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MODELLING TILLAGE EFFECTS ON SOIL PHYSICAL PROPERTIES AND MAIZE (*ZEA MAYS*, L.) DEVELOPMENT AND GROWTH

By

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ABSTRACT

MODELLING TILLAGE EFFECTS ON SOIL PHYSICAL PROPERTIES AND MAIZE (*ZEA MAYS*, L.) DEVELOPMENT AND GROWTH

By

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Conservation tillage controls soil erosion by keeping residue cover at the soil surface. The presence of a residue cover in a humid temperate climate affects soil environment by increasing soil surface water content, thus decreasing soil temperature and plant development. The effects of four residue covers on soil temperature, soil water content, plant development and growth, and final biomass were studied at East Lansing, Michigan, on a Conover loam (Fine-loamy, mixed, mesic Udollic Ochraqualf). Soil temperature on the fully covered plots were on the average 2 ^{o}C colder than the bare surface. In 1990, due to a cold spring, maize development was delayed by two leaves on the 100% residue covered plots. In 1991, temperatures in the spring were warmer, reducing the period when the meristem was below ground, thus maize development delay was smaller. Soil surface water content was higher on the covered plots than the bare plots. The effect of the residue cover on soil water content was negligible below 50 cm on the fallow plots. Leaf growth was delayed but not reduced. Leaves senesced faster in 1991 on the 100% covered plots. Plant water content was higher at harvest on the covered plots than on the bare plots. In 1991, differences in growth were smaller. Plant development prediction using soil

temperature while the meristem was below ground gave better results than using air temperature for the whole growing season. The CERES models leaf development prediction was improved by changing the soil temperature prediction model to account for residue cover and using soil temperature at 2.5 cm to calculate thermal time. A model of soil surface properties changes due to rainfall intensity and residue cover was added to better predict water infiltration, soil surface bulk density, and ponding capacity. The model was run for four sites in Michigan to evaluate the consequences of residue management on rainfed maize final yield, and annual runoff. The no-till strategy increased the length of the vegetative stage and plant water availability; this increased yield and economic return for rainfed maize. The annual runoff was higher on the no-till strategy.

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LIST OF SYMBOLS

Albedo	....	Field albedo
ALX	....	Delay in maximum temperature due to geographic location
A_m	....	Residue cover capacity (ha kg^{-1})
AMP	....	Yearly air temperature amplitude
As	....	Aggregate water stability (%)
ASW	....	Air dry soil water content
BD(L)	....	Bulk density of layer L
CANCOV	....	Canopy cover
CODTILL	....	Tillage code number
D1	....	Fraction of easily decomposable residue
DEPTILL	....	Depth of tillage (cm)
Doy	....	Day of the year
E_c	....	Canopy evaporative demand reduction coefficient
E_m	....	Surface residue evaporative demand reduction coefficient
Eo	....	Potential evaporation
Eos	....	Bare soil potential evaporation
FC	....	Fraction of soil covered by surface residue
FF	....	Water factor to calculate change in soil albedo
FOM(L)	....	Fresh organic matter content of layer L
FRACTILL	....	Fraction of residue incorporated at tillage (%)
KE	....	Precipitation intensity
K_l	....	Decomposition rate of the labile pool (day^{-1})
K_r	....	Decomposition rate of the resistant pool (day^{-1})
KSMACRO	....	Saturated water conductivity with macropores
KSMTRX	....	Saturated water conductivity without macropores
MULCH	....	Amount of residue left at the surface (kg ha^{-1})
MULCHALB	....	Residue albedo
MULCHCOV	...	Residue cover
$MULCH_l$	....	Amount of surface residue in the labile pool (kg/ ha)
$MULCH_r$	....	Amount of surface residue in the resistant pool (kg ha^{-1})
MULCHSAT	....	Residue water content at saturation (cm)
MULCHSW	....	Residue water content (cm)
OC(L)	....	Organic carbon content of layer L
POND	....	Amount of surface water ponding (cm)
PONDMAX	....	Maximum surface water ponding capacity (cm)
PRECIP	....	Amount of precipitation or irrigation (cm)
RAIN	....	Precipitation amount (cm)
Rstl	....	Surface property reduction coefficient
Salb	....	Wet soil albedo
Salbedo	....	Dry soil surface albedo

SAT(L)	....	Soil water content at saturation
SCN	....	Residue C:N ratio
SOILCOV	....	Fraction of soil covered
Solrad	....	Daily solar radiation (MJ m^{-2})
ST(L)	....	Layer L soil temperature
SUMDTT	....	Thermal time from emergence
SUMKE	....	Cumulative precipitation intensity
SW(L)	....	Soil water content of layer L
TA	....	Normalized soil temperature
TAV	....	Yearly air average temperature
TEMPFAC	....	Temperature factor affecting residue decomposition
TEMPM	....	Daily air average temperature
TEMPMN	....	Daily air minimum temperature
TEMPMX	....	Daily air maximum temperature
TILLBD	....	Bulk density at time of tillage
TILLPOND	....	Ponding capacity at time of tillage
TIME	....	Interval length (hr)
TLN	....	Total leaf number
TMA	....	Soil surface temperature
WATFAC	....	Water factor affecting residue decomposition
ZD	....	Soil temperature damping coefficient

Chapter 1: Residue management and soil environment

Introduction

"Typically each hectare in the U.S. is losing soil and producing an average sediment of 6.7 Mg/ha. Croplands are the source of nearly 50% of the sediment and erosion; these lands erode about 30% more than the overall erosion average for all lands" (Miller and Donahue, 1990).

The increasing demand for food production pushed farmers to use lands less suitable for agriculture. The rapid need for new land and economic productivity requirements prevented farmers from adequately preparing the land and using conservation techniques. Because of diminished soil cover and decreased soil aggregate stability, soil erosion increased on land prepared for agriculture or construction. Water and wind remove the surface layer of soil that is rich in organic matter and nutrients necessary for crop growth and brings to the surface a coarser and poorer material. The land then becomes less productive, increasing the need for external inputs such as water and fertilizers. The rebuilding of soil productivity is a slow process. Hence soil erosion impairs agricultural land use for the present and the future (Wolman, 1985).

Soil erosion also has other deleterious consequences upon the environment. The soil removed from one location by erosion is translocated to other environments where its high levels of nutrients and fine particles are undesirable. For example, these nutrients, when added to streams and lakes, favor eutrophication, and the presence of fine particles increases the turbidness of the aquatic habitat (Frere, 1976).

Conservation tillage has been developed to control soil erosion. However, we need to evaluate the performance of new techniques in different environments and their consequences on yields and costs of production. To better control and evaluate soil erosion we need to understand the processes involved. The following is a brief description of processes involved in soil erosion.

The erosion process

Erosion occurs in three stages: detachment, transport, and deposition. A soil particle or aggregate is detached from the soil surface when a force with higher energy than its binding forces is exerted on the soil surface. Wind or water with energy higher than the gravity force exerted on soil can detach particles from the surface and carry them away. When the energy drops below the particles' terminal velocity, the element settles. Three main erosive processes are usually considered in accelerated erosion: splash erosion, run off erosion, and wind erosion.

Splash erosion

Water falling on the soil surface reaches it with an energy that is a function of the storm intensity or the sprinkler irrigation characteristics. The physical impact of a water drop on a soil aggregate of fine sand and silt particles may break it apart because of the particles' light weight and low binding forces. This creates a muddy water that clogs soil pores and forms a crust at the soil surface causing greatly reduced infiltration rates and increased run-off (McIntyre, 1958, Al-Durrah and Bradford, 1982). Aggregate stability and the energy of water drops reaching the soil surface determine the extent of splash erosion.

<u>Runoff erosion</u>

When precipitation rate is higher than soil infiltration rate, water that cannot infiltrate stays at the soil surface and ponds. The amount of water that can pond is determined by the slope, soil micro-relief created by tillage, and physical barriers such as plants and surface residues. When no more water can be stored and the precipitation rate is still higher than the infiltration, water runs off (Brakensiek and Rawls, 1982).

Due to their bipolarity, water molecules bond with soil elements weakening the bond between soil particles. Thus at high water content, a soil aggregate is more likely to be broken by a disruptive force of low energy. When water runs off, the soil surface is saturated and thus more erodible. Water detaches soil particles and moves them, increasing its abrasive effect on other aggregates, thus accelerating the erosion process (Foster, 1982). When the surface water slows down, its energy decreases and the particles settle. Runoff erosion is hence dependent on soil water infiltrability, soil surface ponding capacity, pathways of surface water, and aggregate stability.

Wind erosion

Winds with sufficient energy can detach soil particles from the soil surface. When the soil surface is dry, soil particles are lighter and easier to detach, making the blowing wind more erosive. The distance detached soil particles travels depends on their weight and the wind energy or velocity (Chepil and Woodruff, 1963; Lyles *et al.*, 1985). Three types of soil particle movement are considered: surface creep of large particles (0.5 to 1.0 mm), saltation of medium size particles (0.05 mm to 0.5 mm), and suspension of small particles (less then 0.05 mm). Larger particles travel less in distance but have a higher abrasive role on other particles. When they move at the soil surface they bump into other soil aggregate particles and tend to break them into smaller particles. Small soil particles picked up by wind can reach higher winds and thus travel longer distances than larger particles. Wind erosion magnitude is linked to wind velocity at the soil surface and soil aggregate stability

Prevention of soil erosion

Soil erosion can be decreased by diminishing particle detachment that depends on soil binding forces and the magnitude of disruptive forces on the soil surface.

Soil aggregate stability

As seen above, the strength of soil aggregate binding is important as it defines how easily a soil particle can be detached from the soil surface. Aggregate stability depends on the quantity and quality of cementing agents in the soil layer. The major cementing agents are clay particles, ion oxides (primarily $CaCO_3$, Fe_2O_3, Al_2O_3) (Römsken *et al.*, 1987), and soil organic matter (Chaney and Swift, 1984). These agents increase the bonding between soil particles and create peds or aggregates more resistant to erosive forces.

Whereas clay particles and ion levels depend mostly on the weathering of the parent material, organic matter depends more on agricultural soil management and climate. Because soil organic matter decomposes, agricultural practices such as burning crop residues or deep plowing that remove new additions of fresh organic matter at the surface will decrease aggregate stability, making particle detachment more likely.

Hence keeping soil organic matter in the surface layer at sufficient levels (up to 7% of organic carbon) provides better aggregate stability reducing soil erosion risks. A complementary approach to soil erosion prevention is to decrease the disruptive forces reaching the soil surface. Disruptive forces can be arranged in three classes: water drop impact energy from rainfall or irrigation, water movement at the surface, and wind velocity.

Splash erosion

A drop of water strikes the soil surface with energy that is decreased when a plant canopy or surface residues intercepts it. Water then trickles down to the soil surface and reaches it with minimal energy. The decrease in raindrop splash erosion depends then on how many drops are intercepted. Thus surface cover by a crop or residue cover provides a major control to splash erosion (Mannering and Meyer, 1963; Foster *et al.*, 1985).

Runoff erosion

Keeping the incoming water rate lower than the infiltrability will prevent runoff erosion. While this is possible with irrigation, we do not have any control on storms. Hence we need to keep soil infiltrability in a satisfactory range. Soil infiltrability is dynamic, and is a function of the matrix conductivity, and quantity and continuity of macropores. If during a storm or irrigation splash erosion occurs, soil infiltrability decreases as macropores clog. Consequently, preventing splash erosion is a first step in runoff erosion control (Mannering and Meyer, 1963). Furthermore, if the soil has a high ponding capacity, it is able to store water that will infiltrate later; less water will run off. Tillage increases ponding capacity by increasing surface micro-relief and cutting slopes (terracing, ridge till, contour tillage). Barriers to water movement such as plants and surface residues also increase ponding capacity (Wischmeier and Smith, 1978).

Wind erosion

To control wind erosion, it is necessary to decrease wind velocity at the soil surface, by natural wind breaks (hills, forests, ...), man-made barriers (edges, walls, buildings,...), and tillage that increases surface roughness. A residue cover provides a barrier that decreases wind velocity at the soil surface.

Erosive forces, kinetic energy and travelling distance determine how far soil particles are translocated. Thus soil surface topography and characteristics are important to reduce soil displacement as they control water and wind velocity, and travelling distance.

Reducing soil displacement

The distance water travels depends on soil topography and water velocity; both are a function of land slope. Terraces that cut slopes and contour tillage have been used to modify natural topography to limit water movements. Natural barriers to water movement, such as plants and crop residues, reduce water velocity decreasing its erosive power and increasing soil particles settlement (Stein *et al.*, 1986). In some agricultural systems, grass strips have also been installed to intercept soil particles in their stems and roots, thereby limiting soil displacement (Langdale *et al.*, 1979).

Residue cover as means to control soil erosion

Residue cover plays three important roles in erosion control: it furnishes organic matter to the top layer increasing its aggregate stability; it intercepts erosive forces of water and wind; and it limits soil displacement (Meyer *et al.*, 1970). Soil surface cover can be obtained by construction, natural vegetation, cropping, or mulching. In some traditional agriculture systems, soil is left fallow during a certain period to conserve and increase soil water or because climate is improper for cropping. Because soil surface cover is low during that period, soil erosion probability is more likely to occur. Surface residue from previous crops and planted sods can provide cover to help control erosion during fallow and early crop development.

Tillage systems creating a soil cover

In the United States, the 1930's dust bowl pushed farm land management in a new direction. Conservation tillage became a recommended practice that leaves sufficient cover to protect the soil from erosion. Conservation tillage includes a large range of systems ranging from no-till systems where seeds are drilled through the crop residues, to systems where only one or two tillage operations are done before planting. Recent innovations in machinery design allows farmers to till the surface layers to break pans and alleviate compaction, and to prepare seed beds without burying the crop residues. As a comparison, traditional moldboard plowing buries up to 90% of surface residues whereas chisel plow buries only up to 50% and a direct drill buries only 5% (Shelton *et al.*, 1990).

Agricultural advisors often recommend a minimum soil cover of 30% at planting to control soil erosion (Dickey *et al.*, 1990). Small amounts of residue cover at the soil surface decreases soil erosion. Laflen *et al.* (1980) reported that a coverage of 10% could result in a decrease in soil erosion of 20%. Knowledge of coverage throughout the season for several types of residue and climate will assist in decisions regarding residue management for soil conservation. This is important on highly erosive soils as erosion usually happens in one event of large magnitude, for example, a storm or strong winds. If an erosion event happens after the residue is decomposed and before crops develop, soil coverage will be insufficient to prevent erosion.

In 1975, the USDA (United States Department of Agriculture, 1975) Office of Planning and Evaluation predicted that minimum tillage would be used on 95% of the U.S. planted cropland by the year 2010; however, Mannering *et al.* (1987) estimated that because of economic factors, farmers would use conservation tillage on only 50% to 60% of the cropland. These economic factors include cost of switching to new machinery, learning curves, and also changes in yields. Conservation tillage reports show that residue cover enhances crop yields in the southeast region by increasing the amount of water available for transpiration (Reicosky *et al.*, 1977), but has detrimental effects by decreasing soil temperature and delaying crop development in the northern Corn Belt (Amemiya, 1977; Griffith *et al.*, 1977; Bennett, 1977). Better understanding of residue impact on crop development and economic evaluation with the help of simulation models is needed to help developing appropriate technologies for erosion control.

Residue management and crops

In the Corn Belt, residue cover is required to control soil water erosion. It reduces runoff, increases infiltration, and decreases soil water evaporation, thus leaving more water for plant uptake (Griffith *et al.*, 1977). The northern Corn Belt is characterized by a cool spring with slowly rising temperatures. Soil cover slows soil warming by intercepting incoming solar energy and keeping soil water content higher. Lower soil temperatures delay plant's early vegetative development and, in a cool temperate climate, may cause a shorter maturity period before autumn frost occurs.

In the northern Corn Belt and regions with cool wet springs, there is a trade-off between increased water resources and delayed plant development. Disparity between maize yields from conventional to conservation tillage are not evident every year. Because of complex interactions between many effects of conservation tillage on the plant's environment, deciding whether switching to conservation tillage would be beneficial is difficult.

Simulation of crop production system

Crop models can help farmers make decisions because they can give information on crop response for a wide variety of environments and management inputs. Crop models have been used to evaluate new technologies or practices (Fischer *et al.*, 1990) and for technology transfer (Ritchie, 1986). However the values of information given is limited by the assumptions of the models. The use of a model to decide if conservation tillage will be beneficial or not is constrained by the model ability to predict infiltration, runoff, surface cover, and plant growth and development.

The NTRM (Nitrogen, Tillage, and Crop-Residue Management; Shaffer and Larson, 1987) model predicts soil conditions and water balance under several tillage treatments. A limitation to the use of the model is that the input data required such as soil temperature and soil hydraulic properties are quite extensive and not readily available.

The EPIC (Erosion-Productivity Impact Calculator) was developed to estimate soil erosion and crop productivity (Williams and Renard, 1985). Even though the model step is one day, prediction of erosion during a storm event has questionable reliability because soil erosion is predicted using the runoff curve number.

Furthermore EPIC and NTRM are not development oriented crop models. Hence, delay in crop development induced by conservation tillage cannot be accommodated. The consequences of the crop development delay induced by residue cover cannot be studied with those models without modification.

The CERES (Crop Estimation through Resource and Environment Syntheses) family of models facilitates quantitative determination of growth and yield of maize (*Zea Mays*, L.) and other cereals under a wide range of soil and weather conditions (Jones and Kiniry, 1986; Ritchie *et al.*, 1989). The CERES models predict plant development through thermal time calculation in connection with genetic specific details. This approach allows us to better understand the consequences of conservation tillage on development and growth for several crops and varieties, and for different climates if the difference in plant growing point temperature is used for plant development prediction. The current CERES models (Version 2.1) assume constant soil physical properties over time. Crop residues are assumed to be incorporated in the soil profile at the beginning of a simulation. These constraints limit the use of CERES models for evaluation of different tillage practices, especially conservation tillage. If the CERES models could be modified to consider the impact of tillage on both the soil environment and the dynamics of soil surface properties, they would become more valuable for assessing tillage impact on the plant and soil system.

Objectives of this thesis

A better understanding of a crop residue cover impact on the soil surface is necessary to develop an improved simulation of residue cover consequences on crop development and growth and soil environmental conditions. An experiment was designed to study maize response to soil temperature and water content affected by surface residue. Soil temperature patterns and soil water dynamics were studied. Crop response was measured through leaf development rates.

A model of residue management and crop response was developed from both the experimental data collected and the existing literature. The approach adopted was to alter the CERES-Maize model, version 2.1, (Jones and Kiniry, 1986; Ritchie *et al.*, 1989) to account for residue management and tillage effects on soil properties. This imposed some constraints in the modeling approach. The time increment of the CERES model is one day. This implies that mechanistic numerical models with small time increments are not appropriate or must be modified for inclusion in CERES models. Input variables should be readily available or easily measurable. Adding tillage and residue management will require new input variables and routines, but these should conform to the general CERES philosophy, inputs and operational structure. Specific modeling objectives were:

- To model the amount of crop residue at the soil surface resulting from tillage management, and its decomposition to predict soil cover.
- Simulate the consequences of a crop residue mulch on soil evaporation, ponding capacity, infiltration and soil temperature.
- Evaluate the effects of residue cover on crop development and growth.

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Chapter 2: Crop residue influence on thermal time and maize (*Zea Mays*, L.) development

Abstract

Soil residue cover delays maize development while its meristem is below ground by decreasing soil surface temperature. A field experiment was conducted in 1990 and 1991 at East Lansing, Michigan, on a Conover loam, to study the effect of four crop residue loading rates on maize development. The residue cover decreased the amplitude of changes in soil temperature inducing a delay in maize development. The delay was of 2 leaves in 1990 which had a cooler spring than in 1991 which only had a delay of 0.5 leaves because the spring weather was warmer. The delay in plant development was highest with a 100% residue cover and smallest with a 30% residue cover. The longer the meristem was below ground, the larger the delay in plant development. Prediction of plant development using thermal time was best using soil temperature at 2.5 cm with a base temperature of 8 ^{o}C while the meristem was below ground and using air temperature when the meristem was above ground. Air temperature gave reasonable predictions but with different correlations between treatments. The use of soil temperature is essential to predict plant development especially in a cool spring climate or when the soil temperature differs from air temperature.

Introduction

In order to control soil erosion, new tillage systems provide increased crop residue coverage on the soil surface. Under a temperate, cool climate, this increase in soil residue coverage can delay plant development of important agricultural crops by decreasing soil temperature in spring. The delay in plant development may decrease crop yield when the maturity stage is shortened due to cold temperature. Since plant development responds to crop residue at the soil surface, we should account for the effect of crop residue cover on thermal time calculations to predict the length of phenological stages.

Early work by Réaumur in the 1730's as cited in Wang (1960) showed that the sum of daily mean temperatures was nearly a constant to reach a given maturity stage for any plant. Since then, several methods of temperature summations to predict maturity stages have been developed (Gilmore and Rogers, 1958; Brown, 1975; Hunter *et al.*, 1977; Bauer *et al.*, 1984). Because of the wide variety of terms for this concept, Gallagher (1979) recommends using the term thermal time as a generic terminology for temperature summation methods.

Wang (1960) criticized summation methods, partly because plants do not respond to air temperature the same way during various developmental stages. Response differences are due to differences in minimum physiological temperature and differences in location of the response. Thus, using the same base temperature for all stages and a recorded temperature that is not always the temperature of the location of the response leads to prediction errors.

Ritchie and NeSmith (1991) describe different thermal time calculations for several stages of plant development with different base temperatures below which development stops, and different maximum temperatures, above which only the maximum value is added, or in the case of reversible processes, a lower value is added. They report several possible errors in the thermal time calculations: reading errors due to time of manual recording of minimum and maximum values, value errors due to the location of sensors compared to the plant, and average temperature calculation errors when the maximum and minimum temperature are not sufficient to calculate the mean value. These errors can be overcome by using automated recording. However, such equipment is not available at all locations. Also, some thermal time calculations may require data such as soil temperature or solar radiation, that are not recorded.

For most crops, attainment of phenological stages are predicted from thermal time calculated from air temperature. Watts (1972) showed that when meristem temperature was modified but leaf and root temperature were kept constant, rapid changes in plant development were observed. Because biological activity is a function of temperature, and leaves, stem, and reproductive organs are differentiated in the meristem, meristematic temperature should be used in thermal time calculation to more accurately predict attainment of phenological stages.

Cellier *et al.* (1992) measured maize meristem temperature by inserting a thin thermocouple near the meristem. They showed differences between meristem and air temperature ranging from - 6 ^{o}C at night to + 7 ^{o}C during the day. They proposed a simple functional model to calculate the temperature difference from solar radiation, air temperature, and dew point. The empirical coefficients used by the model are climate dependent. Thus, new calibration is needed to use this model in a different environment.

During the early developmental stages of several crops such as maize (*Zea Mays*, L.) or wheat (*Triticum aestivum*, L.), the meristem of the plant is 1 to 2 cm below the soil surface. Therefore, meristematic temperature is closer to soil temperature at 2 cm than air temperature and using soil temperature would give a better estimation of meristematic temperature than air temperature. Fortin and Pierce (1991) showed better correlation in plant development prediction using soil temperature at 2.5 cm to calculate thermal time than using air temperature.

Soil temperature appears to be a better indicator of plant development than air temperature while the meristem is below ground, and it is easier to measure than meristematic temperature.

As seen in Chapter 1, residue cover has been reported to delay plant development by decreasing soil surface temperature. Soil temperature differs from air temperature measured at 2 m where the temperature sensors are usually positioned in a weather station. In the humid, temperate climate of North America, average soil surface temperature is higher than average air temperature due to incoming solar radiation throughout the year (Bouyoucos, 1913). However, in the early spring, when cool, wet weather is common, soil temperature is often decreased by high water content (Swan *et al.*, 1987). Residue cover on the soil surface reflects solar radiation and acts as an insulator, slowing soil warming during the spring. This effect is more noticeable in a temperate, cool climate with wet and cool springs because high soil water content maintained by residue cover is combined with low energy income (Van Wijk, 1963; Allmaras *et al.*, 1977). Thus, a better understanding of the consequences of a mulch cover on soil temperature is critical to better predict plant development rates.

