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Simultaneous Heat and Water Model of a Freezing Snow-Residue-Soil System II. Field Verification

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ABSTRACT

Frozen soil has a major effect in many hydrologic and erosion situations, but it is very difficult to predict, especially on tilled agricultural soils with crop residue and intermittent snow cover. A **S**imultaneous **H**eat **A**nd **W**ater (SHAW) model to provide this predictability by simulating the interrelated heat, water and solute transfer through snow, crop residue and soil was presented in a companion paper (Part I). Detailed climatic, soil temperature, water content and frost depth data were collected for six diverse tillage-residue conditions during two winters to verify the model predictions. When compared to measured values, simulated soil temperatures were excellent, simulated frost depths were quite good, and simulated soil water profiles were good. Minimal calibration was necessary because the model uses fundamental equations for heat and water transfer with readily definable site parameters.

INTRODUCTION

Tillage, crop residue cover and snow cover greatly affect the occurrence, depth and permeability of frozen soil. Severe runoff and erosion commonly occur as a result of rainfall or snowmelt on impermeably frozen soil. Many studies have examined the effects of snow, tillage and residue on the depth and permeability of frozen soil (Post and Dreibelbis, 1942; Stoeckeler and Weitzman, 1960; Willis et al., 1961; Benoit et al., 1986). In northeastern Oregon, studies show that standing stubble reduced frost penetration an average of 35% compared to bare-surface plots (Pikul et al., 1986). In Minnesota, plots where a 5-cm, 5100 kg/ha layer of oak leaf litter was removed averaged 20 cm deeper frost than undisturbed plots, and removal of a 13-cm snow layer caused plots to freeze an average of 38 cm deeper than snow-covered plots (Thorud and Duncan, 1972).

Studies show that tillage and crop residue management affect soil freezing, but their effects have been difficult to predict. In Part I, Flerchinger and Saxton (1988) developed a one-dimensional **S**imultaneous **H**eat **A**nd **W**ater (SHAW) model which simulates the physics of a snow-residue-soil system and provides predictability and understanding of frozen soil occurrence. To test the validity of the model, a detailed set of climatic, soil temperature, water content and frost depth data were collected for six diverse tillage-residue conditions over two winter seasons. Frost depth, soil temperature and water content predicted by the model were compared with field measurements. Solute transport was not included in model verification.

FIELD PROCEDURE

Data to test the model were collected over two winter seasons (1985-86 and 1986-87) on the USDA Palouse Conservation Field Station located 3 km NW of Pullman, WA. Six plots were established in a Palouse silt loam (fine-silty mixed Mesic Pachic Ultic Haploxeroll) on a 17% south-facing slope having been annually cropped with winter wheat. Plot treatments included two residue levels: low (L) and high (H); and three types of tillage: no-till (NT), fall chisel (FC) and conventional tillage (CT). No-till is an effective conservation practice gaining acceptance by farmers whereby a crop is sown directly into the stubble from the previous crop; fall chisel enhances over-winter infiltration by coarsely fracturing the soil and creating macro-porosity seldom blocked by ice; and conventional tillage implies a clean-tilled, finely pulverized seedbed often obtained with a plow and disk operation, and is highly susceptible to runoff and erosion. Residue levels were established in the fall prior to tillage using wheat straw and all plots were seeded with a double-disk drill in late October.

Both years of the study period had three freeze-thaw cycles within the upper 15 cm of soil (the first freeze cycle for 1985-86 came in mid-November before instrumentation was in place). Air temperature and precipitation data for the study period along with historic means are summarized in Table 1. Colder-than-normal air temperatures during November and December of 1985 resulted in frost penetration down to 30 cm on plots with little residue (quite deep for this region). Although precipitation was below normal for this period, persistent cold temperatures provided some snow cover for much of the winter. Temperatures during the 1986-87 winter season were very close to normal, except for a brief cold spell in November and a more severe one during the latter half of January. Maximum frost depth during the second year was approximately 12 cm.

