THERMAL ENVIRONMENT OF SEASONALLY FROZEN SOIL AFFECTED BY CROP AND SOIL MANAGEMENT

Brenton S. Sharratt
United States Department of Agriculture (USDA), Morris, Minnesota, U.S.A.

INTRODUCTION

The thermal regime of soils during winter and spring can have a profound influence on civil engineering designs, watershed hydrology, and agricultural productivity. Alfalfa (*Medicago sativa* L.) and winter wheat (*Triticum aestivum* L.), for example, can die as a consequence of heaving as soils freeze and thaw. Heaving may lift plants above the soil surface where there is a greater risk for exposure of crown and root tissues to lethal temperatures of about −20°C. In addition, the presence of frozen layers within the soil profile can impede water infiltration during snowmelt and rain events as well as retard drainage as the soil thaws in spring. Drainage, as well as soil temperatures, can also affect the timing of field operations such as planting. Agricultural productivity, therefore, depends on moderating soil temperatures during winter and rapidly thawing the soil profile in spring. Soil temperature and thaw can be regulated to some extent through crop residue and soil management.

The thermal regime of seasonally frozen soils is dependent on the interrelated processes of heat and water transfer at the soil surface and within the soil profile. The processes of heat and water transfer at the soil surface are governed by atmospheric conditions and physical properties of the soil at the soil–atmosphere interface. Atmospheric conditions such as air temperature, humidity, solar radiation, wind, and precipitation influence the energy available for processes such as soil heating and evaporation. In cold regions, snow cover will modify the atmospheric conditions at the soil surface. Texture, density, water content, and ice content are important physical properties of soils affecting the transmission of heat through a frozen soil. Ice formation typically occurs in soils at temperatures below 0°C due to capillary and adsorption forces that reduce the free energy status of water in soils. The process of freezing and thawing affects the quantity of heat transmitted through soils since heat ($334\,J\,g^{-1}$) is liberated as pore ice freezes and must be absorbed to melt pore ice. The process of ice formation and melting requires nearly 100 times the heat ($4.2\,J\,g^{-1}$) expended in warming or cooling water by 1°C. Thus, heat transfer processes in soils are influenced by phase transitions that occur as soils freeze and thaw. Atmospheric conditions and physical properties of the soil at the soil–atmosphere interface can also be modified by the quantity and orientation of crop residue on the soil surface as well as by the depth and type of tillage.

CROP RESIDUE

Crop residues can mitigate soil erosion, protect plants from winter temperature extremes, and provide a favorable environment for seed germination in the spring. Residues act as a barrier to heat and water transfer between the atmosphere and soil, thereby retarding heat loss from the soil during winter and hindering the warming of soil in spring. This thermal retardation is illustrated in Fig. 1 for a clear day in late autumn, winter, and spring. On warm autumn and spring days, soil without residue cover was warmer during the daytime and cooler at night than soil with residue cover. On cold winter days, however, soil with residue cover remained warmer throughout the day than soil without residue cover.

Residue management alters the amount and orientation of crop residue on the soil surface. Various techniques employed in managing crop residues include cutting stubble at various heights, burning residue, removing residue from the seed row, and altering the color of the residue. The winter thermal regime of soil can be dramatically affected by the height of stubble, especially in regions where strong winds redistribute snow. Taller stubble traps more snow and thereby provides additional insulation to the soil that can reduce frost penetration, hasten thawing of the soil profile, and elevate soil temperatures (Table 1). Burning crop residue in autumn or spring can hasten soil warming in the spring by removing residue from the soil surface and temporarily elevating soil temperatures by 100°C or more (1). These high temperatures, however, are only sustained for a few minutes during the burn and near the soil surface. In