An experiment was designed to evaluate the use of soil temperature under a residue cover to improve maize (*Zea Mays*, L.) development prediction.

Material and methods

A field experiment to measure the impact of surface crop residue on crop development was performed at the Michigan State University farm, East Lansing, Michigan (42^{o} 42'N, 84^{o} 28'W) during the years 1990 and 1991. The soil at the site was a Conover loam (Fine-loamy, Mixed, Mesic, Udollic Ochraqualf, soil description is given in Appendix 1).

Four crop residue levels were evaluated under fallow and a growing maize crop. The experimental units were 12 m^2 in size in the fallow treatment and 24 m^2 in size where maize was planted. Cropped units were larger to eliminate border effects. Fallow units were installed south of the cropped units to avoid any shading from the maize canopy.

All plots were moldboard plowed in the fall and received secondary tillage prior to planting in the spring. Maize (hybrid 'Pioneer 3751') was planted on the northern plots at a density of 7.25 plants m^{-2} on 8 May 1990, and 14 May 1991. Plots were raked after planting to level the surface. Plots were fertilized with urea at a rate of 142 kg N ha^{-1}.

Maize stalks, saved from the previous harvest, were chopped with a grinder and applied at the soil surface after planting. Loading rates were estimated from the equation given by Van Doren and Allmaras (1978):

$$\text{Load} = - \text{Ln}(1 - \text{cover}) / \text{Am} \qquad [2.1]$$

The residue density coefficient (Am) was estimated by measuring the area covered by small weighed samples of chopped maize residue using a leaf area meter. The coefficient found was 0.00029 ha kg^{-1} ± 0.00003. In 1990, loading rates were 11.6 Mg ha^{-1}, 1.75 Mg ha^{-1}, and 0.92 Mg ha^{-1} to reach a soil cover of 100%, 40%, and 25%. In 1991, loading rates were 13.3 Mg ha^{-1}, 4.1 Mg ha^{-1}, and 1.2 Mg ha^{-1} to reach a soil cover of 100%, 70%, and 30 %. Soil cover was checked by the photographic method (mimeo prepared by J.V. Mannering, Agronomy department, Purdue University, "Estimating surface cover photographically"). A control plot was left without residue cover.

Soil temperatures were measured at depths of 2.5 cm, 10 cm, and 30 cm on each plot using copper-constantan thermocouples. Three 1 cm long thermocouples were connected in parallel to get an average reading and avoid failure (Culik *et al.*, 1982). Thermocouples were connected to a datalogger for automated recording (Easy-Logger, OMNIDATA) through a copper-constantan extension wire (ANSI type TX, EXPP-T-20, OMEGA Engineering). Soil temperatures were measured every 5 minutes.

For the no residue and the 100% cover treatments it was assumed that the surface condition was uniform and therefore, soil temperature was uniform. The temperature below a residue, for the intermediate coverage treatments, was expected to be lower than under a bare surface because the random distribution of crop residues at the soil surface affects the energy balance. Therefore, surface sensor location was important. If the sensor was located below a residue, the temperature was closer to a 100% cover temperature. To better estimate the importance of sensor location, a grid of sensors covering a large surface was necessary. In this experiment, a single point measurement was done and temperatures were found intermediate between full covered and bare surface, but closer to bare surface. Since the plant showed a proportional response to the change in temperature, the assumption was made that the sensors were properly placed.

Maximum and minimum soil temperature at 2.5 cm, 10 cm, 30 cm soil depth were recorded hourly as well as the hourly average temperature at 2.5 cm.

To reduce the amount of data saved, the average temperature of the 10 cm and 30 cm sensors was not recorded. Because variations are of less amplitude at these depths, the calculated average from the daily minimum and maximum value at those depths was assumed to be an accurate representation. The variation at 2.5 cm was expected to be high, hence no insulation was put on the surface of the thermocouple and the hourly average value was recorded by the datalogger. Data were aggregated over the day, calculating the daily maximum, minimum, and average values from the hourly maximum, minimum, and average recording. For the bare treatment, and intermediate covered treatment, calculated average at 2.5 cm was 1 ^{o}C lower than the recorded average temperature, but only 0.5 ^{o}C lower for the fully covered treatment. Hence, using the maximum and minimum values of surface temperature to calculate the mean soil temperature would underestimate average temperature especially when daily variations were high.

Air minimum and maximum temperature and rainfall were collected at the nearest weather station (East Lansing 4S station). Because solar radiation was not available at a near location, it was estimated from air temperature and precipitation by a weather generator (Richardson and Wright, 1984). Weather data are listed in Appendix 1.

Vegetative plant development was studied using leaf appearance rate. Fully expanded leaves (FEL) were recorded when the collar appeared and the total number of leaves (TLN) were recorded when the leaf tip appeared. Ten contiguous plants away from the plots' borders were monitored in 1990. Five plants were monitored in 1991.

Soil thermal time calculated for four residue cover treatments from soil temperature measured at 2.5 cm on the fallow plots was compared to air thermal time. Soil temperature was summed from planting to stage V8. After stage V8, air temperature was used. When the average daily temperature was below the base temperature (T_{base}), no value was added to the summation. When the average daily temperature was above the maximum temperature, the maximum temperature minus the base temperature was added. When the average daily temperature was between the base temperature and the maximum temperature, the average daily temperature minus the base temperature was added.

$$TT = \Sigma(T_{soil} - T_{base}) \qquad [2.2]$$

The base temperature used was 8 ^{o}C for the soil and the air (Ritchie and NeSmith, 1991).

Because thermocouples were installed late in 1990, no soil temperature data were available for the first days of the juvenile stage. Based on average soil temperature differences to air temperature, from the date of thermocouple insertion (18 June 1990) until 15 July 1990, soil thermal time for no cover, 25%, 40% and full residue cover treatments was estimated by adding 22 ^{o}C, 10 ^{o}C, 7 ^{o}C, and -2 ^{o}C to air degree day from planting to 18 June 1990.

Results and discussion

Thermal time calculations from daily average soil temperature at 2.5 cm under a maize crop for 1990 and 1991 are given in Figures 2.1 and 2.2. Accumulation of thermal time was faster using soil temperature than air temperature for all cover treatments. Intermediate cover treatments had higher increase rates than the fully covered treatment but lower than the no cover. Fortin and Pierce (1991) showed less difference between air thermal time and fully covered plots than between air thermal time and bare plots. Thermal time for the fully covered treatment was similar to air thermal time especially in 1991 where differences were small.

The longest time required to reach 200 degree days which corresponds to the end of the juvenile stage for most maize varieties of the northern Corn Belt (Ritchie *et al.*, 1986), was 27 days in 1990 and only 15 days in 1991. Differences between the years was due to lower air temperature in 1990 compared to 1991. Bare plots reached 200 degree days five days earlier than the 100% covered plots in 1990 and only 2.5 days earlier in 1991. Because soil temperature was lower in 1990, differences were summed over a longer time, increasing the difference between treatments in 1990.

Differences in thermal time are due to differences in soil temperature patterns compared to air temperature. Soil temperature variation for three continuous days was studied to show the differences between treatments to better explain the consequences on thermal time calculation.

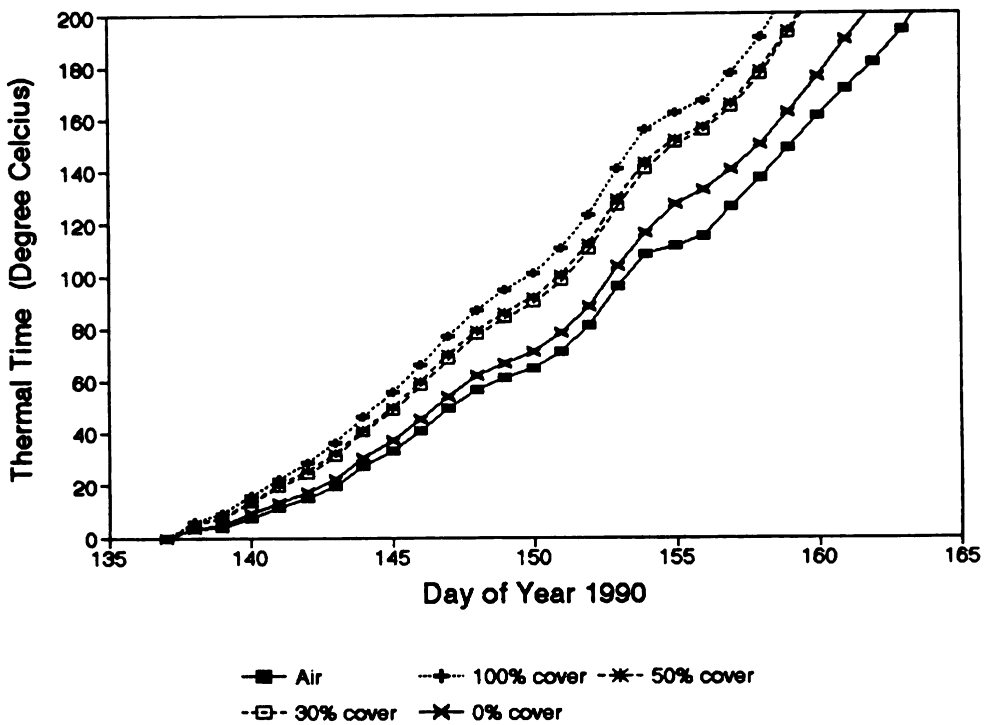

Figure 2-1: Estimated thermal time for Spring 1990 calculated using air temperature and soil temperature under four soil cover treatment with a base temperature of 8 °C.

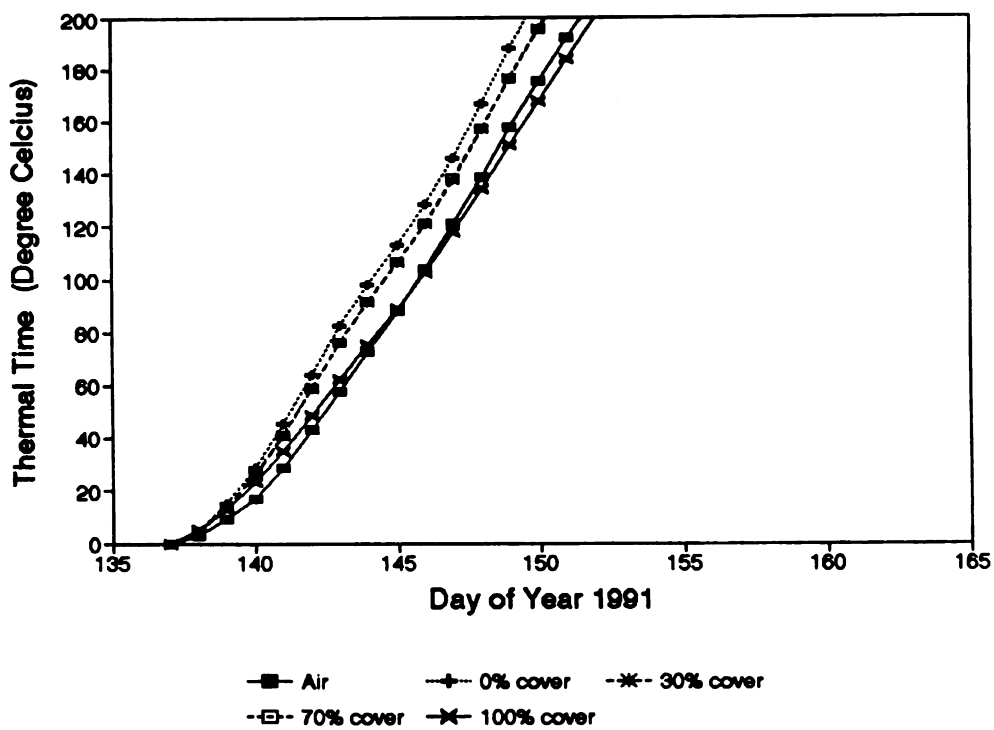

Figure 2-2: Thermal time for Spring 1991 calculated using air temperature and soil temperature under four residue covers with a base temperature of 8 ^{o}C.

Soil temperature

Soil temperature average at 2.5 cm on the bare plots was always higher than air average temperature due to a rapid increase in soil temperature after sunrise (Figure 2.3). Due to the soil buffering effect, soil temperature variation was delayed with depth and its magnitude decreased (Table 2.1). Locating the sensor at 2.5 cm below-ground where the maize meristem is located is then important. Therefore, the meristem, while in the soil, experiences higher temperature than air temperature.

Table 2.1: Minimum, maximum, average and amplitude of soil temperature at 2.5 cm under four residue covers and air temperature on 24 June 1990 and 26 June 1990.

Day:	**June 24 1990**				**June 26 1990**			
Cover Treat.	**MIN °C**	**MAX °c**	**AVG °c**	**AMP °c**	**MIN °c**	**MAX °c**	**AVG °c**	**AMP °c**
Air	10.6	16.1	13.4	5.5	12.8	27.2	20.0	14.4
0%	13.0	17.8	15.5	4.8	8.4	33.2	20.6	24.8
30%	13.9	17.7	16.0	3.8	9.9	29.4	19.8	19.5
50%	14.1	17.7	16.1	3.6	10.3	28.5	19.4	18.2
100%	14.9	17.7	16.4	2.8	12.5	24.6	18.6	12.1

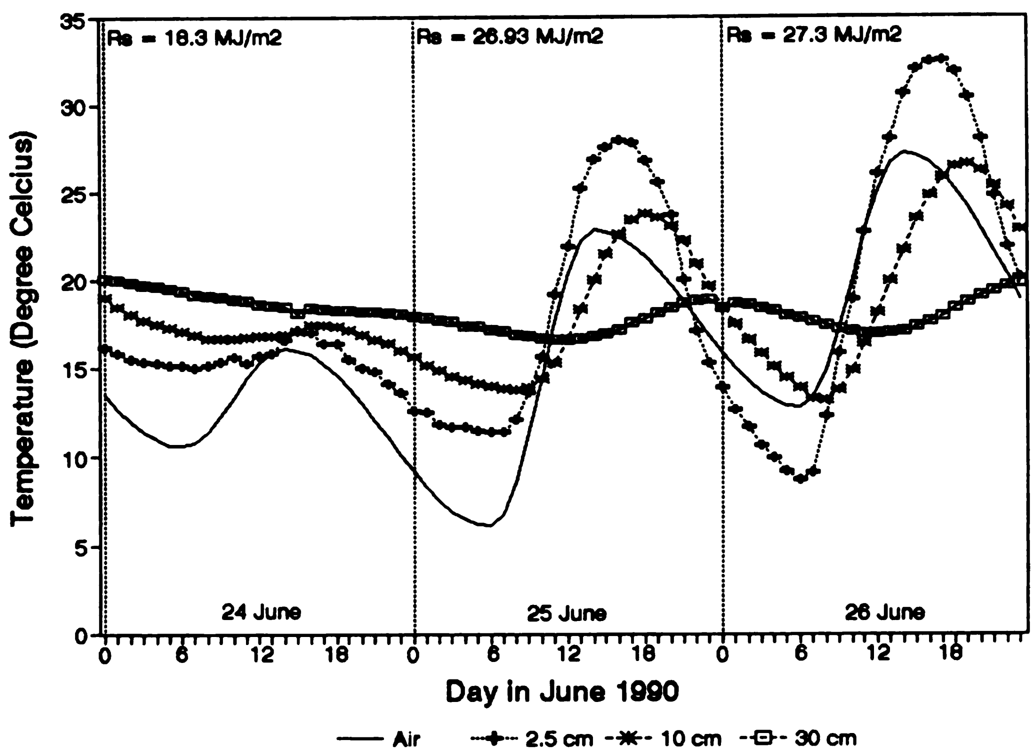

Figure 2-3: Variation of air temperature and soil temperature under a bare surface at 2.5, 10, and 30 cm, between 24 June and 26 June 1990.

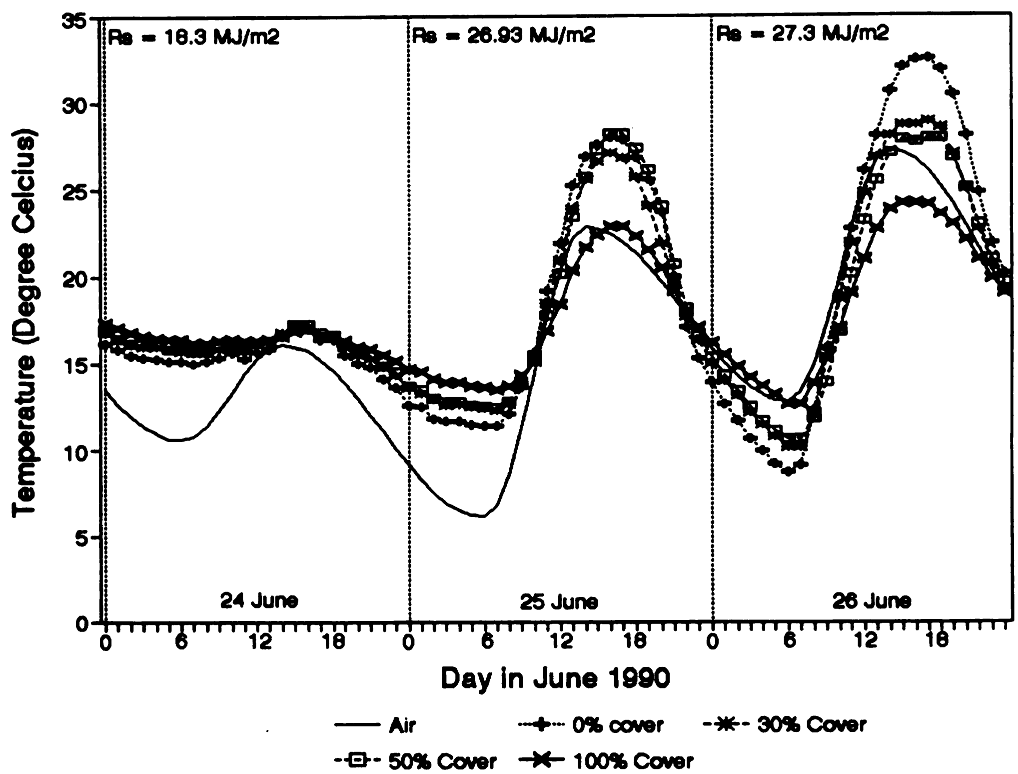

Figure 2-4: Hourly soil temperature variation at 2.5 cm under four residue covers from 24 June to 26 June 1990.

Soil temperature increased more rapidly from sunrise to 3 p.m. EDT, which roughly corresponded to solar zenith, on the no-cover treatment due to higher incoming solar radiation and reached a higher maximum temperature than the covered treatments (Figure 2.4). The maximum temperature reached on the fully covered plot was closer to maximum air temperature, partially covered plots were intermediate (Table 2.2). Hence, it appears that the major effect of the residue cover on maximum soil temperature is through solar radiation reflection and interception (Allmaras *et al.*, 1977).

Minimum soil temperature was also affected by the residue treatments. Residue coverage acted as an insulating layer and decreased the loss of energy from the top layer. Soil with a higher cover had a higher minimum temperature. The bare soil minimum temperature was 8.4 ^{o}C on 26 June 1990, 4 ^{o}C above air temperature, while the fully covered soil minimum temperature was 12.5 ^{o}C (Table 2.2).

Because air temperature variation and solar radiation were low on 24 June 1990, differences between treatments were small and soil maximum temperatures for all treatments at 2.5 cm were similar (Table 2.2). On 26 June 1990, however the difference was much greater.

Overall, residue coverage decreased soil temperature average and amplitude, at least during the spring. The beneficial effect of higher minimum temperature was dampened by slow rising temperatures and lower maximum temperatures. Nevertheless, when there was a cold front passage, the differences

Table 2.2: Minimum, maximum, average and amplitude of air and soil temperature at 2.5 cm, 10 cm, and 30 cm on June 24, 1990 and June 26, 1990.

	24 June 1990				26 June 1991			
Sensor Location	**MIN °C**	**MAX °C**	**AVG °C**	**AMP °C**	**MIN °C**	**MAX °C**	**AVG °C**	**AMP °C**
Air	10.6	16.1	13.4	5.5	12.8	27.1	20.0	14.4
-2.5 cm	13.0	17.8	15.5	4.8	8.4	33.2	20.6	24.8
-10 cm	15.9	19.6	17.8	3.7	13.0	26.7	19.9	13.7
-30 cm	18.0	20.1	19.1	2.1	16.9	19.9	18.4	3.0

in average soil temperature between treatments decreased and even reversed at the end of the front. Then, covered soil was warmer than bare soil. Over the recording period, on the average, soil temperature under a full residue cover was cooler by 1.5°C than an uncovered soil. It tended to bring soil temperature closer to air temperature but slightly warmer by 0.18°C.

Differences in soil temperature patterns between air and at 2.5 cm below-ground where the maize meristem is, affected thermal time accumulation. The presence of surface crop residue affected soil temperature and hence the thermal time experienced by the meristem. Difference between air and soil temperature at 2.5 cm was larger at low crop residue levels and when the daily amplitude of air temperature was large. Because there is a difference in thermal time when air temperature is used instead of soil temperature, the consequences of using one thermal time calculation versus the other on plant development prediction needs to be studied.

Plant development

Plant development was delayed by residue treatment in 1990 and 1991 (Figure 2.5 and 2.6). Because of a cooler spring in 1990 compared to 1991, the number of days before the meristem emerged above the ground was larger (Figure 2.1 and 2.2). Therefore, differences between treatments were higher in 1990 compared to 1991 as the differences between treatments were cumulated over a longer interval. The rate of fully expanded leaves appearance and leaf tip appearance were both delayed by crop residue. The number of visible tips of growing leaves was smaller on the residue treatment than on the no-cover treatment (Figure 2.7). The differences diminished after tasselling and all plants reached the same final number of leaves and height. Therefore, crop residues delayed plant development, but did not modify final development.

Leaf development is better correlated to soil thermal time than air thermal time for both 1990 (Figure 2.8) and 1991 (Figure 2.9). Although correlations were good between air temperature and plant development for each treatment, they were different among treatments.

The correlations between leaf tip number and thermal time calculated from air temperature and from soil temperature recorded on each plot were high in

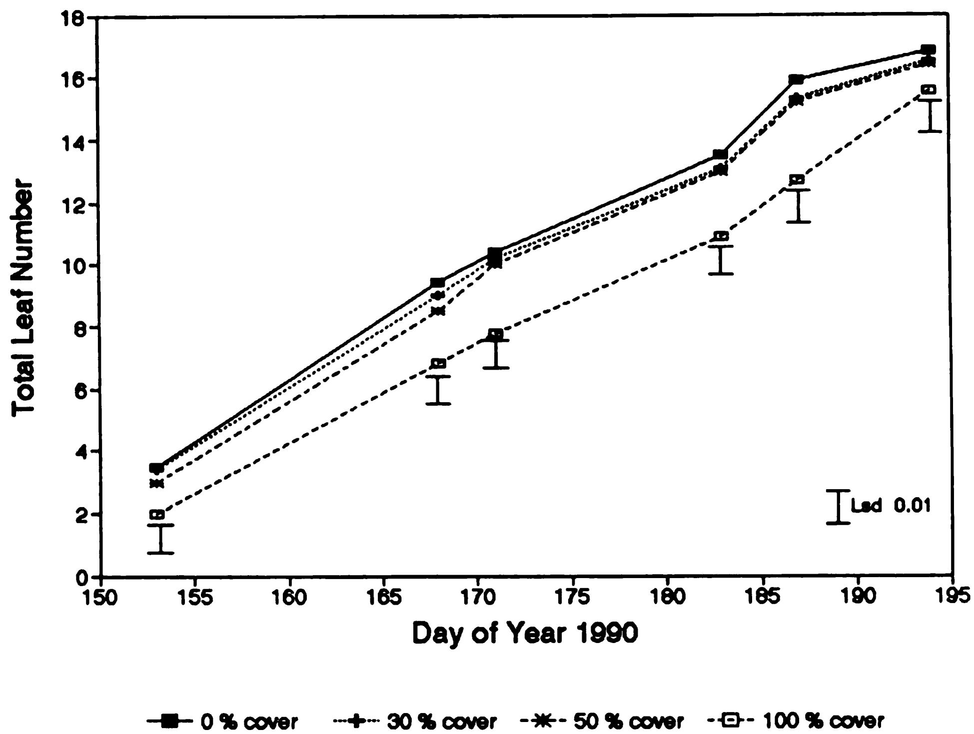

Figure 2-5: Maize early leaf development under four residue covers versus day of the year 1990.