Measured atmospheric data for the study included hourly air temperature, relative humidity, wind speed, solar radiation and precipitation. During the 1986-87 winter, anemometers were also placed at heights of 0.5 and 1.0 m for estimating wind profile roughness. Net radiometers were placed at a height of 1 m over each of

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TABLE 1. Precipitation and Average Air Temperature for Study Period

Period	Daily Temperature Maximum (C)	Daily Temperature Minimum (C)	Precipitation (mm)
1985-86 winter			
November 15-30, 1985	−8.6	−15.3	29.0
December 1985	−1.8	−8.6	20.3
January 1986	4.7	−0.3	71.4
February 1986	5.7	−1.3	95.5
1986-87 winter			
November 4-30, 1986	4.7	−0.8	80.0
December 1986	1.7	−3.3	21.6
January 1987	1.1	−5.2	45.5
February 1987	6.2	−0.6	24.1
Historic mean			
November	6.6	−0.9	67.1
December	2.9	−3.3	78.0
January	1.2	−5.4	73.4
February	4.8	−2.3	53.1

TABLE 2. Residue and Tillage Layer Properties for Field Plots

Plot designation*	H-FC	H-CT	H-NT	L-NT	L-FC	L-CT
Tillage	Fall chisel	Conventional	No-till	No-Till	Fall chisel	Conventional
Slope (%)	14.5	14.5	14.6	15.4	17.0	17.0
			1985-86 winter			
Pre-tillage residue (kg/ha)	6720	6720	16600†	4400†	1680	1680
Post-tillage residue (kg/ha)	7300	2600	16600	4400	0‡	0‡
Residue layer thickness (cm)	2.5	1.0	5.0	2.2	0.0	0.0
Saturated conductivity (cm/hr)	0.39	0.11	0.12	0.12	0.32	0.11
Air entry potential (cm)	−47	− 9	−20	−28	−41	−12
Pore-size distribution index, b	4.08	4.10	4.35	4.35	4.08	4.10
0-10 cm bulk density (gm/cm^3)	1.10	1.12	1.31	1.24	1.10	1.12
10-20 cm bulk density (gm/cm^3)	1.15	1.17	1.31	1.29	1.13	1.15
20-30 cm bulk density (gm/cm^3)	1.21	1.19	1.26	1.26	1.21	1.17
			1986-87 winter			
Pre-tillage residue (kg/ha)	6720	6720	10415†	2130†	1680	1680
Post-tillage residue (kg/ha)	1870	0‡	10415	2130	0‡	0‡
Residue layer thickness (cm)	0.4	0.0	3.0	0.5	0.0	0.0
Surface covered by residue (%)	47.	34.	91.	60.	12.	26.
Saturated conductivity (cm/hr)	0.50	0.85	0.12	0.12	0.49	0.12
Air entry potential (cm)	−47	−35	−20	−28	−41	−40
Pore-size distribution index, b	4.08	4.10	4.35	4.35	4.08	4.10
0-10 cm bulk density (gm/cm^3)	0.93	1.00	1.36	1.23	0.95	0.95
10-20 cm bulk density (gm/cm^3)	1.19	1.32	1.35	1.37	1.11	1.26
20-30 cm bulk density (gm/cm^3)	1.21	1.19	1.35	1.35	1.21	1.17

* H = heavy residue application (6720 kg/ha)
L = light residue application (1686 kg/ha)
FC = fall chiseled
CT = conventional tillage
NT = no-till

† Includes annually applied residue plus partially decomposed residue from earlier applications.

‡ Only a trace left on surface.

the six plots for verification of the model's radiation estimates.

A soil temperature profile for each plot was monitored every three hours using thermocouples placed just beneath the soil surface and at depths of 7.5, 15, 25, 38, 53, 69, 84, 107, 137 and 168 cm. The surface thermocouple was covered with a thin (1-2 mm) layer of soil. Periodic checks seldom found the surface thermocouple exposed, and measurements with an infrared thermometer compared very well with those from the surface thermocouples.