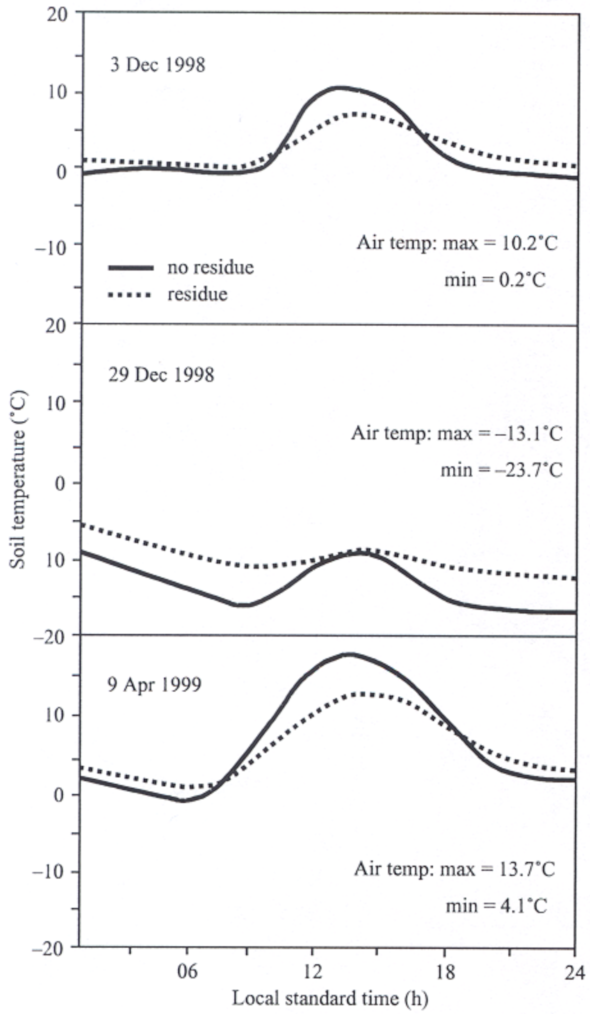

Fig. 1 Temperature at 1-cm depth of a soil with and without soybean (*Glycine max* L.) residue cover and without snow cover on a clear day in late autumn, winter, and spring near Morris, Minnesota.

addition, crop residue can be removed along the seed row to bolster soil temperatures during spring. Daily temperatures can rise by 2°C as the width of the band increases from 0 to 20 cm, but are unaffected by bands greater than 20 cm (2). Residue color can alter soil temperatures, but only on clear days without snow cover. Daily temperatures can be as much as 1–2°C higher for soils covered with black than with natural straw (3).

SOIL MANAGEMENT

Tillage is used to prepare a seedbed, alter the physical properties of soil to curtail erosion, and optimize the thermal regime of the seed zone. In cold regions, methods are sought that roughen, darken, and reduce the amount of residue on the soil surface to hasten soil warming in the spring. No tillage is advocated to conserve the soil resource, but this method often retards warming of the soil. Other methods such as strip tillage, ridge tillage, chisel plow, and moldboard plow are alternatives to managing the soil thermal regime. Strip tillage is accomplished in autumn or spring by cultivating in bands, thus resulting in a residue-free band. Little is known concerning spring temperatures achieved using strip tillage, but temperatures may be similar to those of residue-free bands. Ridge tillage can dramatically affect soil temperature in cold regions (4). Daily temperatures on a southerly slope can be elevated as much as 2°C over those on a level surface and 5°C over those on a northerly slope (Table 2). Spring soil temperatures are generally higher for moldboard and chisel plow owing to the rougher, darker, and smaller amount of residue on the soil surface compared with other tillage methods. Daytime temperatures can be 15°C higher, while nighttime temperatures can be 5°C lower, for moldboard plow than no tillage (5).

Crop and soil management practices that retard heat loss from soils in winter also slow the warming of soil in spring. Discovery of new residue management or tillage techniques that enhance soil warming during winter and spring is essential to the viability of agriculture in cold regions. These techniques will be identified only by

Table 1 Depth of frost penetration, day of year of complete soil thaw, and minimum soil (1-cm depth) temperature as influenced by corn (*Zea mays* L.) stubble height over three winters near Morris, Minnesota

	Stubble height			
	No stubble/residue	**15 cm**	**30 cm**	**60 cm**
Frost depth (cm)	91	78	46	22
Day of thaw	122	120	98	87
Soil temperature (°C)	−12.5	−10.0	−6.5	−6.0

Table 2 Average soil temperature at 1 cm depth on various aspects of a ridged soil surface for a clear, spring day at Fairbanks, Alaska[a] and Morris, Minnesota

		Aspect (°C)				
Location	**Date**	**North**	**South**	**West**	**East**	**Level**
Fairbanks	6 May 1990	4.9	9.0	7.5	7.3	8.0
Morris	22 March 1999	−2.0	2.5	0.6	0.4	0.7

[a] (Based on Ref. 4.)

improving our understanding of those physical properties of residue and soil that influence heat and water transfer between the soil and atmosphere.

REFERENCES

1. Rasmussen, P.E.; Rickman, R.W.; Douglas, Jr., C.L. Air and Soil Temperatures During Spring Burning of Standing Wheat Stubble. Agron. J. **1986**, *78*, 261–263.
2. Shinners, K.J.; Nelson, W.S.; Wang, R. Effects of Residue-Free Band Width on Soil Temperature and Water Content. Trans ASAE **1994**, *37*, 39–49.
3. Sharratt, B.S.; Flerchinger, G.N. Straw Color for Altering Soil Temperature and Heat Flux in the Subarctic. Agron. J. **1995**, *87*, 814–819.
4. Sharratt, B.S. Soil Temperature, Water Content, and Barley Development of Level vs. Ridged Subarctic Seedbeds. Soil Sci. Soc. Am. J. **1996**, *60*, 258–263.
5. Gupta, S.C.; Larson, W.E.; Linden, D.R. Tillage and Surface Residue Effects on Soil Upper Boundary Temperatures. Soil Sci. Soc. Am. J. **1983**, *47*, 1212–1218.