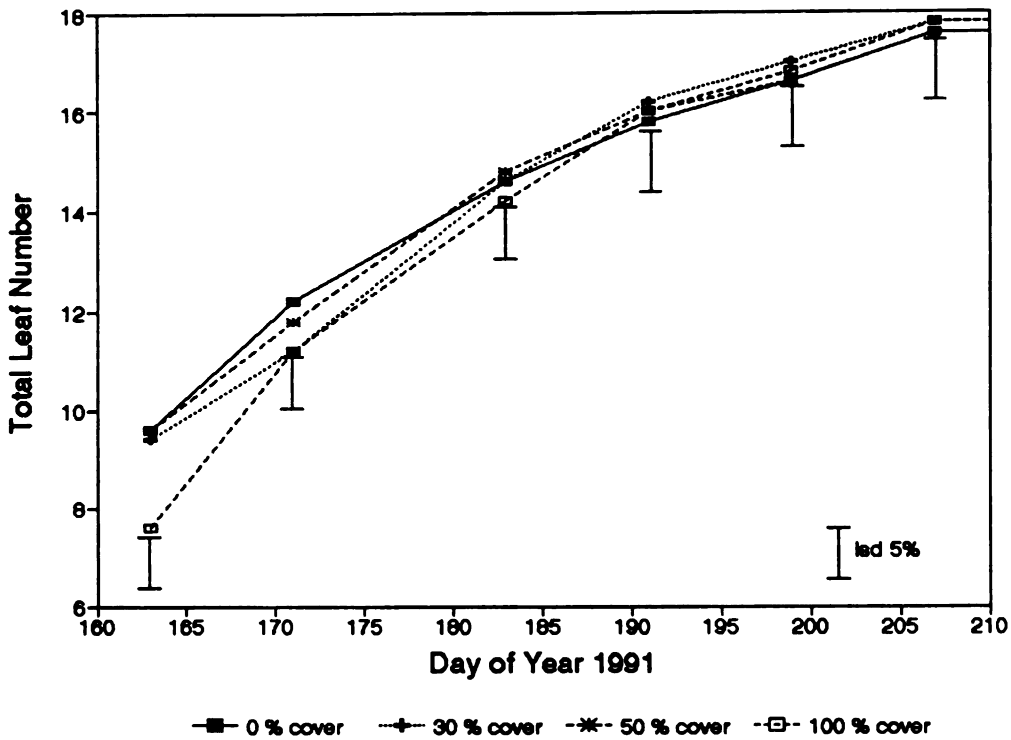

Figure 2-6: Maize leaf development under four residue covers versus day of the year 1991.

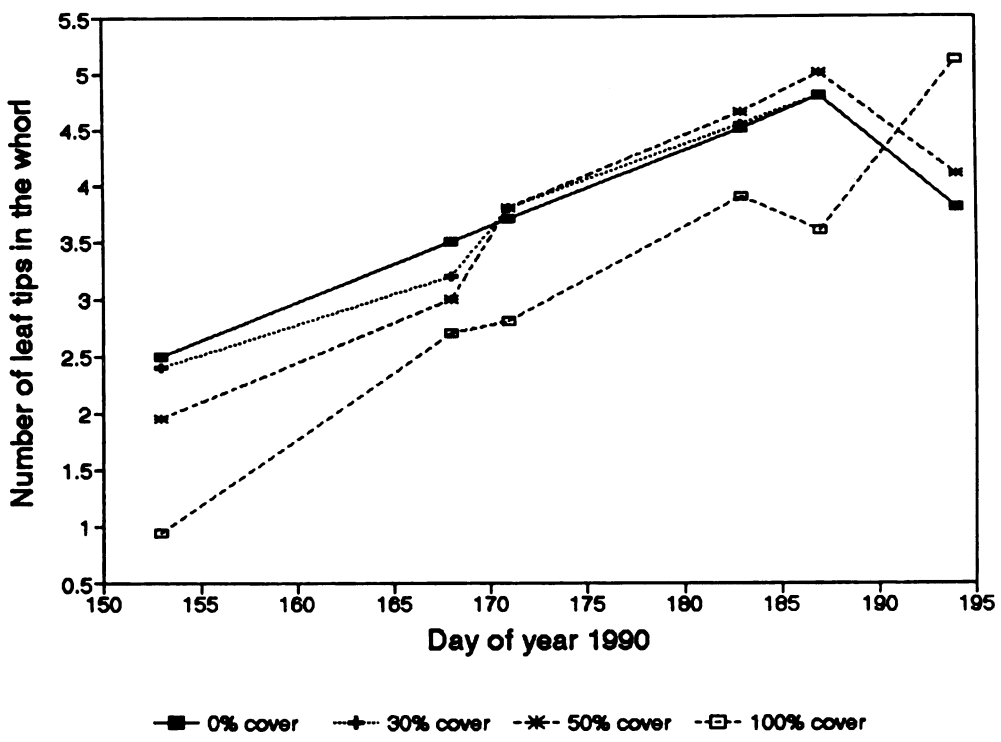

Figure 2-7: Number of leaf tips in the whorl (total leaf tip number minus total collar number) versus day of the year 1990.

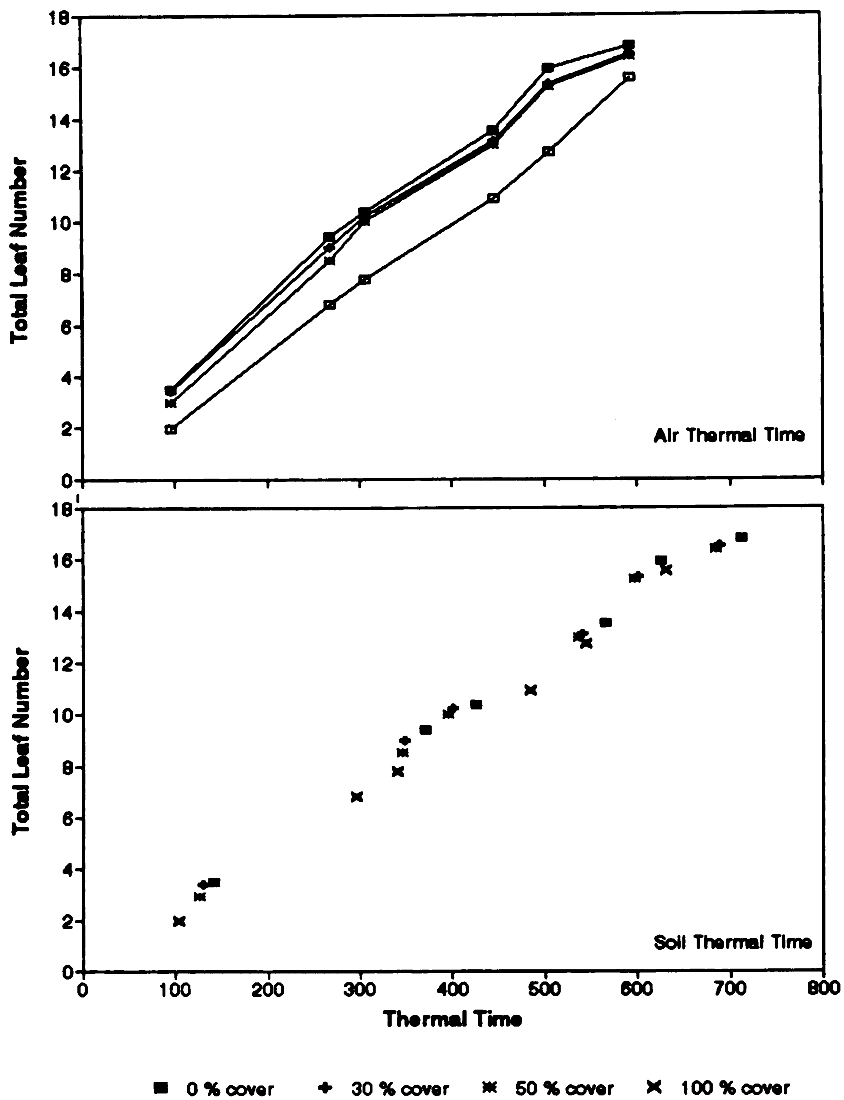

Figure 2-8: 1990 early leaf development versus thermal time from planting calculated from air and soil temperature at 2.5 cm under four residue covers using a base temperature of 8 °C.

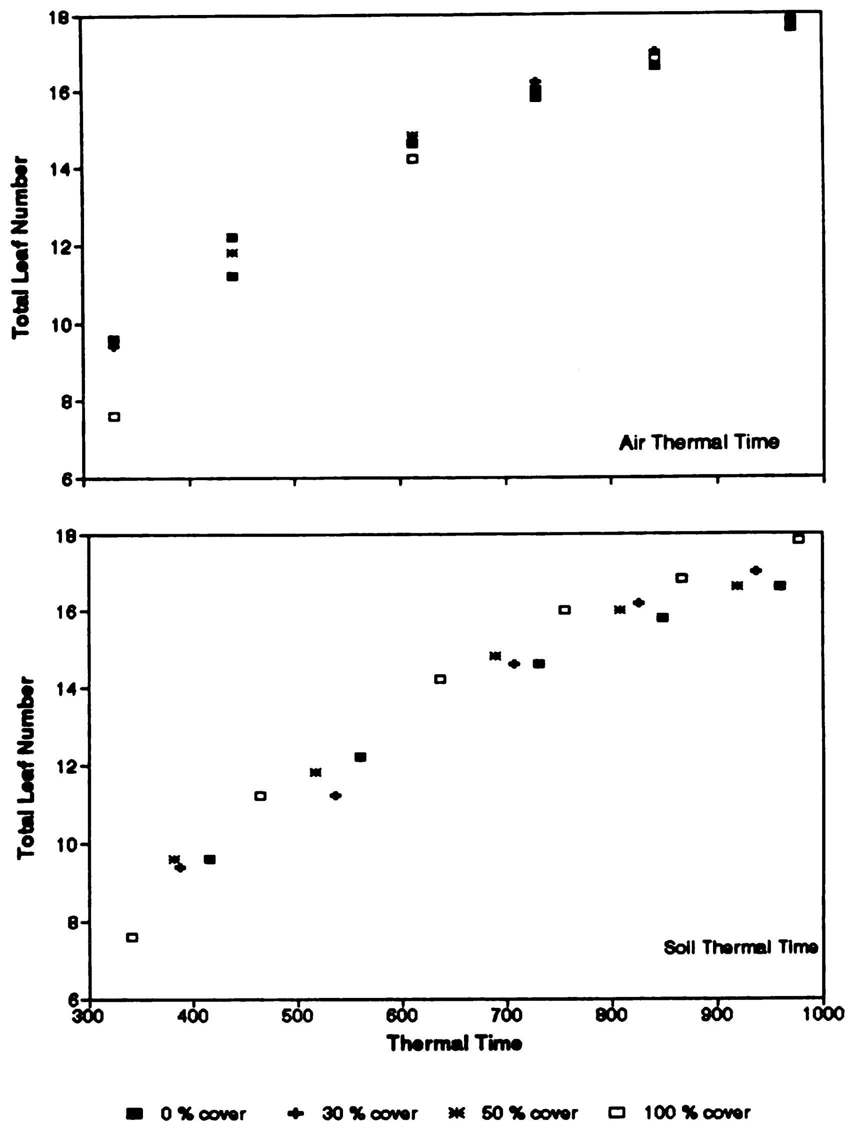

Figure 2-9: 1991 leaf development versus thermal time from planting calculated from air and soil temperature at 2.5 cm under four residue covers using a base temperature of 8 °C.

Table 2.3: Correlation coefficient for leaf tip number prediction from thermal time.

Treatment	Thermal Time	Constant	STDE	Slope	R^2
0% cover	Air	1.62	0.73	1/37.12	0.982
30% cover	Air	1.51	0.63	1/37.98	0.986
50% cover	Air	0.95	0.65	1/36.80	0.986
100% cover	Air	-0.53	0.32	1/37.68	0.997
All	Air	0.89	1.06	1/37.39	0.950
0% cover	Soil	0.32	0.47	1/42.07	0.993
30% cover	Soil	0.50	0.38	1/42.09	0.995
50% cover	Soil	-.004	0.38	1/40.68	0.995
100% cover	Soil	-0.75	0.36	1/39.9	0.995
All	Soil	-0.05	0.45	1/40.91	0.991

both cases but improved when soil temperature was used to calculate thermal time (Table 2.3). For better understanding, the inverse of the slope is given in Table 2.3 as it represent the phyllochron. Slopes were similar among treatments but higher, 1/40 compared to 1/37, when soil temperature was used. When all data were aggregated the correlation was higher using soil temperature for the early plant development than using air temperature. The intercept was much smaller (-0.05 leaves) compared to air thermal time correlation 0.886. The intercept can be interpreted as the delay in the plant development. When air temperature was used the intercept increased from -0.53 leaves on the fully covered plots to 1.62 leaves on the uncovered plot. Variation among treatments was smaller when soil temperature was used from -0.75 leaves on the fully covered plots to 0.32 on the bare plots. Differences in plant development may exist due to delayed germination which may have occurred due to lower soil temperature. Furthermore, the error on leaf number prediction was always smaller when soil temperature was used.

Errors in prediction

These data indicate that air temperature to predict plant development gives less error when the soil is covered but larger error when the surface is bare. Using a base temperature of 6 °C, as used in France to calculate thermal time (Bloc *et al.*, 1983), would bring the air thermal time in the same range of values as soil thermal time calculated with a base temperature of 8 °C and would diminish the prediction errors (Figure 2.3). Thermal time curves were in the same range of values and slopes. Therefore, using air thermal time with a base temperature of 6 °C gave better estimation of plant development for some locations. Although this may be true for the East Lansing location, where the bare soil surface was warmer than the air on a average value of 2 °C, it may not hold for other locations or for residue covered soils. The AGPM (Association Générale des Producteurs de Maïs, France) decided to offset the thermal time by a constant for some of the study sites where the soil temperature was constantly low (F. Ruget, 1992, personal communication) to overcome the error in development prediction.

Although changing the base temperature in thermal time calculation gives better prediction, there would still be an error in the prediction of the plant

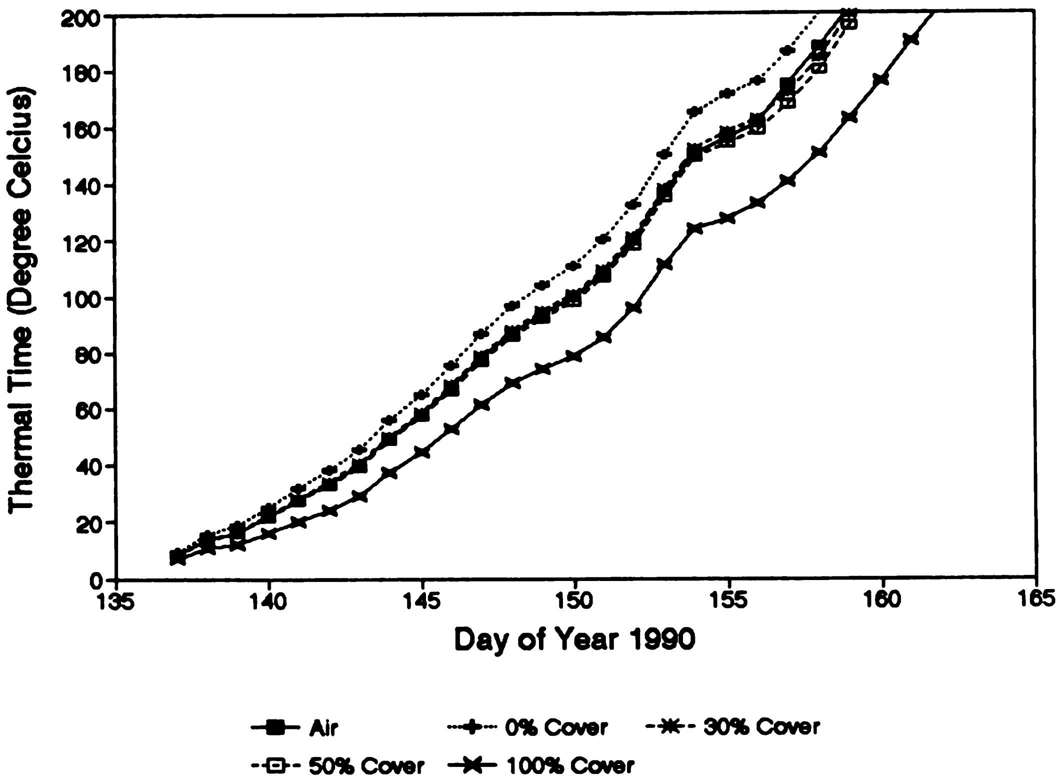

Figure 2-10: Thermal time using air temperature with a base temperature of 6 °C and soil temperature with a base temperature of 8 °C.

development but it would be smaller than using a base temperature of 8 ^{o}C. This change does not hold for all climate conditions or soil conditions. Hence, soil temperature provides the most appropriate value for the thermal time calculation.

The choice of the base temperature is important because it affects the value of thermal time especially when the temperature is close to the base temperature which is often the case in the early development stages in temperate zones. It may slightly affect the correlation between development and thermal time but it changes the calculated development rate by changing the temperature accumulation rate.

Base temperature was evaluated from minimum temperature required to induce a response in maize development. Hesketh and Warrington (1989) reported different base temperatures for different physiological processes: base temperature varied from 5.85 ^{o}C for leaf primordia calculation to 8.9 ^{o}C for germination and emergence. Kiniry (1991) reported a base temperature of 8 ^{o}C for leaf tip appearance and 10 ^{o}C for germination and elongation determined in controlled environment. Hesketh and Warrington (1989) reported different rates of leaf tip appearance for different base temperatures.

Base temperature is based on the physiological response of the plant at different developmental stages, therefore we shouldn't change the base temperature but should change the parameters used in thermal time calculation. Using soil temperature with a phenological sound base temperature will give more accuracy to the prediction of plant development as it will be valid in all environments.

Furthermore, we should be cautious in the use and definition of thermal time needed to attain a developmental stage. Most of the values are derived from field data and are usually calculated from air temperature. Detail on the calculation of thermal time, temperature used, and values of base temperature must be known to be certain that the value recorded is accurate. Correction should be needed to obtain the true value of thermal time experienced by the meristem.

Conclusion

This experiment demonstrated that maize development is sensitive to crop residue mulches. The surface crop residues slowed plant development by decreasing soil surface temperature. The delay in maize development and growth was longer during the cooler year (1990) than the warmer year (1991). To accurately predict plant development, soil temperature should be used to calculate thermal time while the plant meristem is below ground. The base temperature to be used is 8 ^{o}C as it represents the minimum physiological response of maize development. Adding a model of crop residue to the thermal time based crop models provides a more powerful tool to study the consequences of residue management on final yield for several climatic conditions.

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Chapter 3: Surface crop residue influence on maize (*Zea Mays*, L.) growth and soil water content.

Abstract

Residue cover decreases soil surface temperature and increases soil surface water content. A field experiment was conducted in 1990 and 1991 at East Lansing, Mich., on a Conover loam, to study the effect of four crop residue loads on soil water content, maize leaf surface area, and final biomass. The residue covered plots had delay in plant development induced by reduced soil temperature. The development delay lasted until maturity. Plant water content was higher on the covered plots especially when the temperature were lower in 1990. Plants on the covered plots took up water from the upper layers and for a longer period than plants on the bare plots. Leaves grew slower on the residue covered plots, but their maximum size was not affected. Leaf surface area was similar among plots when compared at identical development stages. Leaves senesced faster on the 100% cover plots than on others. Further work is needed to evaluate the effect of a residue cover on the root growth and distribution, and the consequences for the plant throughout its development.

Introduction

The experiment described in Chapter 2 showed a delay in plant development due to decreased soil surface temperature induced by surface residue cover at the East Lansing location. The effect of delayed development on the final yield, which is of interest to the farmer, is not consistently different. Several authors (Jasa and Dickey, 1990; Reicosky *et al.*, 1977; Griffith *et al.*, 1977; Amemiya 1977; Bennett 1977) reported that yields were about the same for conservation tillage and conventional tillage. Because of improved water infiltration and water conservation resulting from a residue cover, yields are improved in lower rainfall years and dry locations (Griffith *et al.*, 1977). Reicosky *et al.* (1977) reported that on poorly drained soils, maize yields were decreased because poorly drained soils are usually colder due to higher water content. When vegetative maize development is delayed by lower soil temperature created by a residue cover, maize yield loss due to short maturity period is more noticeable. Hence, residue cover often decreases maize yield under cool temperate climates (Griffith and Mannering, 1985).

Residue cover increases soil water availability to plants by keeping soil water infiltrability high (Freebairn and Gupta, 1990) and reducing soil water evaporation (Griffith *et al.*, 1977). Residue cover has been reported beneficial in the southern states because the delay in development is lower due to higher temperatures in the spring. Increased water content benefits the crop (Reicosky *et* *al.*, 1977). Residue cover decreases the probability of water deficit by increasing water infiltration and reducing evaporation.

Residue cover at the soil surface decreased soil temperature at 10 and 30 cm depth. The difference among treatments varied with the change in air temperature. Most of the experimental work on the effect of soil temperature on root morphology has been done in controlled environments. The minimum temperature for maize root growth is 10 ^{o}C and the optimum temperature is 30 ^{o}C (Cooper, 1973). At 17 ^{o}C, maize root growth is less than half the maximum value. Mackay and Barber (1984) found that maize root length at 18 ^{o}C was half that at 25 ^{o}C when maize was grown with a constant air temperature of 25 ^{o}C. Pahlavanian and Silk (1988) found the relative length increase and root biomass deposition to be strongly temperature dependent. Gregory (1983) found that lateral root development was correlated to meristem temperature development. As seen in Chapter 2, plant development was delayed by a residue cover. The delay in plant development probably caused a decrease in root length due to lower soil temperature at 10 and 30 cm depths. Temperature effect on root distribution can not be separated from soil water distribution. High water content at the soil surface maintains more roots in the surface layers (Barber, 1971; Unger *et al.*, 1981). Plants with roots in the top soil layers take up more water from small rains. If a severe water stress occurs later in the season, this rooting pattern may hinder water uptake. The optimum temperature for maize root elongation is 30 ^{o}C (Anderson and Kemper 1964). Low soil temperature impairs root growth by and increasing water viscosity. Maize root nutrient uptake, especially nitrogen, is decreased when soil temperature decreases (Voorhes *et al.*, 1981).

This study was designed to evaluate the consequences of a residue cover on soil water content, maize leaf surface area, plant water content at harvest, and final biomass and yield.