Soil frost depth was measured in all six plots using cylindrical gypsum moisture blocks read every three hours and frost tubes (McCool and Molnau, 1984) read daily. Moisture blocks provided frost indication at only discrete depths. Blocks were placed at the same depths as thermocouples down to a depth of 38 cm. Frost tubes, which consisted of a clear plastic tube filled with methylene-blue dye solution, offered measurements over continuous depths, but considerably lagged the frost front as the soil thawed. Frost tubes generally indicate the depth of the 0°C isotherm, which may be somewhat deeper than the zone of ice formation, particularly in dry soils.

A soil-water profile (liquid plus ice) was determined for each plot every one to two weeks throughout the winter. Soil samples to a depth of 25 cm were collected for gravimetric analysis using a 2-cm soil sampler. Deeper water contents were obtained using a neutron probe. Snow depths were measured daily and snow density and water equivalent were measured periodically.

Soil and residue properties controlling heat and water flow through different residue-tillage surface conditions are essential for model simulation. Residue and near-surface soil properties have the largest effect on moisture and heat transport. Field measurements were therefore concentrated on defining properties of the residue and tillage layers and are summarized in Table 2. Soil properties beneath the tillage layer were estimated based on bulk density and texture.

Residue present on the surface was determined by collecting, weighing and drying the residue from three 25 cm by 25 cm random samples. Percent cover was obtained by photographing a grid system laid over the surface, then determining the percentage of grid points where residue covered the soil.

Saturated conductivity, saturated water content, air entry potential and pore-size distribution index define the hydraulic characteristics of the soil. Saturated water content was assumed equal to the porosity and was estimated from bulk density and an assumed particle density of 2.65 gm/cm^3. Surface bulk density was measured using an *in situ* water-displacement method (SCS, 1987). Saturated conductivity was measured using a Guelph permeameter (Reynolds and Elrick, 1985) and air entry potential was measured using an air entry permeameter (Bouwer, 1966). Matric potential—moisture content curves for representative tillage layer samples were obtained by Kenny (1988) for various tillage operations on a Palouse silt-loam soil using a filter paper technique for measuring water potential.

Kenny (1988) measured soil thermal conductivity for various densities, moisture contents and tillage operations using a thermal conductivity probe similar to that described by Jackson and Taylor (1965). Weighting factors in equation [10] (Part I) of 0.2, 2.5 and 1.0 for the mineral fraction, air porosity and water content, respectively, were determined based on these measurements. Thermal conductivity of the mineral fraction was taken as 7.3 W/m/C based on a weighted average of approximately 75% quartz (sand and silt) and 25% clay minerals with conductivities of 8.8 and 2.9 W/m/C respectively. Based on DeVries (1963), the weighting factor for ice content could range from 0.50 for nearly spherical ice crystals to 0.75 for ellipsoidal crystals. Ice crystals are more nearly spherical, thus the weighting factor was assumed to be 0.50.

Wind profile parameter z_m was 6 mm for the residue-soil surfaces and 1.5 mm for snow-covered plots based on average wind travel at three heights for several days. Although wind profiles were not measured for each plot, the profile measured was generally downwind of all plots and would tend to give the average roughness height of all plots. Roughness parameter z_H for a residue-soil surface was taken as $0.2z_m$, or 1.2 mm, as suggested by Campbell (1977). A distinction is typically not made between thermal and momentum roughness parameters for snow, and z_H was therefore assumed equal to z_m. The zero-plane displacement d was taken as zero for all soil-residue surfaces or the depth of snow when snow was present.

MODEL CALIBRATION

Data from the moderate freeze period in December 1986 for the two extremes in residue and tillage, i.e., the heavy residue no-till plot (H-NT) and the light residue conventionally-tilled plot (L-CT) were selected for calibration of the SHAW model. Calibration consisted of determining surface albedo by comparing measured and predicted net radiation. Parameters adjusted during calibration were residue albedo, soil albedo and parameters describing the fraction of surface covered by shallow snowpacks.

Soil albedo was calibrated using plot L-CT, which was essentially bare after tillage. Although soil albedo varies with water content (Bowers and Hanks, 1965), a constant soil albedo of 0.25 provided a reasonable comparison between daytime (positive) values of simulated and measured net radiation for this period as shown in Fig. 1. Slope of the regression line for positive values of net radiation was 1.14 with a correlation coefficient (r^2) of 0.81. Most of the outlying points in Fig. 1 were attributed to snow on the ground when the model predicted no snow, or to frost which formed on the net radiometers.

