington. Since that time, there has not been a gathering of individuals interested in the freezing and thawing phenomena of agricultural soils. A workshop was held at Morris, Minnesota on March 22-23, 1994 to aid interaction and cooperation among scientists from across the USA with interest in processes and properties of frozen agricultural soils. The specific objectives of the workshop were to aid cooperation among scientists, discuss current research projects and methodologies, and identify research needs and priorities. The presentations made at the workshop, some of which appear in this issue, discuss the biological, chemical, and physical properties and processes of soils altered by freezing and thawing. This information helps development of sound management strategies for preserving our soil, water, and air resources.

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