Material and methods

Experimental design is detailed in Chapter 2. Soil volumetric water content was measured using a neutron probe. One polyvinyl access tube was installed on each experimental plot. The neutron probe was calibrated when the access tubes were installed by measuring gravimetric water content and bulk density at several depths. The linear regression between neutron counts and soil volumetric water content was:

$$\theta = 0.286 * (\text{COUNT/Standard count}) - 0.021 \qquad R^2 = 0.68 \qquad [3.1]$$

Neutron probe readings were taken at depths of 10, 30, 50, 70, 90, and 110 cm in 1991, on each plot starting 8 July 1991 to 1 September 1991. No neutron probe readings were taken in 1990.

Surface water content was measured using time domain reflectometry (TDR) in which soil dielectric conductivity is measured by sending an electromagnetic wave through a stainless steel parallel line buried in the soil. The electromagnetic wave through a stainless steel parallel line buried in the soil. The dielectric constant of the soil is correlated with the average volumetric water content along the transmission line (Topp and Davis, 1982). Correlation has been proved valid for most of the soil types as long as organic matter content is not too high. The calibration curve given by Topp and Davis (1982) was used for the Conover loam soil. The TDR waves were saved on a portable computer and analyzed in the laboratory on a more powerful computer using an algorithm written in BASIC (D. Knezek and F.J. Pierce, 1990, personal communication). Duplicate set of parallel lines made of two 0.47 cm diameter stainless steel rods, distant by 5 cm, were installed vertically from the surface to depths of 10, 20 and 40 cm in 1990. To measure the water content in the 2.5 cm surface layer, 10 cm long transmission lines were installed diagonally in order to have a sufficient length of transmission line. In 1991, depths of measurement were changed to 7, 15, 26, 40 cm.

Leaf area was measured using a correlation that exists between leaf length and width. At the same time that plant development was monitored, leaf length from collar to tip and leaf maximum width were measured using a meter stick on the development monitored plants in 1990 and 1991. For the growing leaves, leaf length was measured from the whorl to the tip. Percent of leaf senesced was visually estimated. These measurements were used to estimate total and photosynthetically active leaf area using the equation (Sanderson *et al.*, 1981):

$$\text{Area} = (\text{Length} * \text{Width}) * 0.75 \qquad [3.2]$$

Maximum leaf length and width over the season were recorded on 12 July 1990 and 26 July 1991.

The development and growth monitored plants were harvested on 13 October 1990 and 17 September 1991. Leaf, stem, and cob were weighed at harvest and then dried at 84 ^{o}C for 48 hours. Dry matter and water content of the leaves, stem, cob, and grain were recorded. Grain number per plant was also counted.

Analyses of variance were performed and differences between means were tested using the least significance difference test (LSD) at an alpha level of 0.05.

Results and discussion

Residue cover on the fallow plots increased water content of the surface layers up to a depth of 40 cm (Figure 3.1 and 3.2). Increase of water content on the covered plots was mainly due to decreased evaporation. Jackson (1975) observed that evaporation affects only the first 30 cm of the soil profile. The difference between treatments was larger at the surface and decreased with depth. The 100% cover considerably diminished soil water evaporation and kept the soil surface layer at a water content close to the drained upper limit. Intermediate cover decreased the rate of soil water evaporation depleting water in the surface layer but maintaining higher water content in lower layers. Soil water content at depths below 50 cm was not significantly affected by the residue cover on the fallow plots. In 1991, due to frequent rainfall, the difference between treatments

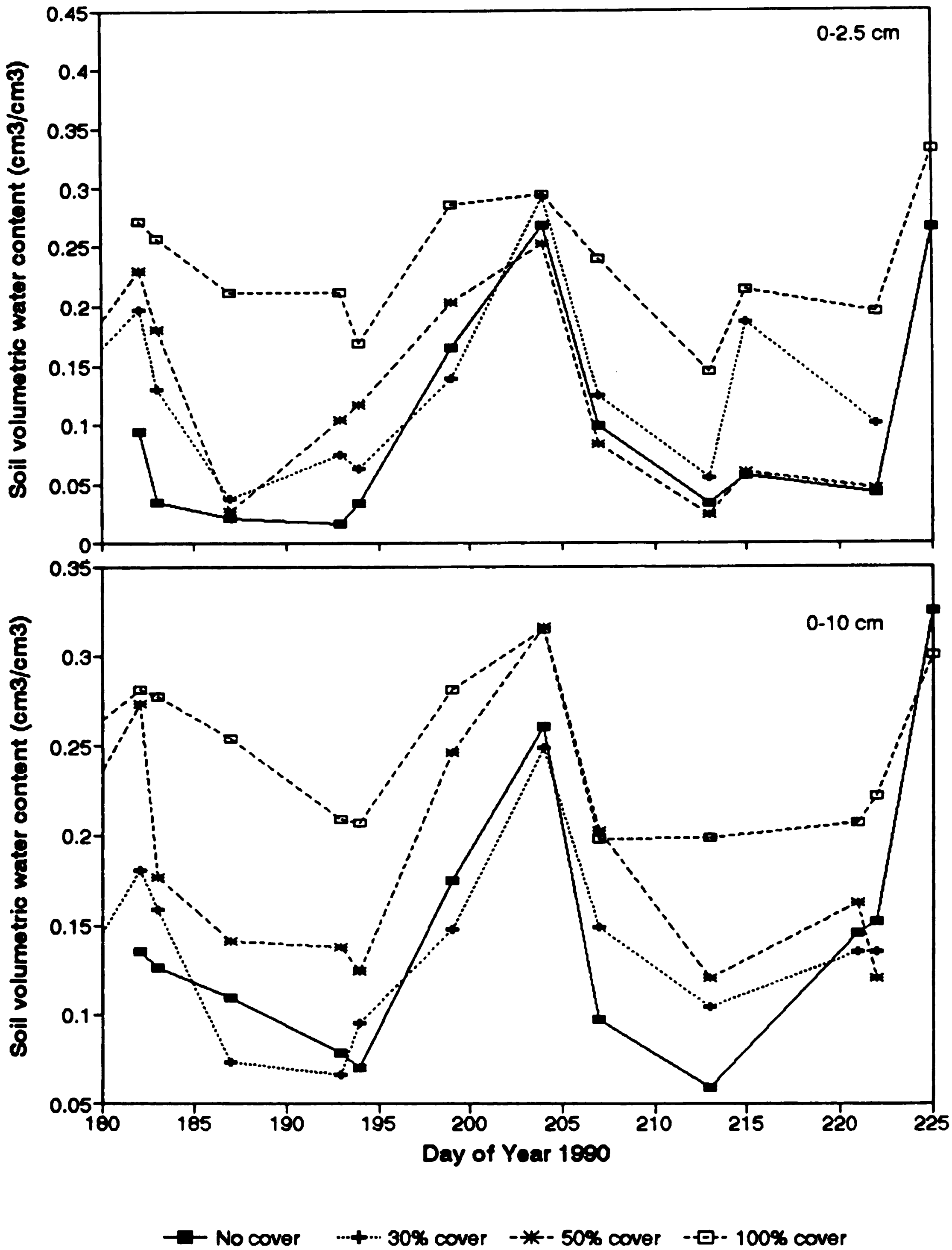

Figure 3.1: Surface volumetric water content for the 0-2.5 cm and 0-10 cm layers under for residue cover on fallow plots during summer 1990.

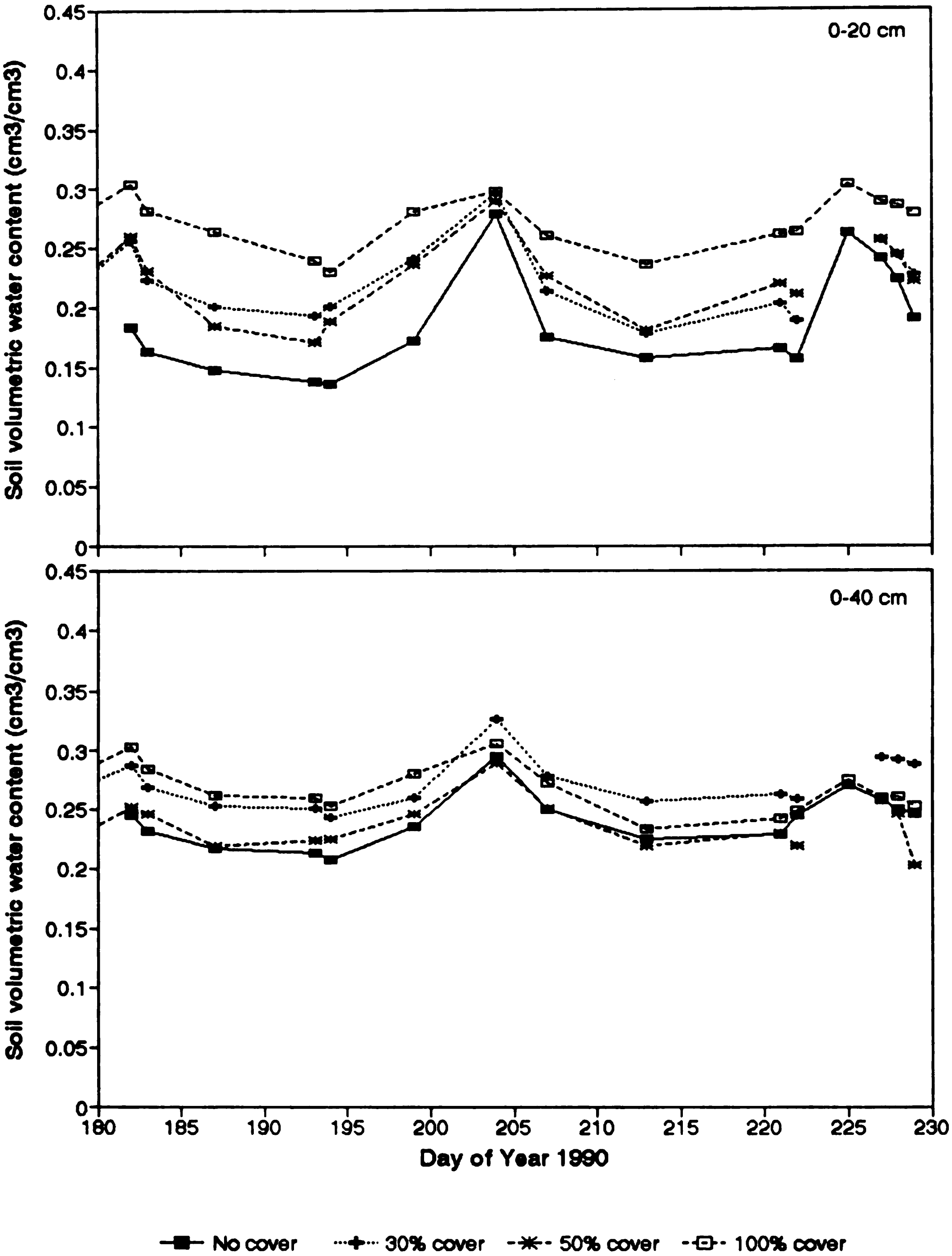

Figure 3.2: Surface volumetric water content from 0 to 20 cm and 0 to 40 cm under four residue cover during summer 1990 on fallow plots.

was smaller (Figures 3.3 and 3.4).

Surface layer water content on the cropped plots followed the same trends as on the fallow plots. Differences between treatments were noticeable at 40 cm (Figure 3.5 and 3.6). The plants did not seem to have benefitted from higher soil water content by taking up more water during the measurement period (9 July 1990 to 18 August 1990). This was probably because active roots were deeper. Soil water change in the 40 cm depth was higher on the fully 100% cover and 70% cover treatment throughout the measurement period (Figure 3.7). Soil water content change from the surface to a depth of 1 m was similar among treatments until the beginning of August 1991. After, soil water decrease was higher on the 70 and 100% cover plots than on the 0 and 30% cover. This difference in plant water uptake at the end of the season is more linked to plant development than root activity. Because plants on the covered plots were delayed, they needed more water for their growth than the plants entering the grain maturity stage.

Plant leaf surface area was studied as an indicator of plant growth and response to water stress. Although at time of measurement in 1990, maize was not completely developed on the fully covered plots, study of the first 9 leaves was possible because those leaves were fully developed. In 1990, covered plots seemed to have larger and longer leaves although the difference was not always statistically significant. Due to slower growth induced by lower soil temperature on the residue covered plots, plants had more time to transport carbohydrate to the leaves. Differences were less in 1991, and were probably due to a shorter vegetative

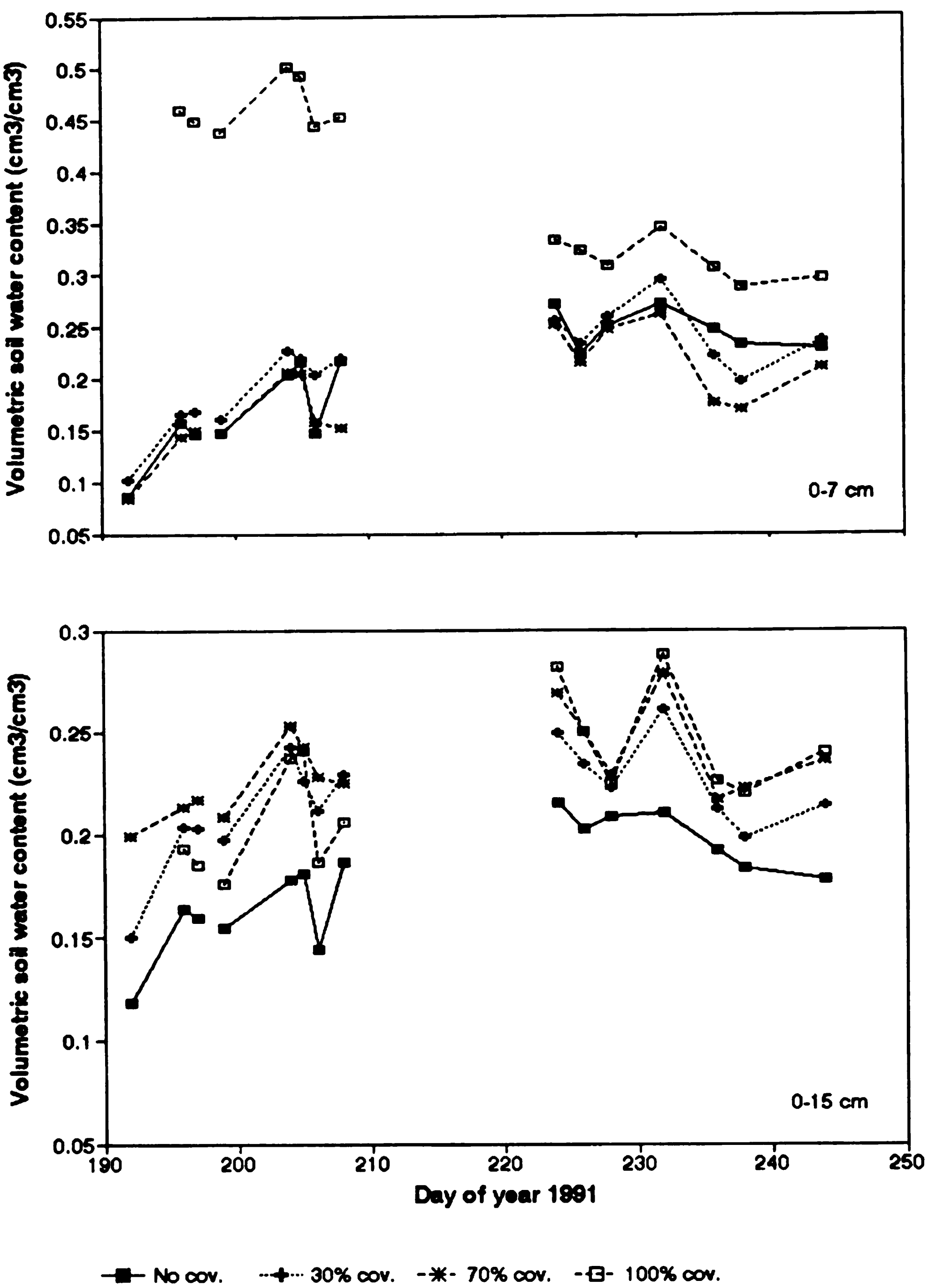

Figure 3.3: Surface volumetric water content from 0 to 7 cm and 0 to 15 cm under four residue covers on fallow plots during summer 1991.

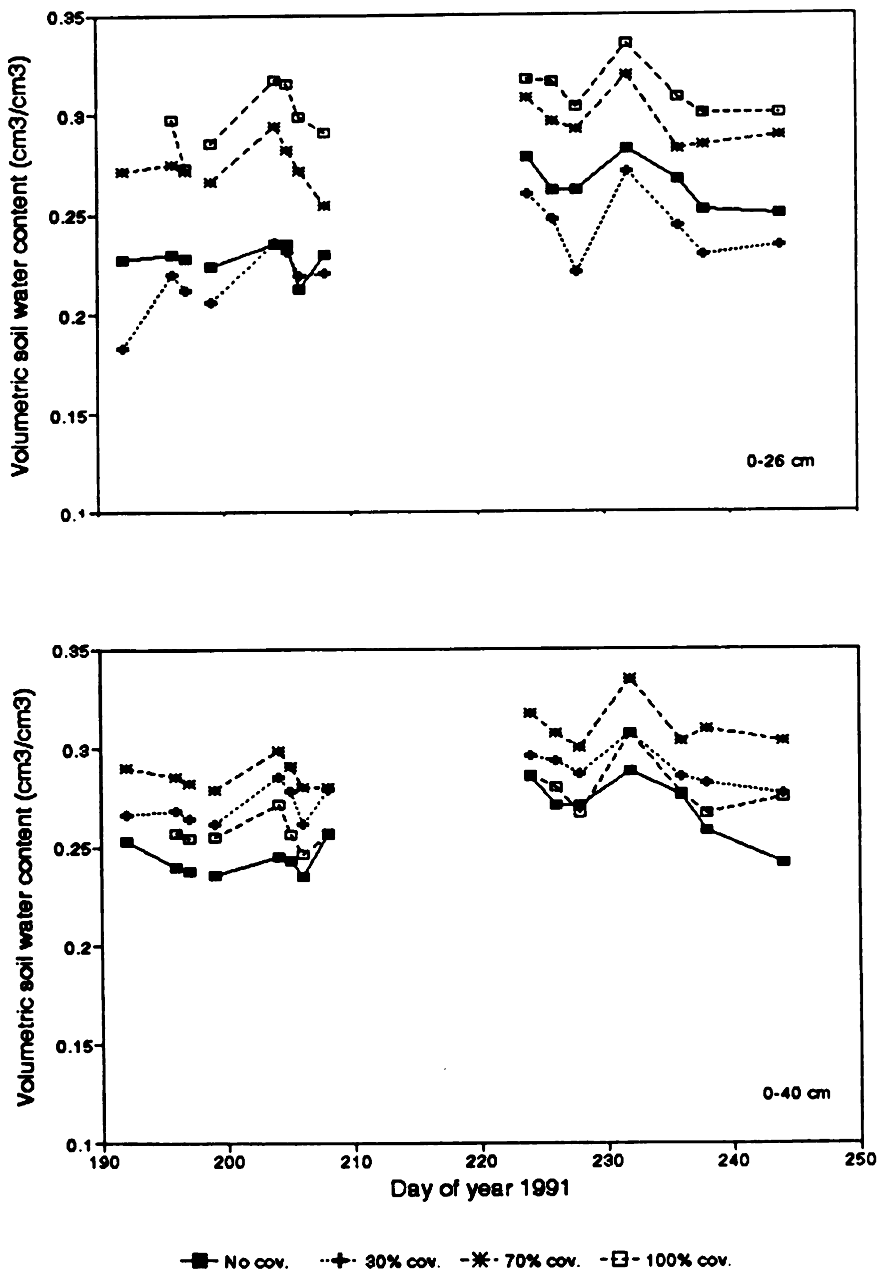

Figure 3.4: Volumetric water content from 0 to 26 cm and 0 to 40 cm under four residue covers on fallow plots during summer 1991.

development time because of higher temperatures. Leaf length and width of the final leaves were shorter in 1991, most probably for the same reasons.

To determine if leaf area was modified by residue cover, leaf area versus day of the year was plotted (Figures 3.8, 3.10) and soil thermal time (Figure 3.9, 3.11). At all times of measurement, the leaf area of the fully residue covered plots was usually lower than the bare plots especially in 1990. When leaf area versus thermal time was plotted the differences lessened for the increasing section of the curve. In 1991, more measurements allowed comparison of total leaf area to green leaf area. As seen in Figure 3.11, green leaf area is decreased in the fully covered plots whereas the total leaf surface area is relatively unaffected (Figure 3.12).

Residue cover had a major effect on delaying leaf surface area development, but did not have much effect on final total surface area. The area senesced faster in 1991 on the fully covered plots especially after anthesis.

Despite the late harvest date in 1990 water content of the cob and the stover was still high. In both years, the higher the residue cover the higher the water content of the grain and the stover (Table 3.1). This difference indicates that the delay in maturity extended all the way to the end of the season. Differences between years are explained by differences in rainfall patterns and temperature regimes at the end of the season. Because September 1990 was cooler and more humid than September 1991, maturity was delayed and water content was higher. For the same reasons differences among treatments were smaller in 1991 than in 1990.

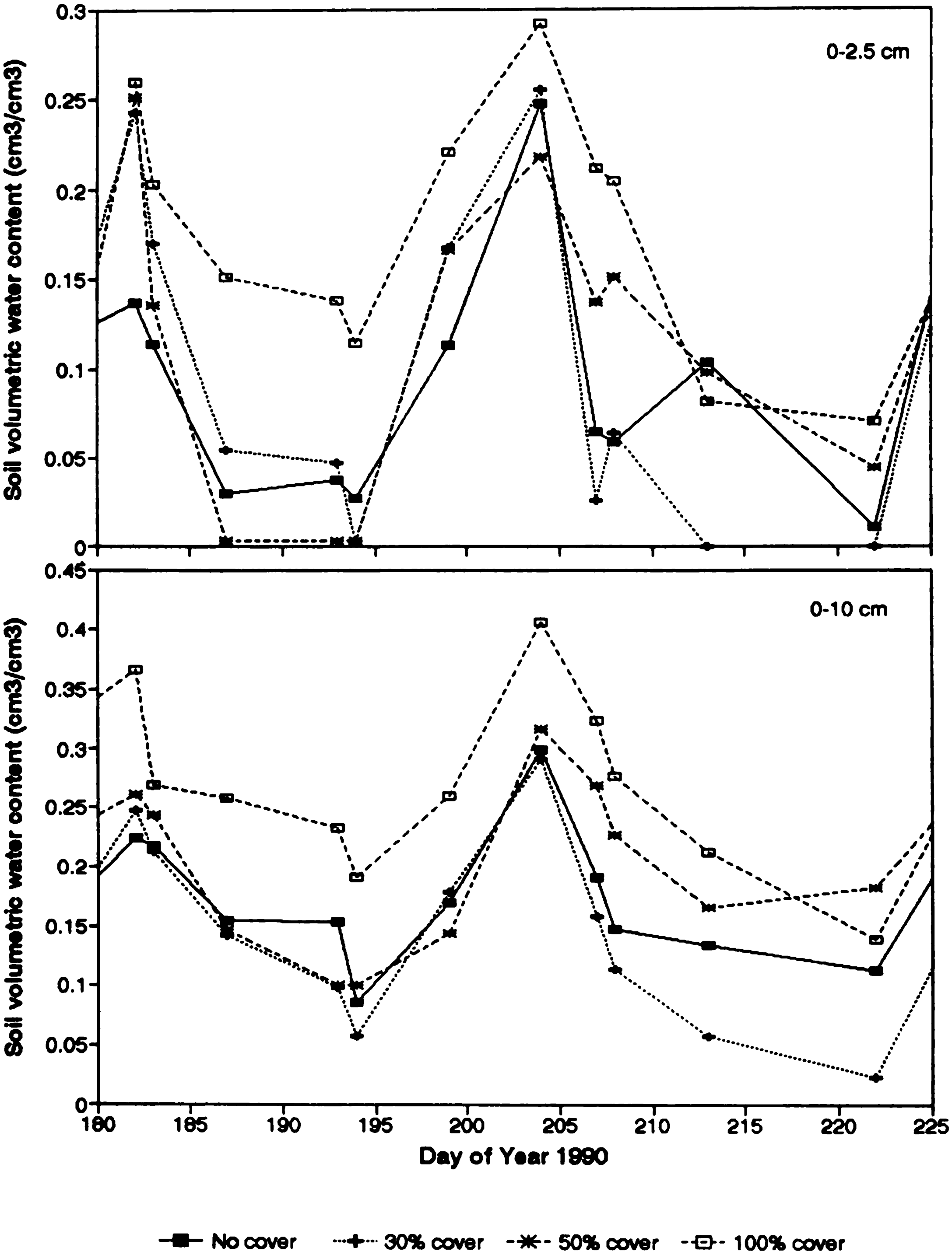

Figure 3.5: Surface volumetric water content from 0 to 2.5 cm and 0 to 10 cm under four residue covers on maize cropped plots during summer 1990.