While daytime, net radiation was estimated reasonably well, nocturnal long-wave radiation (negative net radiation) compared rather poorly for two probable reasons. First, the net radiometers may not be as accurate during the night due to calibration sensitivity for long-wave radiation and frost formation on the radiometers. Second, cloud cover and atmospheric emissivity were estimated from daytime solar radiation and assumed constant for the day. Therefore, on clear days with cloudy nights (or vice versa), it is not likely that nocturnal simulated atmospheric emissivity will be correct.

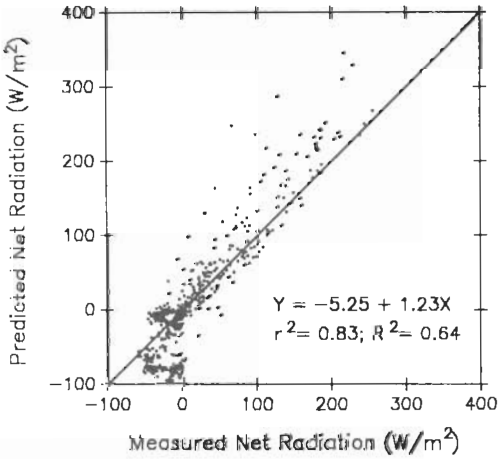

Fig. 1—Predicted vs measured hourly net radiation rates compared to a 1:1 line for plot L-CT, a conventionally-tilled bare soil surface during December 1986.

The calibrated value for soil albedo (0.25) was used with data from plot H-NT to calibrate residue albedo. Net daytime radiation was significantly less on the residue-covered plot (H-NT) than on the bare soil (L-CT). A value of 0.40 for residue albedo provided good comparison between simulated and measured daytime net radiation. Nocturnal radiation again had fairly poor agreement.

Parameters describing the fraction of surface cover for shallow snowpacks were calibrated using the approximate time of snowcover depletion and the net radiation for the period of snowcover. Values of 0.07 m for d_{min}, which was approximately the height of the furrows, and 2.0 for a in equation [1] (Part I) were selected. These values provided good comparisons between simulated and observed snowcover depletion and net radiation for both residue-covered no-till and conventionally-tilled bare soil surfaces.

MODEL VERIFICATION

Model verification was accomplished by first examining soil temperature, water content and frost depth from the calibration period, and then applying the model to situations more and more unlike calibration conditions. Model results were examined for the moderate freeze in December 1986, the shallow freeze in November 1986, and the relatively deep soil freeze in January 1987 on the two plots used for calibration. Using the values for albedo and partial snow cover from the calibrated plots, the model was run for the four remaining plots for the entire 1986-87 winter, and for all six plots for the 1985-86 winter. During model verification, no further parameter adjustments were made. Only those parameters listed in Table 2 representing variations in field plot conditions were reset.

December 1986

The SHAW model was first verified using plots H-NT and L-CT over the short time period in December 1986 for which net radiation estimates were calibrated. Soil temperature and moisture profiles were initialized using measurements collected on December 4 (day 338). Calibrated and measured input parameters, hourly weather data and periodic measurements of temperature and water content at the lower boundary (167 cm deep within the soil profile) were input to the model.

Comparison of frost tubes, moisture blocks and simulated values of frost depth for plots L-CT and H-NT in Figs. 2 and 3 illustrate the effectiveness of tillage and residue management on frost depth since these plots were subjected to the same climatic conditions. Moisture blocks, being at discrete depths, tended to underestimate frost depth. Frost tubes, which indicate the depth of the 0°C isotherm, tended to overestimate frost depth and lagged the actual frost depth as the soil thawed. Simulated frost depth was most often between frost tube