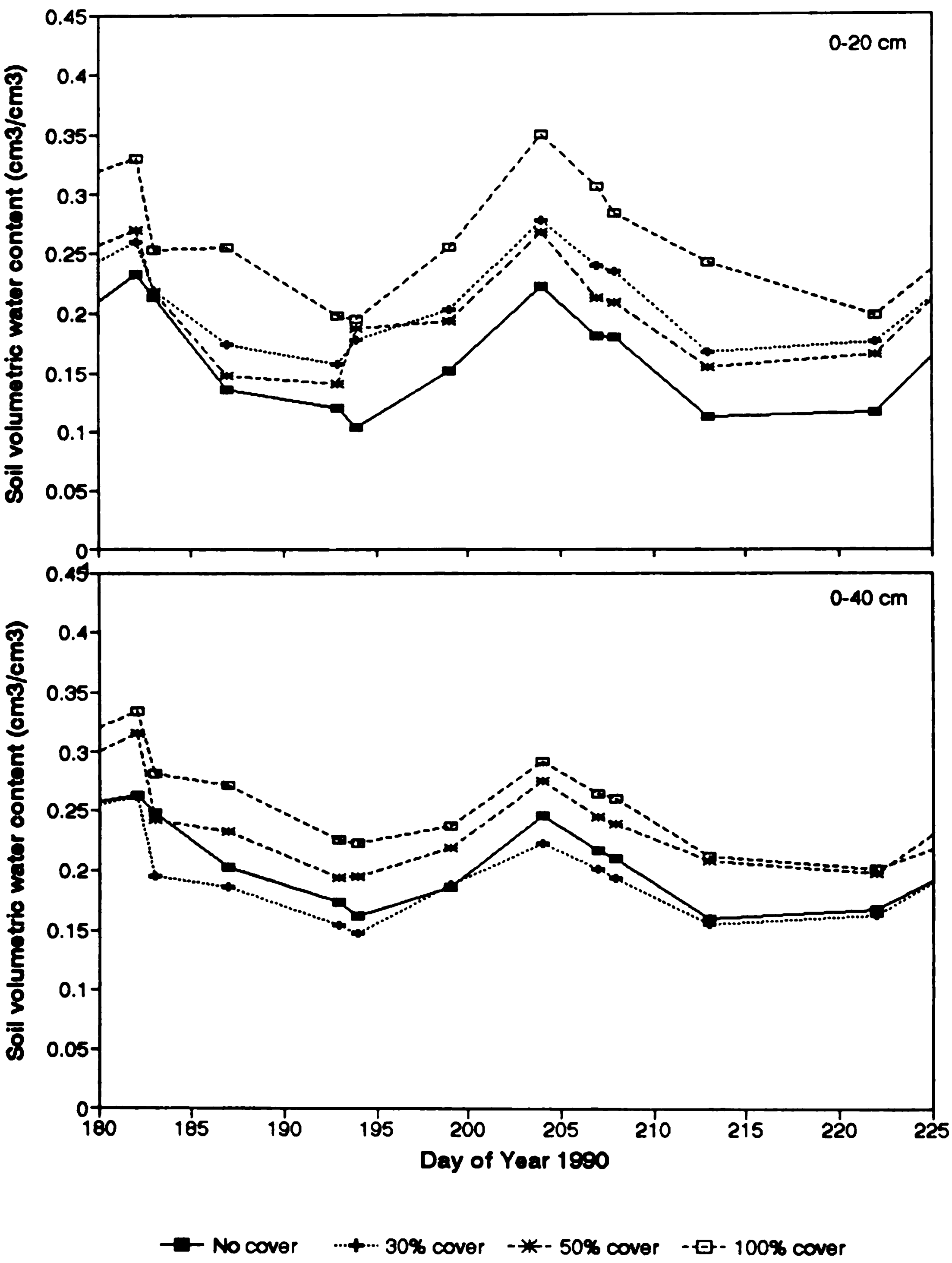

Figure 3.6: Surface volumetric water content from 0 to 20 cm and 0 to 40 cm under four residue covers on maize cropped plots during summer 1990.

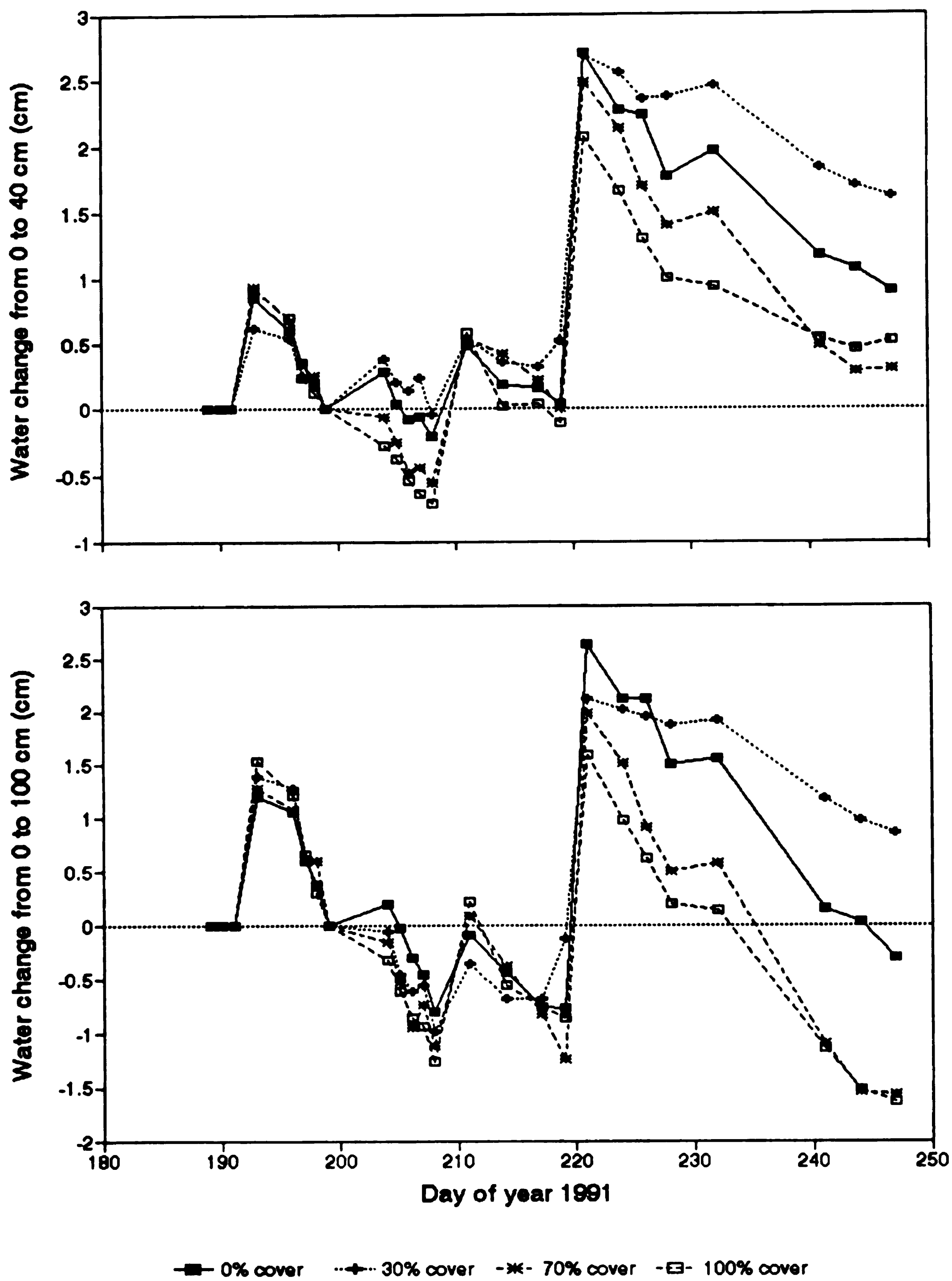

Figure 3.7: Soil water content variation (cm) in the top 20 cm and 100 cm under four residue covers, on maize planted plots, during summer 1991.

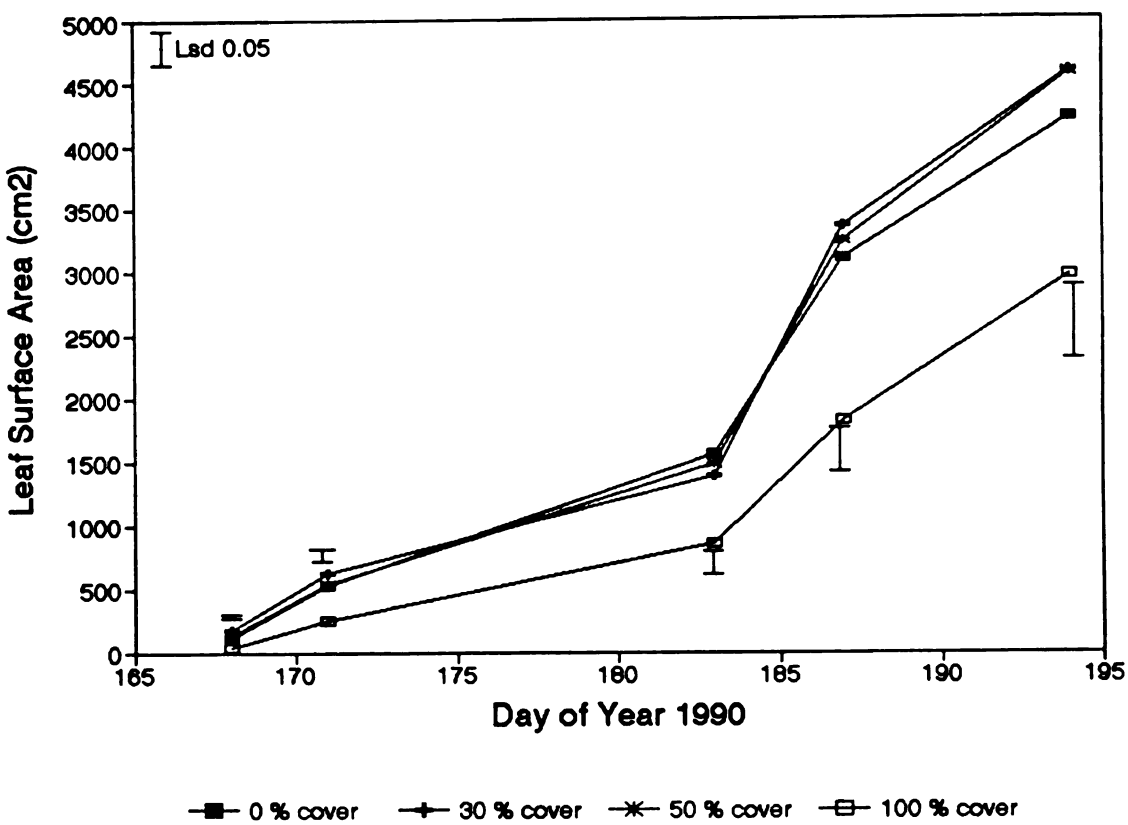

Figure 3.8: Plant leaf surface area for four surface residue cover treatments versus day of year 1990.

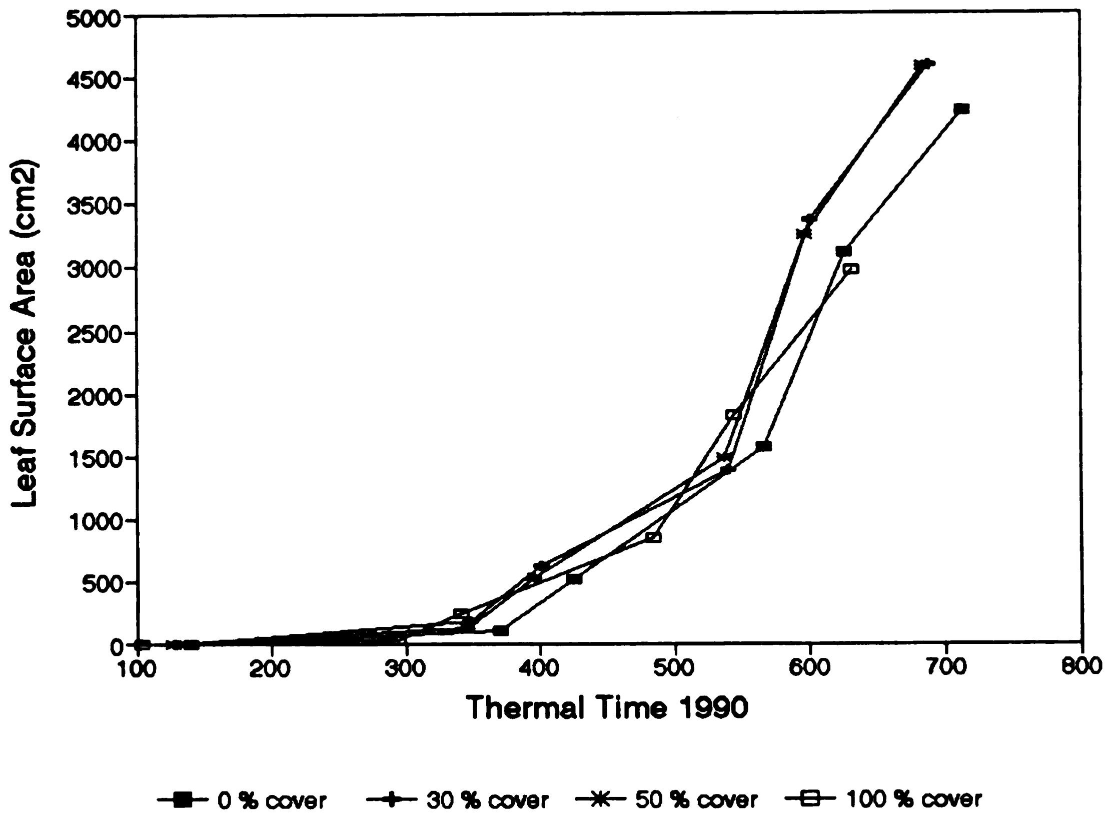

Figure 3.9: Plant leaf surface area versus thermal time calculated from soil temperature in 1990.

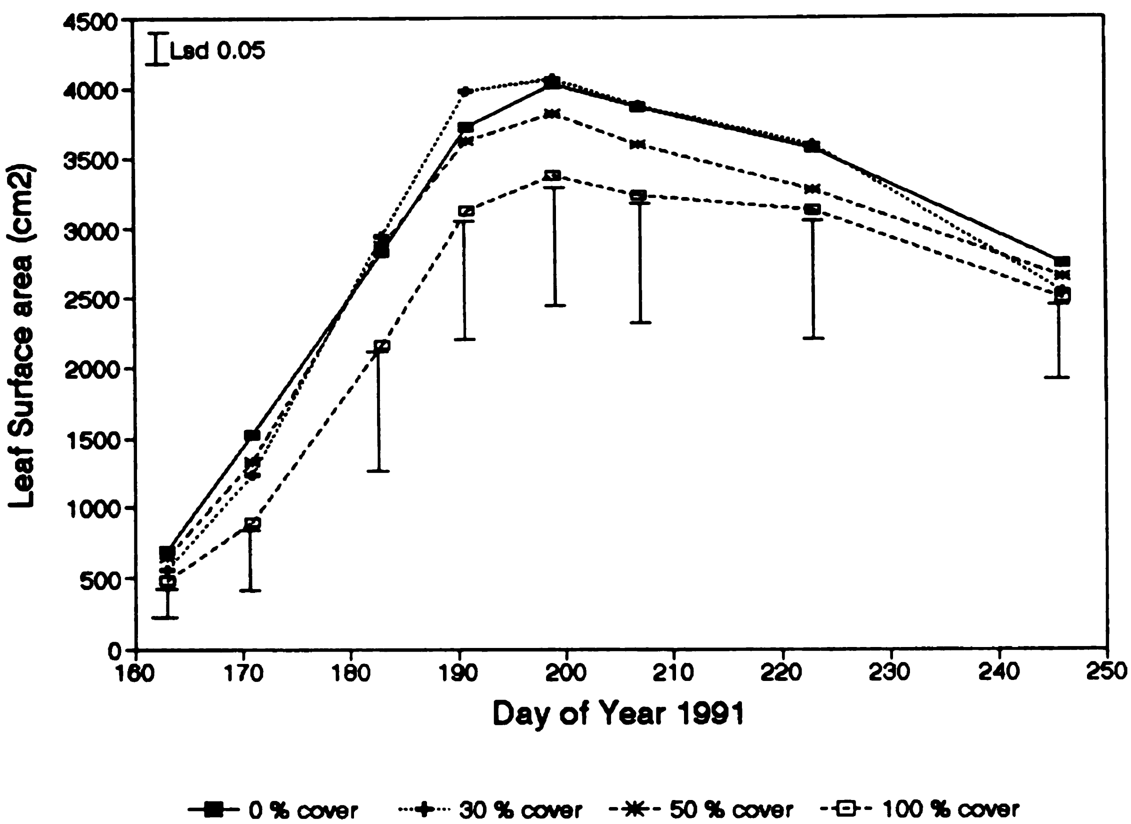

Figure 3.10: Plant leaf surface area for maize plants grown under four residue covers versus day of the year 1991.

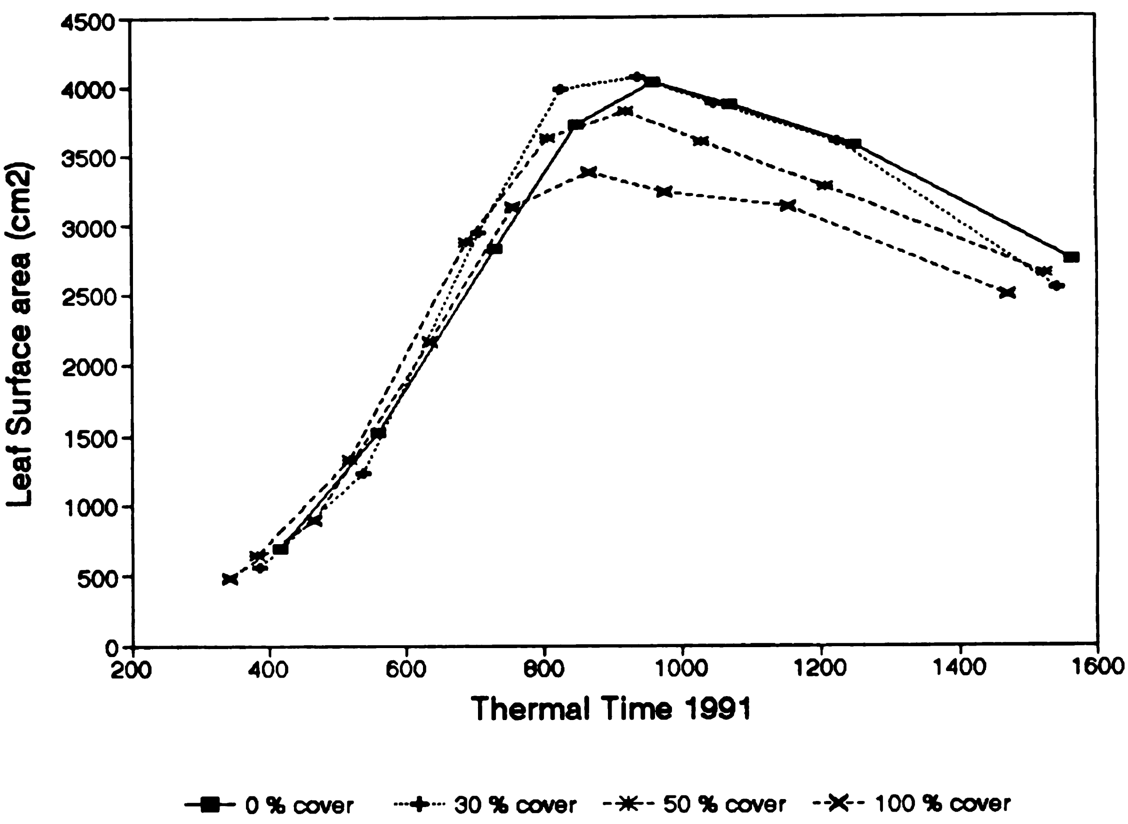

Figure 3.11: Plant green leaf surface area for maize grown under four residue covers in 1991.

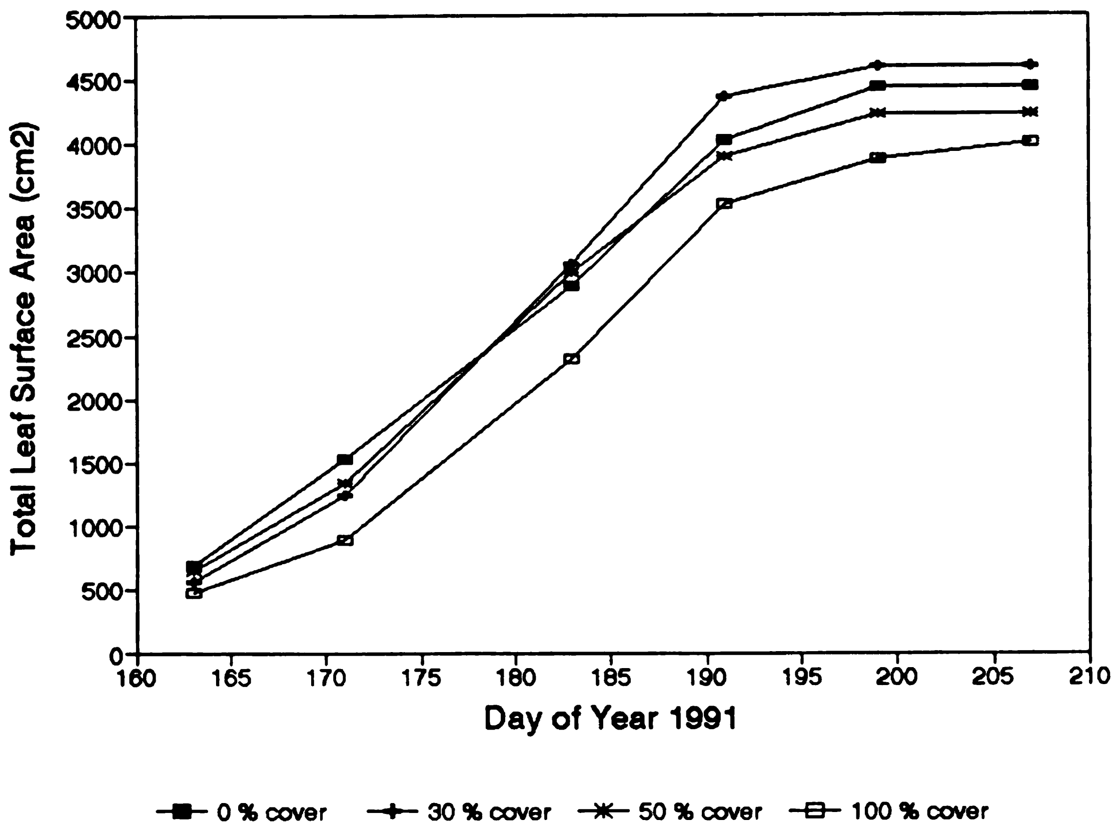

Figure 3.12: Total leaf surface area for maize plants grown under four residue cover treatments in 1991.

Table 3.1: Stover (leaves and stem) and cob water content at harvest in 1990 and 1991 under four residue cover treatments.

Soil cover	13 October 1990 water content (%)		27 September 1991 water content (%)	
	Stover	**Cob & Grain**	**Stover**	**Cob & Grain**
0 %	79.3	29.2	29.1	16.3
30 %	80.6	31.7	37.5	16.0
50 %	81.4	35.9	28.2	15.2
100 %	84.1	41.1	43.2	17.8
LSD	2.5	6.5	6.8	2.9

Residue cover had more impacts on the grain water content at harvest in a wet year than a dry year. Kernel weight was not affected by the treatment or climate, but the grain number per ear was affected in both years. In 1990, flowering occurred on the bare plots on 25 July and several days later on the other treatments, after a rainfall of 40 mm. In 1991 flowering occurred on 18 July after a period of 10 days without rain. Lower water supply or higher temperature that increased the potential evaporation decreased the grain number in 1991 compared to 1990 (Table 3.2) possibly because of a difference in time of grain formation (Grant *et al.*, 1989).

While intermediate residue levels slightly increased grain number, the fully covered plots had a smaller grain number. As discussed in the leaf expansion data, time of water deficit matched grain differentiation stage and decreased the number of grain in the fully covered plot. Kernel weight was unaffected by treatments probably due to compensation growth.

Table 3.2: Grain number per plant , kernel weight (g), and total grain weight per plant (g) for four residue cover treatments in 1990 and 1991.

	1990			1991		
	Grain number per plant	**Kernel weight g**	**Yield g plant^{-1}**	**Grain number per plant**	**Kernel weight g**	**Yield g plant^{-1}**
0%	608	0.251	152.3	451	0.228	103.0
30%	614	0.256	157.3	443	0.252	111.6
50%	620	0.245	151.9	379	0.243	92.1
100%	515	0.260	133.8	381	0.242	92.2
LSD	60.9	0.03	21.0	183.8	0.025	45.5

Conclusion

Residue cover increased soil surface water content by decreasing soil water evaporation. The plant leaf growth was delayed by the residue cover but its maximum growth was unaffected. In 1991, the plant leaves senesced faster on the 70% and 100% covered plots. The effect on the grain yield was not significant but the grain water content was higher on the covered plots. Residue delayed the growth up to maturity but did not affect the yield. The expected differences in root distribution and plant water uptake might affect the yield for other climates or rainfall distribution. Further study on the root distribution under a residue cover for several climatic conditions would help us understand the consequences of a residue cover on plant water and nutrient deficit. The use of crop models which include a soil cover, will allow us to study the consequences of plant delayed development on final yields for several soil and climate conditions.

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Chapter 4: CERES-Till, a model to predict the influence of crop residue cover on soil surface properties and plant development

Abstract

The complexity of the interactions between decreased soil temperature and soil water conservation effects on plant growth and development make generalizing the consequences of conservation tillage for a wide range of soil and climate difficult. Crop modelling has been widely used to evaluate strategies in different environments. This study describes the changes made in CERES functional models to include surface residues and tillage. The processes modelled are: surface residue cover, effect of a residue cover on soil temperature and soil surface water balance, surface bulk density, water ponding capacity and saturated water conductivity changes with tillage and precipitation intensities. The surface residue decomposition model predicted measured wheat residues reasonably well. Plant development prediction was improved as well as soil surface water content prediction. Further work is needed to validate the surface properties modelled (bulk density, ponding capacity and saturated water conductivity).

Introduction

Residue cover is important in soil erosion control because it keeps soil water infiltration high and reduces soil erosion losses (Wishchmeier and Smith, 1978). Thus, it is important to know the residue cover throughout the year to evaluate water runoff and potential soil erosion. Residue cover may affect plant development through alteration of the soil temperature and water content near the soil surface (Griffith *et al.*, 1977). There are trade-offs between increased water content and plant development delay. Reduced evaporation losses can result in more water being available to the plant. Plant development delay may avoid a water deficit period or push a critical development stage into a water deficit period. Despite the negative effect of decreased soil temperatures, a residue cover was found to improve maize yields in Indiana by extending the growing season and increasing water conservation (Griffith *et al.*, 1977). The increased length of the growing season and water conservation is not always beneficial (Griffith *et al.*, 1977). A model that includes residue cover effect on soil erosion and maize development and growth would enable the analysis of conservation tillage effect on crop production for several climates and soil types. As seen in Chapter 1, several models including soil erosion or tillage treatment already exist. Their use is limited, however, by large input requirements or rather poor crop growth routines. The CERES model was chosen for the easiness of use and the wide usage throughout the world for the addition of these features that it heretofore did not have.

The CERES model is a process-oriented program written in FORTRAN and was designed to operate on IBM-compatible personal computers running on MS-DOS. The model uses a standardized input and output structure (IBSNAT, 1989). The CERES model simulates individual plant performance and assumes every plant in the area being simulated is homogeneous. Because field plants compete for resources, three parts of the model require whole plant population concepts. The first part is photosynthesis and light interception which is a function of leaf area index. The second part is transpiration and water uptake which is a function of root density per unit soil volume in different layers, water availability and potential evapo-transpiration. The third part is nitrogen uptake which is a function of root density , nitrogen pools and microbial activity. The crop model state variables describe the changes in crop growth and development, and soil water balance for each day of the growing season. The variables are detailed in three output files. One output file contains plant state variables for above- and below-ground plant biomass, leaf number, surface and weight, stem weight, grain weight and root depth. The second output file contains soil water state variables such as water content for several layers, potential evaporation, and soil evaporation. The third output file contains nitrogen state variables such as nitrogen concentration in the top biomass, total nitrogen uptake, nitrogen mineralization and leaching, denitrification, and nitrate and ammonium content for several layers. A detailed description of input and output files is provided by IBSNAT (1989).

Several model routines were developed to take into account the dynamics of crop residue decomposition and how the residue decomposition affects soil properties and subsequently, crop growth and development. The model includes the influence of surface crop residues on soil temperature and soil evaporation that are the two main effects of a residue cover on plant development and growth (Griffith *et al.*, 1977). It also accounts for soil physical characteristics such as surface bulk density, surface water conductivity, and ponding capacity dynamics (Black, 1973). The model is written in FORTRAN for ease of linkage to the existing CERES group of models, or other similar daily incremental functional models.

Model description

The model structure and components modified are illustrated in Figure 4.1. Some routines only needed alterations (thick line boxes), while some new ones needed to be added (double boxes). This section details the modifications made to CERES models version 2.1. Computer codes of new and modified routines are given in appendix 2.

Surface residue dynamics

The non-tillage version (2.1) of the CERES model incorporated residues in the soil profile the first day of simulation. Inputs are initial amount of crop residue (kg ha^{-1}), depth of incorporation (cm), and crop residue C:N ratio. Residues are

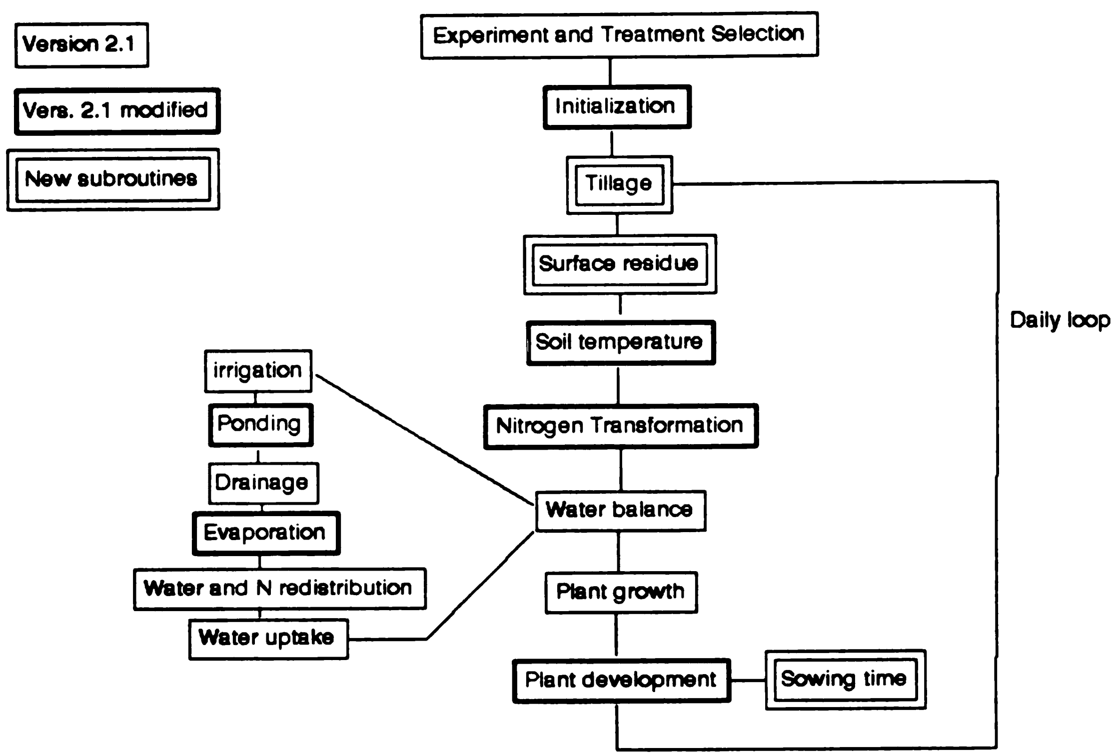

Figure 4.1: CERES model version 2.1 structure, and added (double line) or modified subroutines (thick line) to include residue management and tillage. Unmodified subroutines are boxed with a single line.

assumed to be uniformly distributed in the tilled layers and fresh organic matter pools of each layer updated. To add a tillage component, crop residue must be partitioned between soil layers and soil surface according to the tillage tool used, residue decomposition, and soil coverage. Surface residue decomposition must be predicted to calculate residue cover contribution to soil surface organic matter, soil coverage and protection from erosion.

Residue incorporation in the soil profile

Shelton *et al.* (1990) proposed to use the product of percent of residues remaining after each tillage operation as a way to calculate final residue biomass at the surface. Values of percentage of remaining residue at the surface are estimated from the tillage tools used. Low and high limits are given in Table 4.1 as the amount incorporated increases with residue breakability. Multiplying the coefficients for each tillage operation provides an estimate of the percentage of residue left at the surface. Sloneker and Moldenhauer (1977) gave similar values for crop residues remaining after several types of tillage passes for three types of soil. Residue remaining after tillage is a product of the fraction of residue buried by a tillage operation and the initial amount of residue before tillage. Predicting surface residue decomposition is also necessary to estimate the amount of residue decomposed between two tillage events.

Table 4.1: Influence of field operations on surface residue (Shelton, 1990)

Tillage and Planting Implements	Percent of Remaining Residues**
Moldboard plow	3-5
Chisel plow	
Straight shovel points	50-75
Twisted shovel points	30-60
Knife-Type fertilizer Applicator	50-80
Disk (Tandem or Offset)	
7.5 cm deep	30-60
15. cm deep	40-70
Field Cultivator	50-80
Planters	
No coulter or smooth coulter	90-95
Narrow ripple coulter (less than 3.8 cm flutes)	85-90
Wide fluted coulter (greater than 3.8 cm flutes)	80-85
Sweeps or double disk furrowers (till-plant)	60-80
Drills	
Disk openers	90-95
Hoe openers	50-80
Winter Weathering	70-90

** Use higher values for irrigated maize residue, and lower values for fragile residue such as soybean.

An example of a chisel-disk-planting sequence is:

0.86 x	0.75 x	0.60 x	0.95 =	0.37 x 100 = 37%
Spring Residue Cover	Chisel	Disk	Planting	Final Residue Cover

Surface Residue decomposition

Models of surface crop residue decomposition vary from deterministic, where every step of the process is modelled, to statistical where the final results are predicted from inputs by a simple relation developed on historical data. Shelton *et al.* (1990) proposed a 10% to 30 % loss due to winter weathering to evaluate percentage of residue remaining at the surface at the time of spring planting. This type of model is not weather dependent and would not fit the general purpose of a generally applicable type model. Ghidey *et al.* (1985) and Van Doren and Allmaras (1978) proposed a single first order model that consist of an exponential decrease in the amount of residues at a rate that is a function of residue type and size, water content and temperature. Andrén and Paustian (1987) compared several models of residue decomposition, and showed that a parallel first order model that uses two first order decomposition equations, one for a labile pool and one for a resistant pool, gave as good an overall fit as a single first order model, and better initial loss in the labile fraction. This parallel first order model was chosen to model surface residue decomposition because it first order model was chosen to model surface residue decomposition because it complies with CERES functional structure and daily increment.

Following the procedures of Reddy *et al.* (1980), the initial amount of residue left at the surface (Mulch) was fractioned into two pools: a labile pool ($Mulch_l$) and resistant pool ($Mulch_r$) depending on its C:N ratio (SCN):

$$D1 = 0.8664 - 0.1395 * \ln(SCN) \qquad [4.1]$$

$$Mulch_l = D1 * Mulch \qquad [4.2]$$

$$Mulch_r = (1 - D1) * Mulch \qquad [4.3]$$

where D1 is the fraction of the labile pool.

Each pool follows a first rate decay equation :

$$Mulch_i = Pmulch_i * e^{(-Ki*MIN(TEMPFAC,WATFAC))} \qquad [4.4]$$

where i represents l for the labile pool and r for the resistant pool, Pmulchi is the amount in each pool the previous day and $Mulch_i$ at the end of the day, K_r is the decomposition rate factor of the resistant pool at 25 ^oC and is derived from D1 (Reddy *et al.*, 1980). Andrén and Paustian (1987) used a K_l of 2.96 for buried residue at the optimum temperature of 23 ^{o}C. Because surface residue contact with soil is less than when buried and microbial population is different, using a K_l value of 0.3 was necessary to obtain a good fit of available data. The K_r value used was (Reddy *et al.*, 1980):

$$K_r = 0.035*D1 - 0.0013 \quad [4.5]$$

TEMPFAC and WATFAC are relative modifying factors calculated from air temperature and residue water content. TEMPFAC is equal to zero when air temperature is below 0 ^{o}C or above 60 ^{o}C (Parr and Papendick, 1978). It is equal to 1 between 25 and 40 ^{o}C, and follows a linear relationship from 0 to 1 between 0 and 25 ^{o}C, and 40 and 60 ^{o}C (Figure 4.2).

WATFAC is a factor varying from 0 (maximum reduction) to 1 (no reduction) following the relationship (Figure 4.2):

$$WATFAC=\frac{\ln(MulchSW/MulchSAT)}{\ln(0.01/MulchSAT)} \quad [4.6]$$

where MulchSW is the amount of water (cm) held in the surface residues, MulchSAT the maximum amount of water (cm) that can be held and 0.01 the minimum amount. Details regarding water held in mulches is presented in a later section.

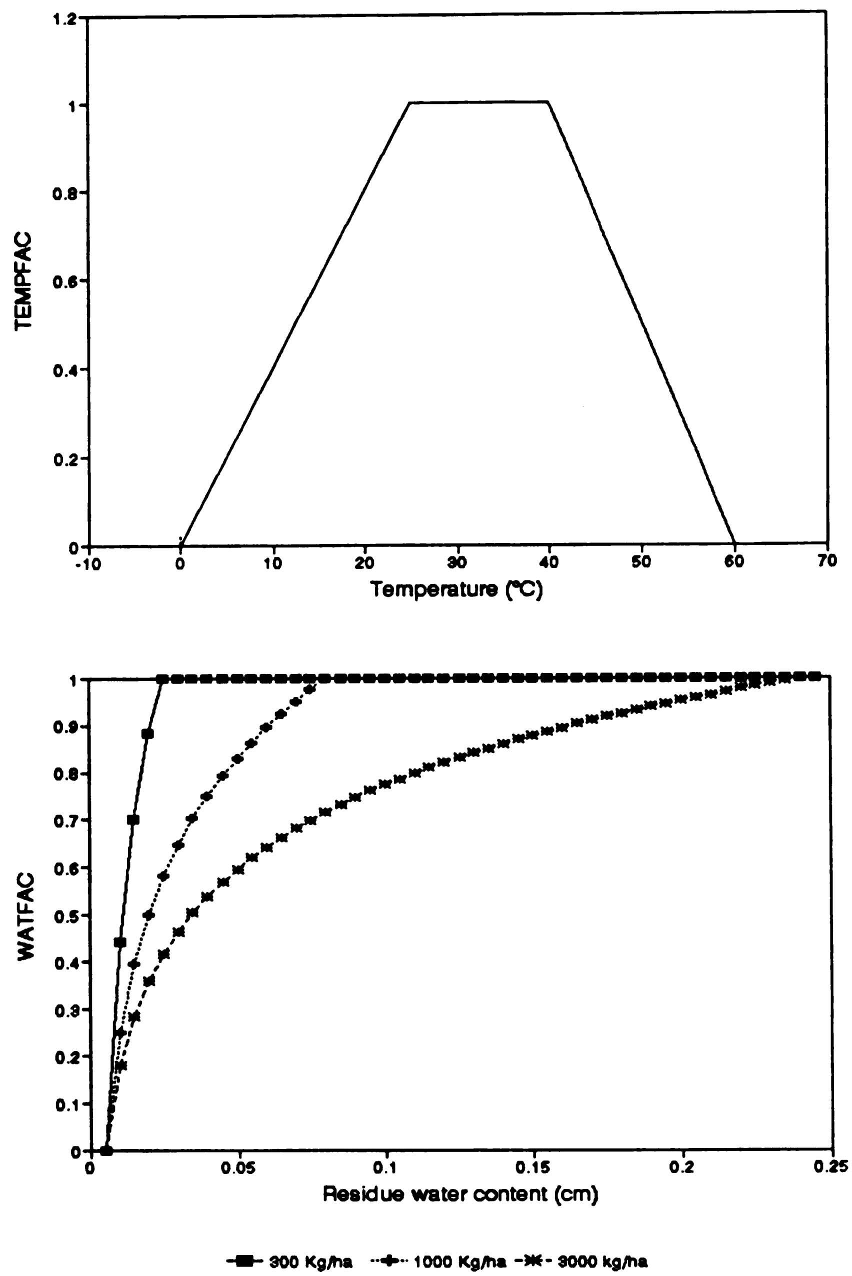

Figure 4.2: Temperature and water content factors affecting residue decomposition. One represents optimal conditions and 0 no activity.

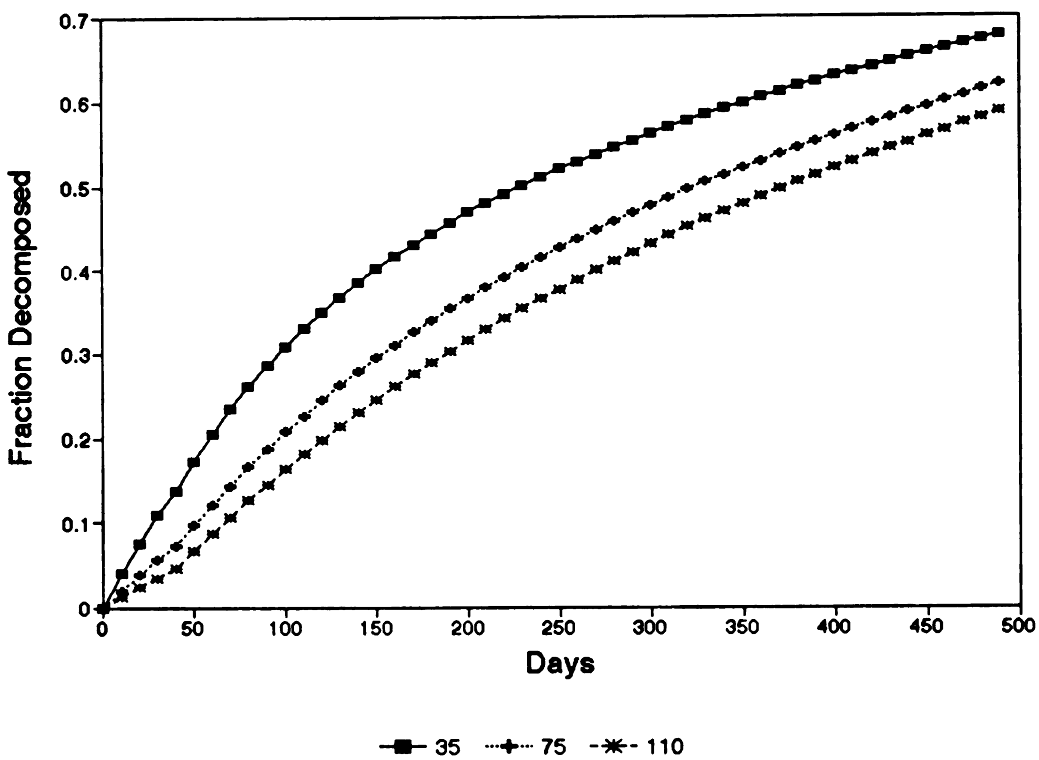

Figure 4.3: Remaining surface residue for three crops representing different C:N ratio, and assuming optimal conditions.

Using the law of the minimum assumption, the minimum value of the water or temperature factor becomes the modifier to decrease the rate of decomposition. Figure 4.3 shows the remaining surface residue for three different C:N ratios, assuming optimum temperature and water content (factor stresses equal to 1). Decomposed organic matter is added to the surface layer organic matter pools when a rain or irrigation occurs.

Incorporated residues decomposition routine follows the logic of the CERES model version 2.1. They are uniformly incorporated in the fresh organic matter (FOM) of each layer tilled. A pool of surface organic matter (Mulch) is created and will follow a decomposition subroutine similar to one already described.

Residue coverage

Gregory (1982), and Van Doren and Allmaras (1978) developed models to predict the percentage of soil covered (Fc) from the weight of residue at the surface (Mulch). The equation is the result of the probability that each piece of residue to fall on an uncovered soil surface (Gregory, 1982) (Figure 4.4):

$$FC = 1 - e^{(-\ Am\ *\ Mulch)} \qquad [4.7]$$

where Am is used to convert mass of residue to equivalent area (ha kg^{-1}) and is residue type dependent (crop, diameter, density).