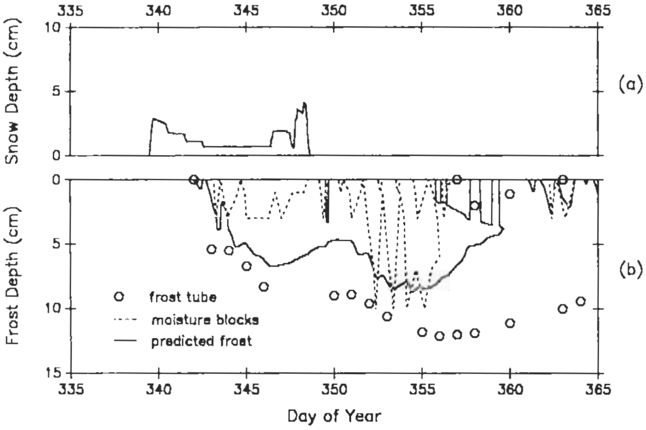

Fig. 2—Snow and frost depth for plot L-CT, a conventionally-tilled bare soil surface, during December 1986. (Measured snow depths were not avaiable).

and moisture block values (Figs. 2 and 3). The good agreement between simulated and measured frost depth illustrates the model's capability to represent significantly different tillage-residue combinations.

Near-surface, soil temperature remained near freezing and had little variation over the simulation period. Average hourly measured surface temperature was 0.36°C for H-NT and 0.46°C for L-CT, and standard deviation for the top three depths (surface, 7.5 cm and 15 cm) ranged from 0.54 to 0.91°C. With such little variation in measured values, the coefficients of determinaion (R^2), which is the fraction of variation in measured temperatures explained by the model, were quite low (generally below 0.38 for the near-surface temperatures). Simulated soil temperatures were better than what the R^2 values indicated. On average, soil temperature for the top three depths was overpredicted by 0.16, 0.10 and 0.03°C, respectively, for H-NT and underpredicted by 0.48, 0.25 and 0.23 for L-CT.

Simulated and measured soil water contents showed good agreement. The initial soil water content profile on day number 338 (December 4) and a comparison of simulated and measured water content profiles at approximately two and four weeks later are presented for plot L-CT in Fig. 4.

November 1986

Simulations for plots H-NT and L-CT using data from November 4, to December 4, 1986 (day number 308 to 338) showed excellent agreement with measured temperatures for both plots. Parameters describing plot characteristics were left unchanged from the calibration period of December 1986. Simulated and measured soil temperatures at the surface, 7.5-cm and 15-cm depths for plot L-CT are illustrated in Fig. 5. The coefficients of determination, R^2, for these three depths were 0.80, 0.91 and 0.93, respectively, for plot L-CT and 0.79, 0.77 and 0.83 for H-NT.

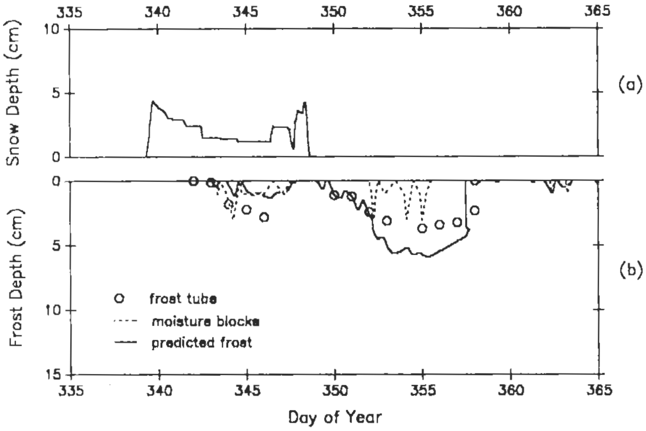

Fig. 3—Snow and frost depth for plot H-NT, a no-till plot with heavy residue cover, during December 1986. (Measured snow depths were not available).