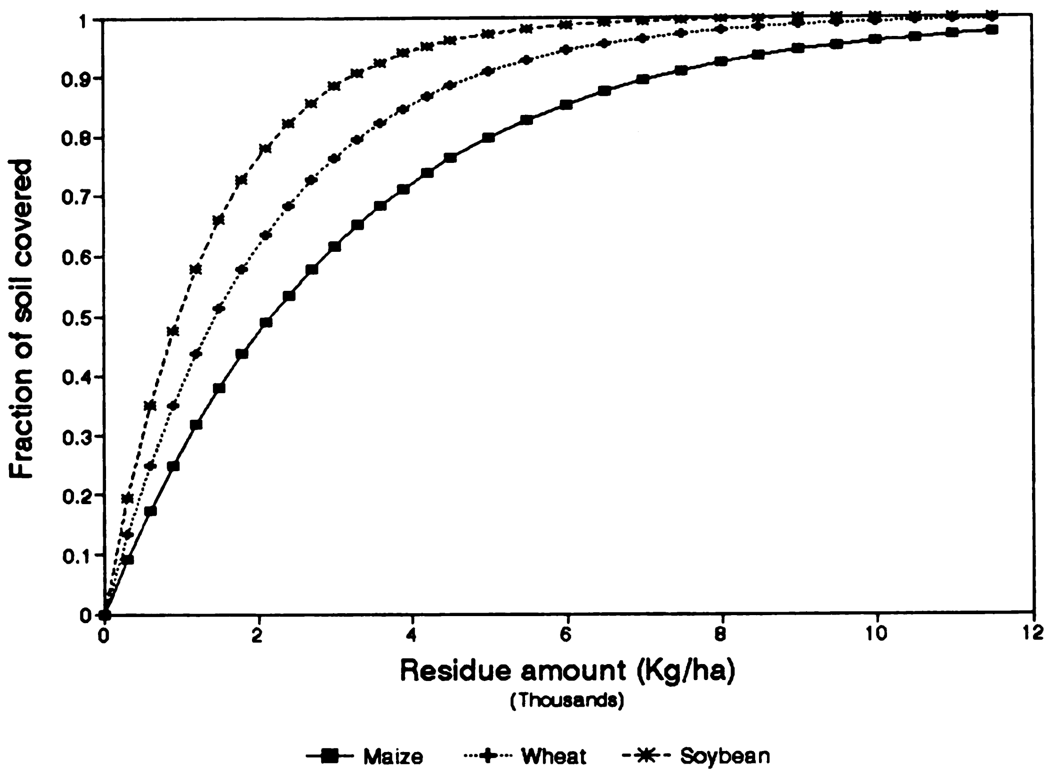

Figure 4.4: Fraction of soil covered versus amount of residue at the surface for three different crops.

Tables of values for Am are given by Gregory (1982) and Greb (1967), and some values are given in Table 4.2. Values of Am can also be measured by weighing crop residue samples and measuring their surface with a surface meter. Chopped maize residue values were measured during field experiments described in Chapter 2 and 3. Small samples of chopped maize residue were weighed and the surface covered by those small samples without any overlapping was measured using a leaf area meter. Values of 0.000358 ± 0.00003 ha kg^{-1} in 1990 and 0.00029 ± 0.00003 ha kg^{-1} in 1991 were found and are in conformity with the literature.

Table 4.2: Values of average mass to area conversion for residues.

Crop	**Am (ha kg^{-1})**	**Source**
Maize	0.00032	Van Doren and Allmaras 1978
Maize	0.00040	Gregory, 1982
Wheat	0.00054	Gregory, 1982 (data: Wischmeier *et al.*, 1978)
Winter wheat stem	0.00027	Greb, 1967
Wheat	0.00045	Gregory, 1982
Winter wheat stems	0.00027	Greb, 1967
Soybean	0.00032	Gregory, 1982
Grain sorghum stems	0.00006	Greb, 1967
Sunflower	0.00020	Gregory, 1982

Mulch thickness

When the residues are spread at the surface pieces overlay each other. To determine how many layers (n) there are in a mulch cover from the average surface covered per kilogram (Am, ha kg^{-1}) and the total residue biomass (Mulch, Kg), we must first calculate the amount of residue (M_i, kg) which overlays the lower layer number i-1 by subtracting from the amount M_{i-1}, the biomass needed to cover S_{i-1} if the pieces were not overlaying each other. Then the fraction of the surface (S_i, ha) this would cover is calculated. These calculations are iterated until no residues are left.

$$M_i = Am * M_{i-1} - \frac{S_{i-1}}{Am}$$

$$S_i = S_{i-1} * (1 - e^{-Am * M_i / S_{i-1}})$$

$$MulchThick = \sum_{i=1}^{n} S_i * Athick \qquad [4.8]$$

The thickness of the mulch is then calculated by summing the average thickness of each layer (S_i * Athick) and used in soil evaporation predictions.

Impact of a residue cover on the soil water balance

The water balance subroutines of CERES have recently been improved (Ritchie, Godwin, Baer, Gerakis, personal communication). Changes include the time-to-ponding approach to better predict water infiltration and runoff, water table movement, and water balance of relatively thin surface layers. Maximum infiltration during a rainfall or irrigation is predicted from surface water hydraulic conductivity, soil water content and cumulative infiltration. If the estimated or measured precipitation intensity is higher than the maximum infiltration rate for the time step, water ponds at the soil surface. If the total amount of water ponding at the soil surface is higher than the ponding capacity, water runs off (Chou, 1990). Surface water evaporation and redistribution are predicted from soil water content and drained upper limit values.

Undisturbed soil cores (7.6 cm in diameter and 7.6 cm high) were sampled using a double-cylinder sampler for measuring bulk density, total porosity, and saturated hydraulic conductivity. Three cores were obtained from soil depth of 0 to 7.6 cm, 7.6 cm to 15.2 cm, and 15.2 to 22.8 cm. Cores were saturated from bottom and then weighed so that total porosity could be measured at saturation. Cores were then equilibrated on a tension table or pressure plate apparatus at matric potentials of -1, -2, -4, -6, -33.3, and -100 kPa. Cores were then oven dried. Bulk density was calculated from the above measurements.

Rainfall interception

Residue at the surface intercepts precipitation. The maximum amount of water that can be retained in the surface residues (MulchSAT, cm) is proportional to the amount of residue at the surface (Mulch, kg ha^{-1}). Parr and Papendick (1978) in the pressure plate method showed that residues could hold up to 3.8 times their weight in water.

The transformation from mass of water to centimeters of water gives:

$$MulchSAT = 3.8 * 10^{-5} * Mulch \qquad [4.9]$$

The amount of precipitation (rain or irrigation, IPRECIP) intercepted is a function of the amount of water held (MulchSW, cm) and the maximum amount that can be retained (MulchSAT, cm). The amount that reaches the soil surface (PRECIP) is:

$$PRECIP = IPRECIP - (MulchSAT - MulchSW) \qquad [4.10]$$

Potential soil evaporation

Water withheld in the residue from previous precipitation is assumed to be free and available for evaporation. The soil potential evaporation is decreased by the amount of free water evaporating from the residues (ΔEos, cm) and the residue water content is updated:

$$\Delta Eos = Eos \text{ and } MulchSW = BMulchSW - Eos \qquad Eos < MulchSW \qquad [4.11]$$

$$\Delta Eos = MulchSW \text{ and } MulchSW = 0.0 \qquad Eos \geq MulchSW \qquad [4.12]$$

where BmulchSW is the residue water content before evaporation.

Similar equations are used for the change in water ponding at the surface (ΔPOND, cm):

$$\Delta POND = Eos \text{ and } POND = BPOND - Eos \qquad Eos < POND \qquad [4.13]$$

$$\Delta POND = Eos \text{ and } Eos = 0.0 \qquad Eos \geq POND \qquad [4.14]$$

where BPOND is the ponded water before evaporation.

Adams *et al.* (1976) used an exponential decreasing function of residue biomass at the surface to model the impact of residue cover on soil evaporation. The equation developed for oat residue (*Avena Sativa*, L.) would need calibration for other types of residue. Unger and Parker (1976) studied the decrease in soil water evaporation under several loading rates of cotton, wheat, and sorghum residue. They show that the decrease in evaporation is closely correlated to soil coverage and residue mulch thickness. Residue mulch thickness is hard to determine unless the soil is fully covered: a rare occurrence in field situations. At lower loading, soil coverage should be sufficient. Data published by Bond and Willis (1969, 1970) were used to calculate the correlation between relative decrease (R_{cov}) in soil water evaporation between a bare surface and a covered surface and fraction of soil covered (F_c). Soil coverage was estimated from the loading rate (see above). The relation found for the two articles and for several potential evaporation rates were similar:

$$R_{cov} = 1 - 0.807 * F_c \qquad R^2 = 0.956 \qquad [4.15]$$

For higher residue loads which provide a full cover, thickness of the residue layer should be used to predict the decrease in soil water evaporation. Unger and Parker (1976) proposed three different logarithmic correlations between the thickness (MulchThick, cm) of the residue layer and the evaporation rate for three potential evaporation rates. The three equations can be summed up in one equation:

$$R_{thick} = e^{(-0.5 * MulchThick)} \qquad [4.16]$$

The minimum of the two coefficients Rcov and Rthick is then used to calculate the relative decrease in soil potential evaporation.

$$R_m = \text{Minimum}\ (R_{cov}, R_{thick}) \qquad [4.17]$$

The potential evaporation beneath a crop canopy and a residue cover is then estimated using the algorithm of Adams *et al.* (1976):

$$E_{cm} = R_m * R_c * Eos \qquad [4.18]$$

where Eos is the potential evaporation of a bare soil (cm), and E_{cm} the potential evaporation of a covered soil (cm). The effect of crop residue is combined with the effect of crop canopy factor (R_c) to calculate the potential soil evaporation (E_{cm}) of a partially covered soil surface (Adams *et al.*, 1976).

Soil temperature

In the older version (2.1) of CERES models, surface boundary soil temperature (TMA) is estimated daily from daily air average temperature (Tempm), daily air maximum (Tempmx), solar radiation (solrad), surface albedo (Albedo) and surface temperature of the previous day (BTMA).

$$TMA = Albedo * BTMA + (1 - Albedo) * (Tempm + (Tempmx - Tempm) * \sqrt{solrad * 0.03}\ ) \qquad [4.19]$$

Fluker (1958) showed that yearly average soil temperatures at all depths were identical to yearly average air temperature. The yearly course of soil temperature follows a sine wave of amplitude that is identical to air yearly amplitude for the soil surface layer and that decreases with depth. Time of yearly maximum occurrence is delayed with depth. The CERES model (version 2.1) calculates standard soil surface temperature (TA) from yearly air average temperature (TAV) and yearly air temperature amplitude (AMP). The day when maximum soil temperature occurs is calculated from the geographical position (latitude and longitude) of the site (ALX).

$$TA = TAV + AMP/2 * COS(ALX) \qquad [4.20]$$

Subsurface layer temperature is modelled using the same algorithm. Occurrence of soil maximum temperature is delayed by depth (ZD). The difference between standard soil temperature and five days running average of surface temperature (ATOT/5) is used to account for variation from year to year. The difference is dampened with depth (ZD) and soil characteristics and added to each layer standard temperature.

$$DT = ATOT/5 - TA \qquad [4.21]$$

$$ST(L) = TAV + AMP/2 * (COS(ALX+ZD) + DT) * e^{ZD} \qquad [4.22]$$

where L represent the layer number from top to bottom.

The following modifications were developed to better predict soil surface temperature in the seed zone and account for surface residue effect on soil temperature. Soil surface albedo was modified to include soil surface residue and soil surface wetness. The general equation of soil surface temperature was also altered.

Soil surface albedo

The solar radiation intercepted by a soil surface is related to its albedo; the higher the albedo the less energy is absorbed and the more reflected. The bare soil albedo changes as water content at the surface changes. Due to low water reflectivity, wet soils have lower albedo (Salbedo) than dry soils. Idso *et al.* (1975) showed that soil albedo can be correlated to soil surface water content. A model of soil albedo (Salbedo) was computed from soil volumetric water content of 0 to 2 cm layer (SW(1)), saturated water content (SAT(1)) and air dry water content (ASW) (Figure 4.5).

$$ff = (SW(1) - ASW)/(SAT(1) - ASW) \qquad [4.23]$$

$$Salbedo = Salb*(1+\frac{1.1}{1+0.0007*e^{-13.5*ff}}) \qquad [4.24]$$

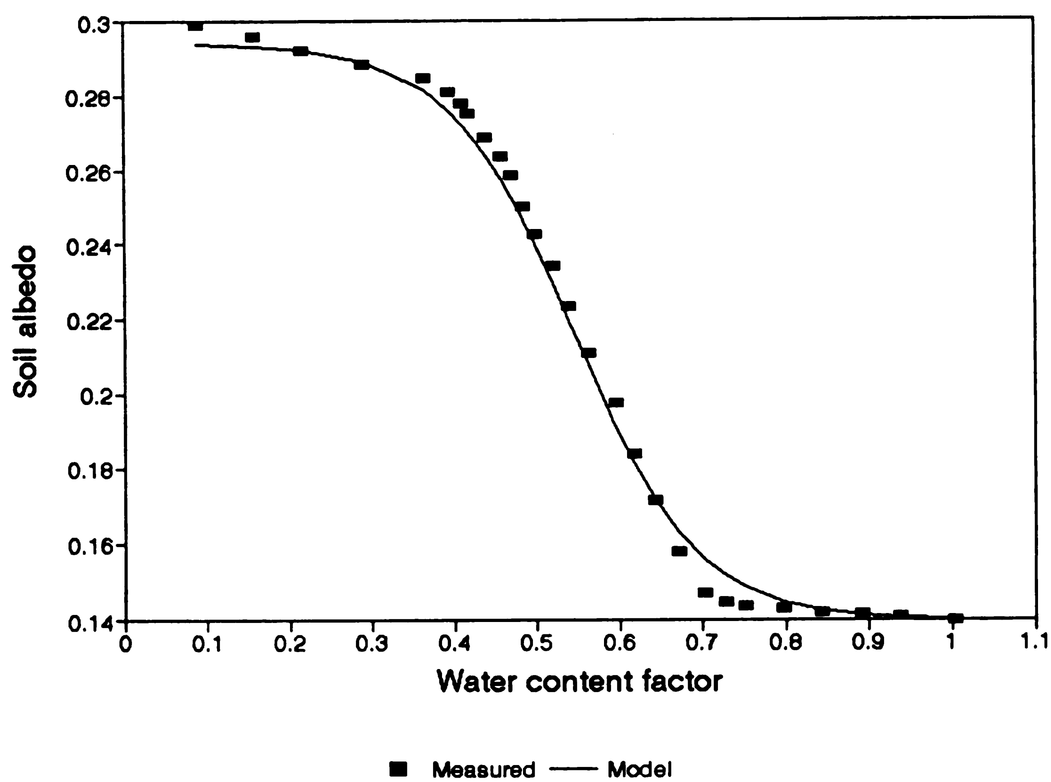

Figure 4.5: Bare soil surface albedo versus soil water content factor from 0 to 2 cm. Adapted from Idso *et al.*, 1975, soil water content was changed to a relative water content factor (SW(1)-0.03)/(0.3-0.03).

Soil albedo is a function of soil coverage. Residue cover increases its albedo (Gaussman *et al.*, 1975), and crops usually have higher albedo than soils. Therefore, covered soils are usually colder than bare soils during the spring. The same equation for canopy coverage as the ones used in the CERES model was used. The variable name was changed to CANCOV. Because crop canopy is above the residue cover, it intercepts the light first, then surface residues reflect incoming light proportionally to their albedo (MulchALB) and finally bare soil surface reflects part of the incoming energy. The following equation calculates the resulting albedo:

$$\text{ALBEDO} = \text{CANCOV}*0.23 + (1\text{-CANCOV})*(\text{Fc}*\text{MulchALB} + (1\text{-Fc})*\text{Salbedo}) \qquad [4.25]$$

Soil surface temperature

Because soil minimum temperature is close to air temperature for covered and uncovered soils (Fortin and Pierce, 1990), the soil surface temperature (TMA(1), ^{o}C) is predicted from daily air minimum temperature (Tempmn) rather than air average temperature. Because a residue cover tends to delay soil temperature changes, a factor calculated from surface residue cover and air minimum temperature of the previous day (OTempmn) was added to improve the prediction:

$$TMA(1) = Tempmn + (mulchcov + salbedo) * \frac{OTempmn - Tempmn}{2}$$

$$+ (1 - Albedo) * (Tempmx - Tempmn) * \sqrt{solrad * 0.03} \qquad [4.26]$$

The damping calculations were altered to estimate the damping coefficient from the surface to the deeper layers rather than using an average value for the complete profile.

Plant development prediction

The CERES-maize model, version 2.1, predicts plant development from air temperature with a base temperature of 10 ^{o}C for germination and 8 ^{o}C for the plant development. As reported in Chapter 2, using the soil temperature to predict plant development while the plant meristem is below ground improves the accuracy of prediction when compared to using air temperature.

The model was modified to use soil temperature in thermal time calculation for Stage 9 (seedling emergence), Stage 1 (emergence to end of juvenile stage), and Stage 2 (end of juvenile stage to tassel initiation).

Surface properties

The extent of the modifications by tillage is highly dependent on the soil conditions, tools used, and speed of tillage. In this model soil conditions after tillage are used as an input and dynamically change when precipitation occurs. The soil layering, which was user dependent in version 2.1, was modified to fixed increments. Increments were based on several possible tillage depths and soil conditions. Layering in the upper 40 cm is as follows: 0-2 cm surface boundary layer, 2-7 cm surface tillage, 7-15 cm tillage depth of most chisels, 15-26 cm moldboard plow bottom layer, 26-40 cm and every 25 cm layer below the plow zone as undisturbed soil.

Three surface properties are considered: soil surface ponding capacity, soil surface saturated conductivity, and soil bulk density of the top 26 cm (layers 1 to 4). The process of change for those three properties follows the same rules; the parameter changes from an initial value to a settled value following an exponential curve of cumulative precipitation intensities (Green and Ampt, 1971) and is detailed below.

Precipitation intensity

Precipitation intensities are rarely recorded. Most of the time the total amount of precipitation is the only data available. Wischmeier and Smith (1958), developed an equation to calculate precipitation intensities from duration and quantity of the precipitation. Unfortunately the duration of precipitation was not recorded for this study. A rainfall intensity generator developed by Baer and Ritchie (personal communication) was used to predict the duration (TIME, hours) and distribution (RAIN, cm) of precipitation during one event. The length of the rainstorm (hours) is estimated from the precipitation amount. Distribution of the rainfall is assumed to be a normal type. Combining the rainfall intensity generator with the equation of Wischmeier and Smith (1958) allows us to calculate the kinetic energy for a storm at the soil surface for every event (KE, J cm^{-2}):

$$KE = (3.812 + 0.812 * Ln(RAIN/TIME)) * RAIN \qquad [4.27]$$

Surface cover (SOILCOV) from residue (Fc) and crop canopy (CANCOV) decreases the amount of energy received by the soil surface proportionally to the surface covered (Wischmeier *et al.*, 1978).

$$SOILCOV = CANCOV + Fc * (1 - CANCOV) \qquad [4.28]$$

Effect of the rainfall intensity decreases with soil depth. The decrease of the effect was assumed exponential with depth (depth, cm) and the coefficient used, 0.15, cancels the intensity at the bottom of the tilled layers (26 cm). Hence, cumulative intensity is calculated for the top four layers.

$$SUMKE(L) = \Sigma\, (1 - SOILCOV)*KE*e^{(-0.15*depth)} \qquad [4.29]$$

SUMKE is reset to zero after each tillage.

Change in surface properties

Changes in soil surface properties follow an exponential decrease of cumulative rainfall intensity (Van Doren and Allmaras, 1978):

$$Xvar = Xstl + (Xtill - Xstl) * e^{(-Rstl * SUMKE)} \qquad [4.30]$$

where Xvar represents the dynamic surface property: ponding capacity (PondMax), saturated water conductivity with macropores (KsMacro) of the four top layers and bulk density BD of the top four layers.

The settled value (Xstl) for surface ponding capacity is read from the input file. If no value is given it is set by default to 0.01 cm. The KsMacro settled value is assumed to be the saturated conductivity without macropores (XKS) of the four top surface layers. Bulk density settled value is read from the input file.

The rate of decrease (Rstl) for the surface property is a function of soil water aggregate stability. Water aggregate stability is correlated to soil organic matter. Several models are available (Tisdall and Oades, 1982). The model chosen was the one described by Chaney and Swift (1984) that agrees with some of the models described by Tisdall and Oades (1982). Modifications were made to the equation to have aggregate stability vary from 1 to 100 rather than using mean weight diameter as a representation of aggregate stability (As). Instead of using soil organic matter content, soil organic carbon (OC) was used. The factor used to convert organic carbon to organic matter was 0.5 (Tisdall and Oades, 1982). Values for As and Rstl are calculated for the top four layers:

$$As = 0.051 * OC \qquad [4.31]$$

The rate of decrease (Rstl) was then computed from AS:

$$Rstl = 5 * (1 - As) \qquad [4.32]$$

Model input modifications

The CERES tillage and residue management input file (File number 4) was altered to allow several tillage operations at different times during the simulation rather than one tillage operation at the beginning of the simulation. The first line was modified to include the amount of residue at the beginning of simulation (kg ha^{-1}), residue C:N ratio, dead root biomass (kg), and average surface coverage of residue (Am, ha kg^{-1}). The following lines contain new tillage inputs: day of tillage (TILLDOY(i)), tillage tool used (CODTILL(i)) depth of tillage (TILLDEP(i)), fraction of residue incorporated (FRACTILL(i)), ponding capacity (TILLPOND(i)), soil water conductivity with macropores (KSMACRO(i)), and bulk density of the top four layers (TILLBD(i,l)) after tillage. Inputs can be measured in the field or estimated from Table 4.1. Default values are given in Table 4.3 and are used by the model if no value is specified in the input file. Subscript i corresponds to the tillage operation number. It has been arbitrarily set to a maximum of ten tillage operations. Examples of input File 4 are given in Appendix 3. Modified codes are given in Appendix 2.

The daily loop of the model has been modified to allow the model to run up to the end of the weather file. Resetting of the soil parameter can be skipped and values from previous runs are used for soil properties, residue amount, and soil water and nitrogen content.

Table 4.3: Default tillage input and tillage coding for the tillage version of the CERES model.

Tillage implements	Cod Till	Dep Till cm	Frac Till %	Till BD g cm^{-3}	Ks Macro cm hr^{-1}	Pond cm
Moldboard plow	1	25	96	1.2	2.09	2.0
Chisel Plow						
-Straight shovel point	2	15	39	1.2	2.06	1.0
-Twisted shovel point	3	15	55	1.2	2.06	1.0
Knife-Type fert.	4	5	35	1.2	2.06	1.0
Disk (Tandem or Offset)						
7.5 cm deep	5	7.5	55	1.2	3.0	1.0
15. cm deep	6	15	40	1.2	3.0	1.0
Field Cultivator	7	10	35	1.2	3.0	1.0
Planters						
-None or smooth coulter	8	5	8	1.2	3.5	0.5
-Narrow ripple coulter	9	5	3	1.2	3.5	0.5
-Wide fluted coulter	10	5	8	1.2	3.5	0.5
-sweeps or disk furrow	11	5	30	1.2	3.5	0.5
Drills						
disk openers	12	3	8	1.2	4.2	0.5
Hoe openers	13	3	35	1.2	4.2	0.5

Model Validation

Residue decomposition model

Stott *et al.* (1990) studied the decomposition of wheat residue left at the surface at five locations. Several sampling dates of amount of residue biomass remaining at the surface make the data set quite useful to validate a model on residue decomposition. Maximum and minimum air temperature, as well as precipitation for the nearest weather station, were found in the report of the weather service. Solar radiation was approximated using generated values (Richardson and Wright, 1984). The soil data used to run the model was standard soil input file given by IBSNAT (1989) for the soil type texture at the site. Management files including planting dates, fertilization, and crop grown were built from available data given in the article.

Five sites, as reported in Stott *et al.* (1990) were studied: site A, Pullman, Washington, 1983; site B, Pullman, Washington, 1984; site C, Bushland, Texas, 1984; site D, West Lafayette, Indiana 1984; and site E, Pullman, Washington, 1985. Stroo *et al.* (1989) used the same data set to validate a mechanistic model that calculates surface residue losses from predicted respiration losses.