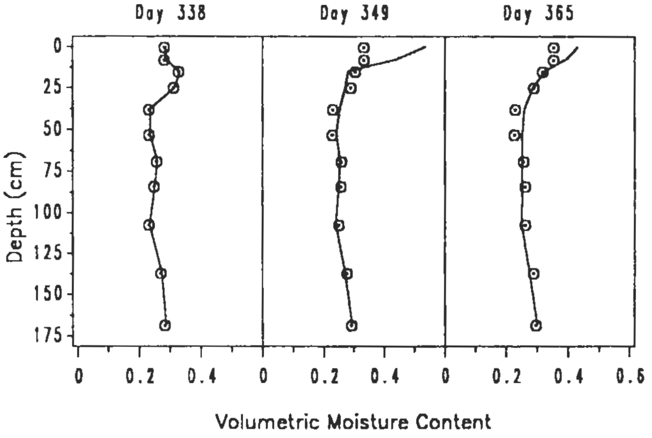

Fig. 4—Soil water profiles (liquid plus ice) for plot L-CT, a conventionally-tilled bare soil surface during December 1986 (predicted ________; measured ⊙).

January 1987

Simulations for December 31 to January 28, 1987 predicted maximum frost depths of 12 cm for plot L-CT, and 6 cm for plot H-NT, on January 11. This compares well with measured values of 10 cm and 3 cm respectively, as measured by moisture blocks, and 14 cm and 6 cm as measured by frost tubes. Colder air temperatures followed later in the month, but 15 cm of snow which fell on January 14 inhibited further frost penetration. Complete melt of the snowpack was predicted three days sooner than observed (approximately January 28) on plot H-NT and two days sooner than observed on L-CT.

Winter of 1986-87

To further verify its operational capabilities, the

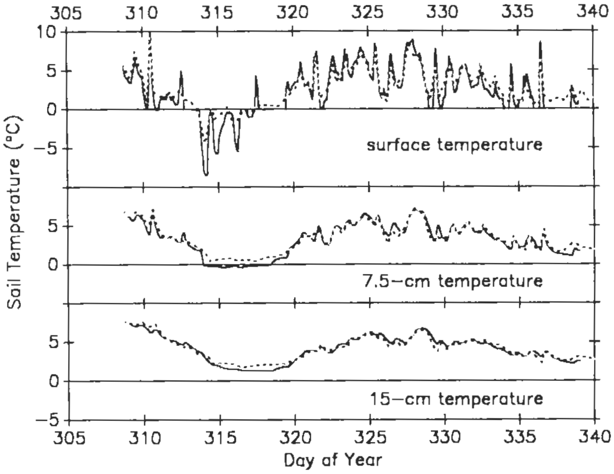

Fig. 5—Soil temperature for plot L-CT, a conventionally-tilled bare soil surface, during November 1986 (predicted ______; measured ----).

SHAW model was run using data from November 4, 1986 to January 28, 1987 (day number 308 to 28) for plots H-FC, H-CT, L-NT and L-FC based on the calibration results from H-NT and L-CT. The model was initialized on November 4 for each plot with measured values of soil temperature and moisture, and was run using measured climatic data for the 85-day simulation period.

Frost depth was consistently underpredicted for plot H-FC, a fall chisel plot with a small amount of residue on the surface. Predicted maximum frost was 6.5 cm on January 11 compared to measured frost depth of 10 cm. Apparently too much insulating effect was attributed to what little residue was present. Predicted frost depths were better for L-NT, a no-till plot with slightly more residue on the surface. Predicted maximum frost depth was 9 cm compared to measured values of 10 and 12 cm by moisture blocks and frost tubes, respectively.

The model simulated frost quite well on plots H-CT and L-FC. Plot H-CT was conventionally tilled, plot L-FC was fall chisel, and both plots had essentially no residue on the surface. Predicted maximum frost depth for both plots was 9 cm on January 11. Measured frost depths for these plots were 7 and 10 cm, respectively, by moisture blocks, and 12 cm for both plots by frost tubes.

Simulated temperatures agreed well with measured values. R^2 values for the top three soil depths ranged from 0.71 to 0.74 for plot H-FC, and from 0.75 to 0.93 for the other three plots. R^2 values for deeper soil temperatures ranged from 0.71 to 0.96 for H-FC, and from 0.84 to 0.97 for the other plots.

Winter of 1985-86

The winter of 1985-86 had three freeze-thaw cycles. The first came in mid-November before instrumentation was in place, and the second and third were so closely spaced that not all of the plots completely thawed between cycles. Drifting of snow caused some variability in snow depth among plots. As a result, measured precipitation for H-FC was increased from 8.4 mm to 16.8 mm on December 8 (day 342) based on snow depth and density measurements. Simulations were made from November 18, 1985 to January 25, 1986 (day 322 to 25), for all six plots using calibration results from December 1986.

The field plots were much drier during 1985-86 than 1986-87. Water content below 30 cm on plots L-FC and L-CT was extremely low—approximately 7 to 9% by volume. Ice formation in such dry soil requires temperatures substantially below 0°C. Frost tubes are not a good indication of frost depth in such dry soils, however the 0°C isotherm obtained from simulated temperatures compared extremely well with frost tube data for these two plots (except when the frost tube lagged during thawing) as shown for plot L-CT in Fig. 6.

Plots H-FC, H-NT and L-NT had considerably more residue left on the surface after tillage in the fall of 1985 than in 1986 (Table 2). The model predicted snow and frost depth adequately for plot H-FC, a fall-chiseled plot with a relatively heavy residue cover. Maximum predicted frost depth was 11 cm compared to 13 cm for frost tube measurements and 10 cm for moisture blocks. The 0°C isotherm indicated by frost tubes was approximately 15 cm deeper than frost depth indicated by moisture blocks on plots H-CT, H-NT and L-NT. Field observations made while collecting moisture samples on December 31 (day number 365) indicate frost depths approximately midway between the moisture block and frost tube data. Observed frost depths for this day were approximately 23 cm for H-CT, 15 cm for H-NT and 20 cm for L-NT. Predicted frost depths on this day were 21, 25 and 28 cm, respectively. Frost depth was overpredicted for plots H-NT and L-NT, but was closely predicted for H-CT.

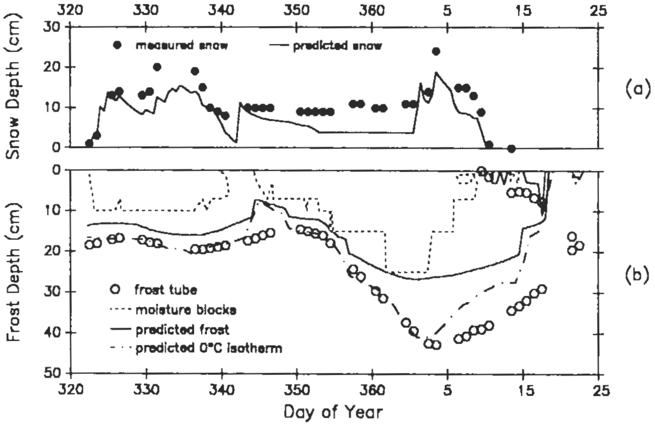

Fig. 6—Snow and frost depth for plot L-CT, a conventionally-tilled bare soil surface, during 1985-86 winter.

CONCLUSIONS

A detailed set of climatic and soil profile data was collected over two winter seasons (1985-86 and 1986-87) on six plots with three tillage treatments and two residue loadings. Both years had three freeze-thaw cycles. Maximum frost depth for bare-surface tilled plots was approximately 30 cm the first year of the study, and approximately 12 cm the second year. Maximum frost depth in residue-covered no-till plots was about half that of bare-surface tilled plots.

After minor calibration, simulations of soil temperature, freezing and water content using the SHAW model compared well with data collected over the two winter seasons. Model calibration consisted of determining appropriate albedo values for soil and straw by using data from one freeze-thaw cycle in December 1986. Results showed that simulated soil temperatures were in very good agreement with measured values, with coefficients of determination ranging from 0.80 to 0.97 in most cases. Simulated frost depth was quite good, being within 2 or 3 cm of actual frost depth for most simulations, and simulated soil water content profiles were good.

The SHAW model has good capabilities for predicting the impacts of various residue-tillage surface configurations on soil temperature, water and freezing. It can be used to evalute tillage-residue management options for hydrology, erosion and crop production. The model is based on fundamental physical equations for heat, water and solute flux; thus it requires minimal calibration and may be easily parameterized for different tillage, residue, topographic and atmospheric conditions.

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