Results obtained from the functional model described above are shown in Figures 4.6 to 4.9 . Results agree in general to the ones obtained by Stroo *et al.* (1989). The model did not accurately predict the loss of biomass at the end of the season for most sites. Stott *et al.* (1990) reported that losses on the Pullman plots in Washington during the summer were attributed to macro fauna activity and

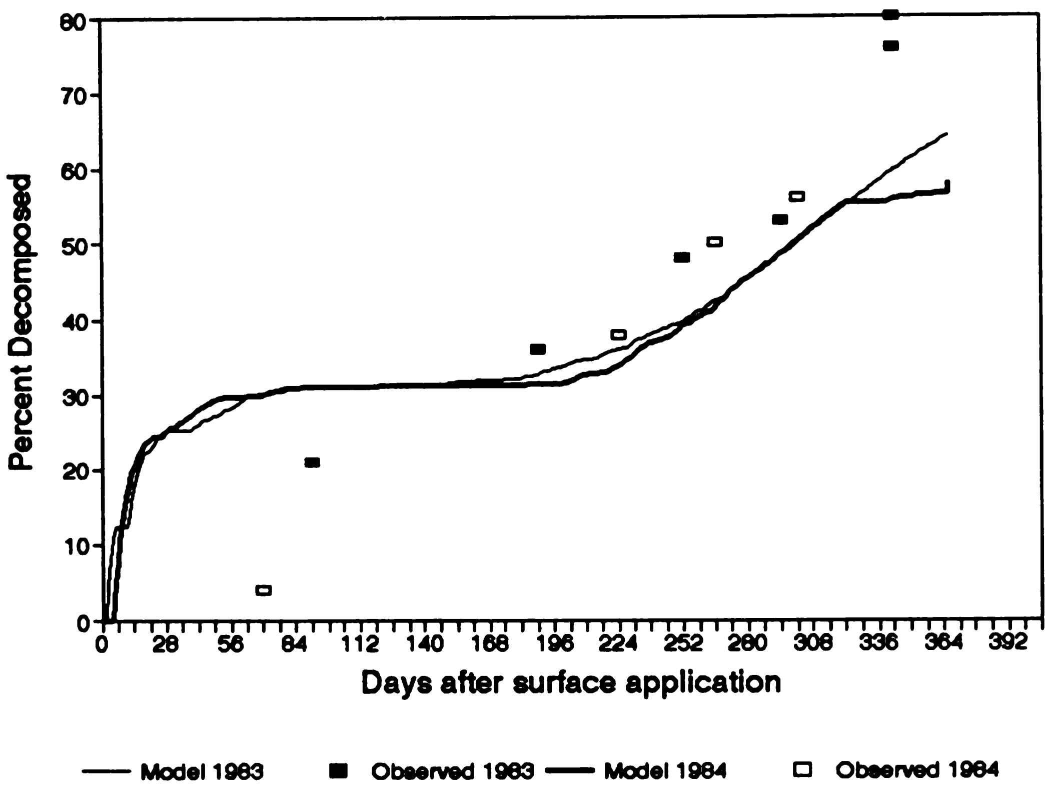

Figure 4.6: Model predictions and observed data from the Pullman, Washington, site (site A and B) for 1983 and 1984. Data are from Stott *et al.*, 1990 .

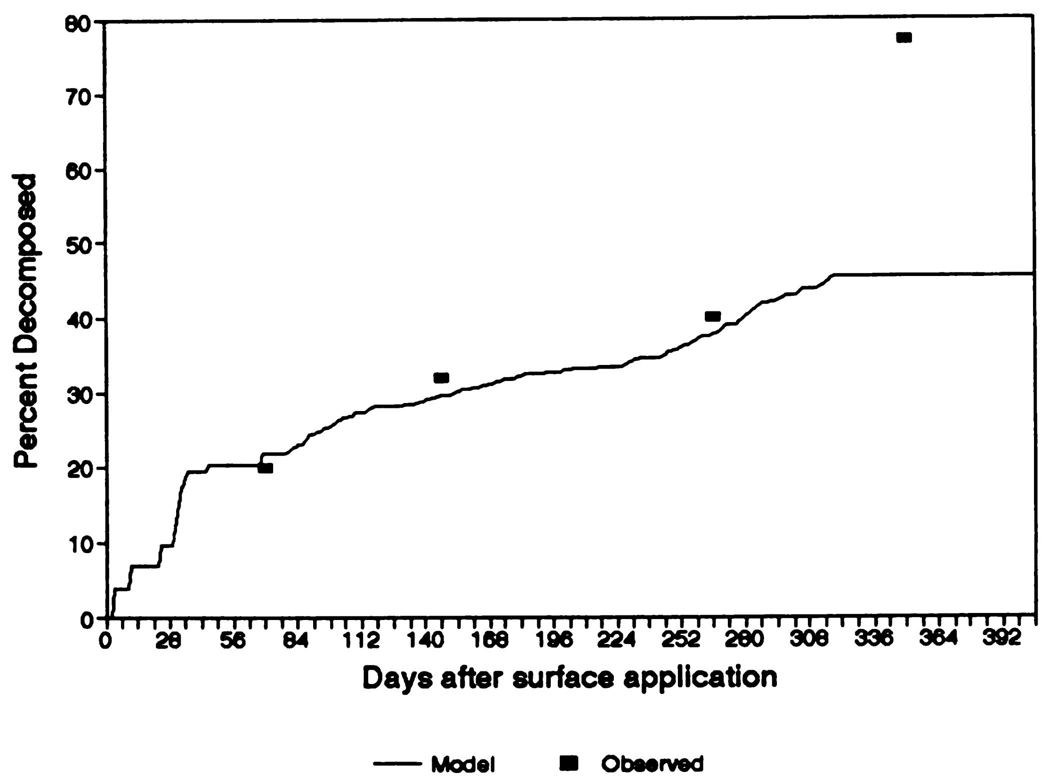

Figure 4.7: Model predictions and observed values for Bushland, Texas 1984. Data are from Stott *et al.*, 1990.

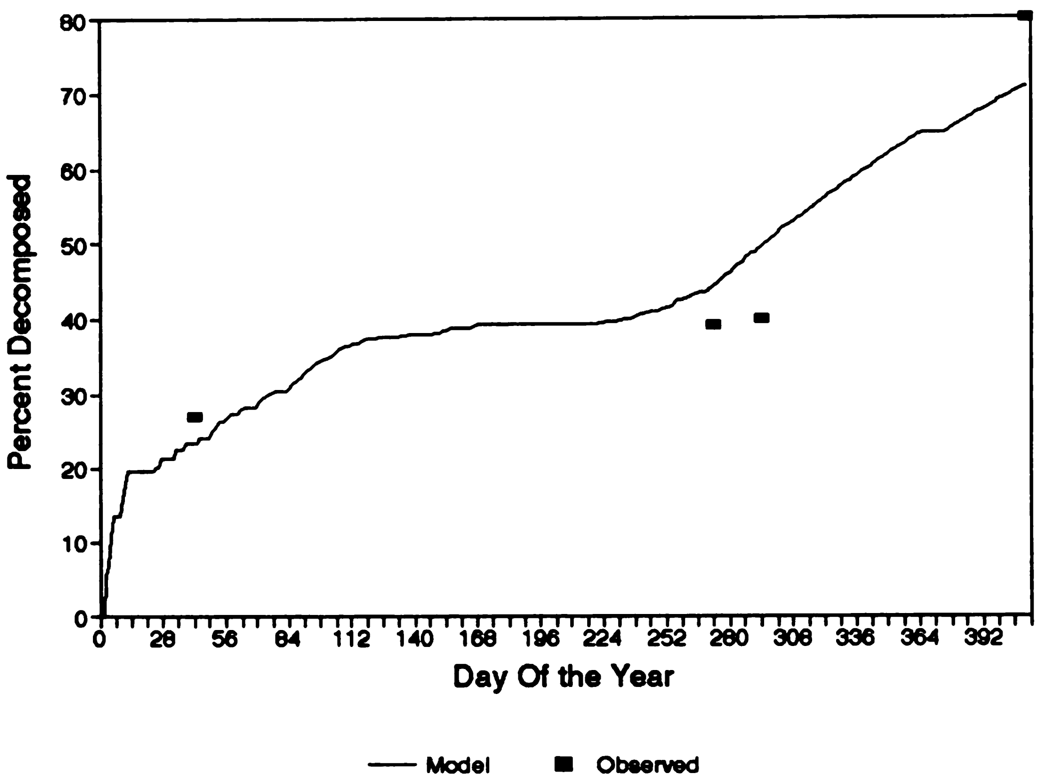

Figure 4.8: Model predictions and observed data from West Lafayette, Indiana, 1984 (site D). Data are from Stott *et al.*, 1990.

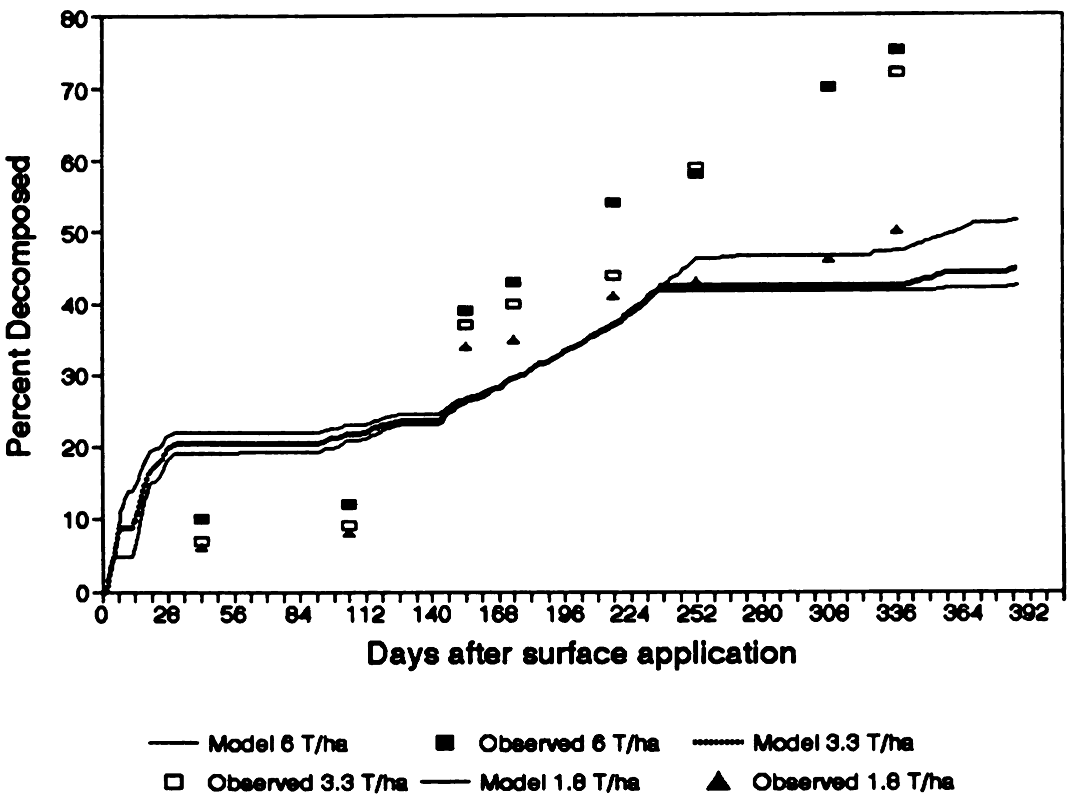

Figure 4.9: Model prediction and observed data for Pullman, Washington, 1985 (Site E). Data are from Stott *et al.* (1990).

were more important when the residue biomass was larger. Stott *et al.* (1990) also reported that at the end of the summer residues were broken in pieces too small to be collected, therefore, biomass loss became difficult to measure. Furthermore, at the end of the summer, the residues were dry and may have been moved by winds. Most plots were surrounded by fields with identical cover, nevertheless because site E at Pullman was not surrounded by fields with similar cover, error estimations on field cover were higher.

Considering the errors in biomass loss estimations and the fact that the climatologic data used to model residue losses were not the ones collected on site, results of the model seem reasonable. Calibration and validation for residues from other types of crop residues are needed to fully validate this model.

Soil water balance

Soil water data collected during summer 1990 and 1991 were used from the experiment described in Chapter 3. Soil characteristics of the surface layers were obtained from core samples collected in the fall at the same location. Drained upper limit and water content at saturation were measured in the laboratory. The model was run for 1990 and 1991 for fallow treatments. Soil volumetric water content was averaged over layers to match the TDR measurements. The model gave good prediction in the no cover treatments (Figures 4.10 and 4.11). In the fully covered treatment, soil water measurements may have been overestimated because of the presence of residues at the surface. Topp *et al.* (1980) reported

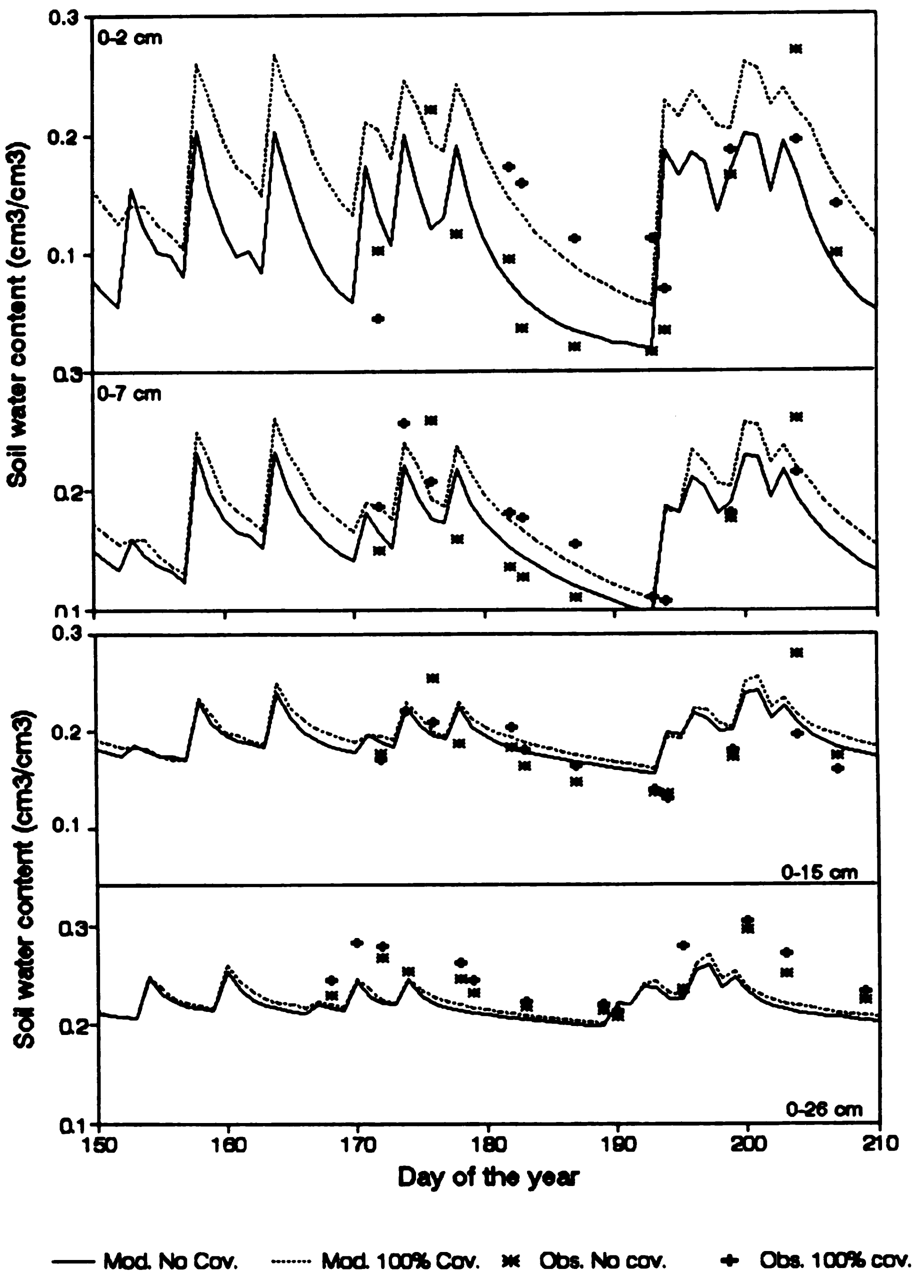

Figure 4.10: Surface water balance of a bare surface and a fully covered surface on a fallow plot for the upper four layers.

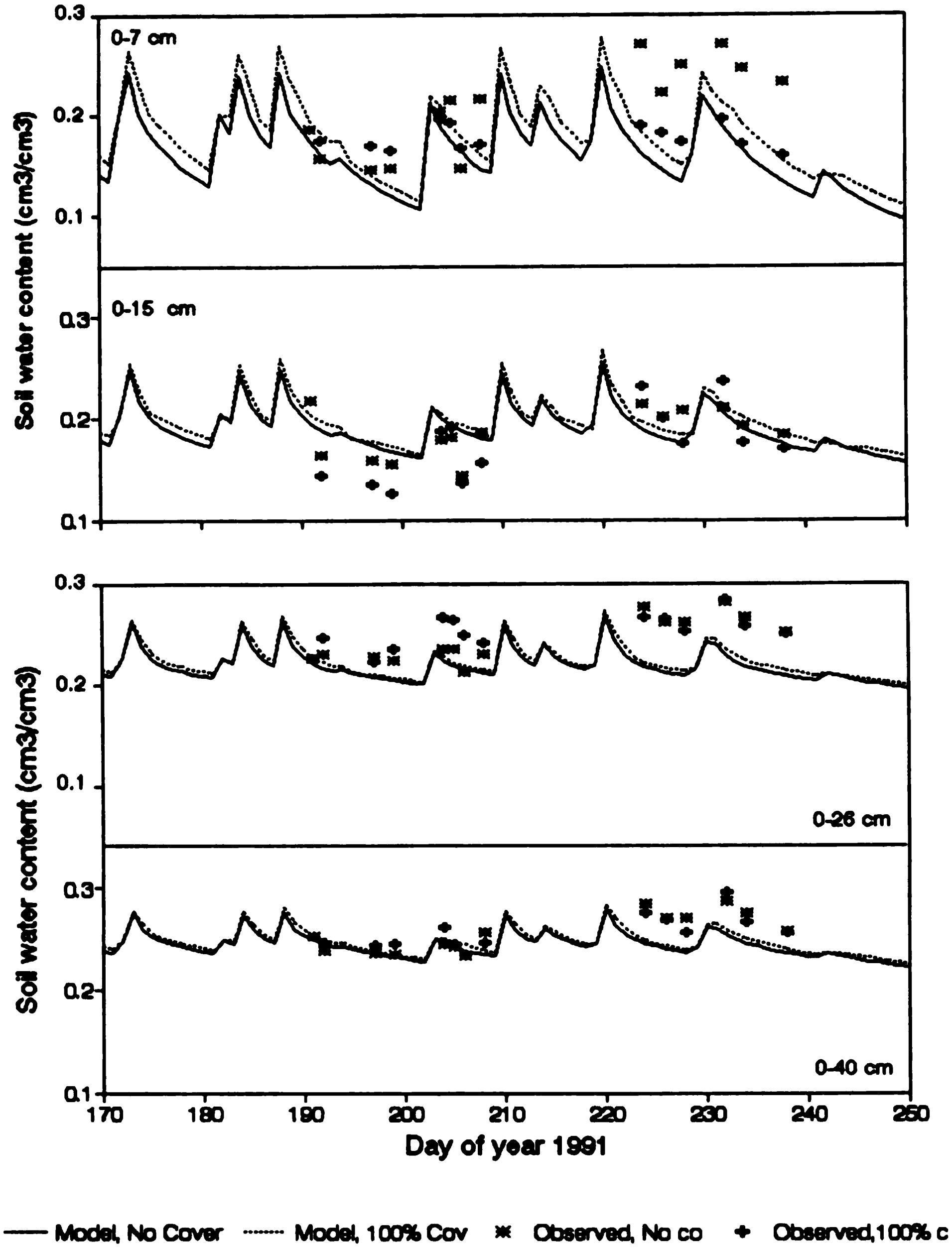

Figure 4.11: Surface water balance of a bare and fully covered soil for the upper four layers on a fallow plot during summer 1991.

that on high organic matter content soils, decreased wave velocity induced an overestimation in soil water content. However, the relative change between treatments gave a good estimation of soil water evaporation. Hence, data were corrected to alleviate the effect of residues at the surface. Considering that rainfall and solar radiation data were from a set some distance away the model prediction of surface evaporation seems reasonable.

Further study is needed to evaluate the error induced by the residue cover when a residue cover is at the surface and TDR transmission lines are installed vertically.

Soil temperature model and leaf development

Soil temperature data collected during the growing season of 1990 and 1991 (see Chapter 2) and during summer 1988 (Fortin and Pierce, 1991) were used to calibrate and develop the model.

Data files needed to run the model are given in Appendix 3. The model was run for the fallow treatments. The results are presented in Figures 4.12, 4.13, 4.14. Part of the prediction error may be due to the fact that air temperature was not recorded at the plots and solar radiation was estimated. The pattern of soil temperature variation agreed with the observed data. The model tended to overestimate soil temperature at higher air temperatures.

Total leaf tip number recorded during the 1990 and 1991 cropping seasons at East Lansing, Michigan (refer to Chapter 2) were used to validate the model

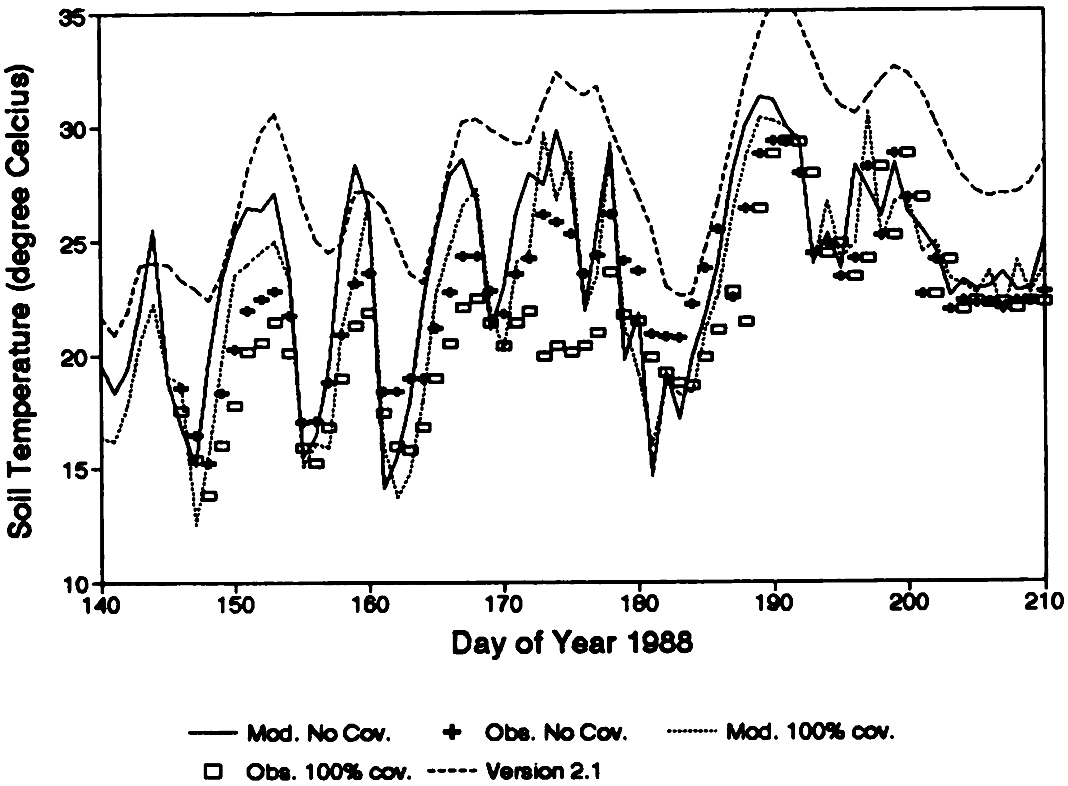

Figure 4.12: Observed and predicted daily average soil temperature at 2.5 cm at East Lansing, Michigan, 1988 for an uncovered and 100% covered soil surface. Data from Fortin (1990).

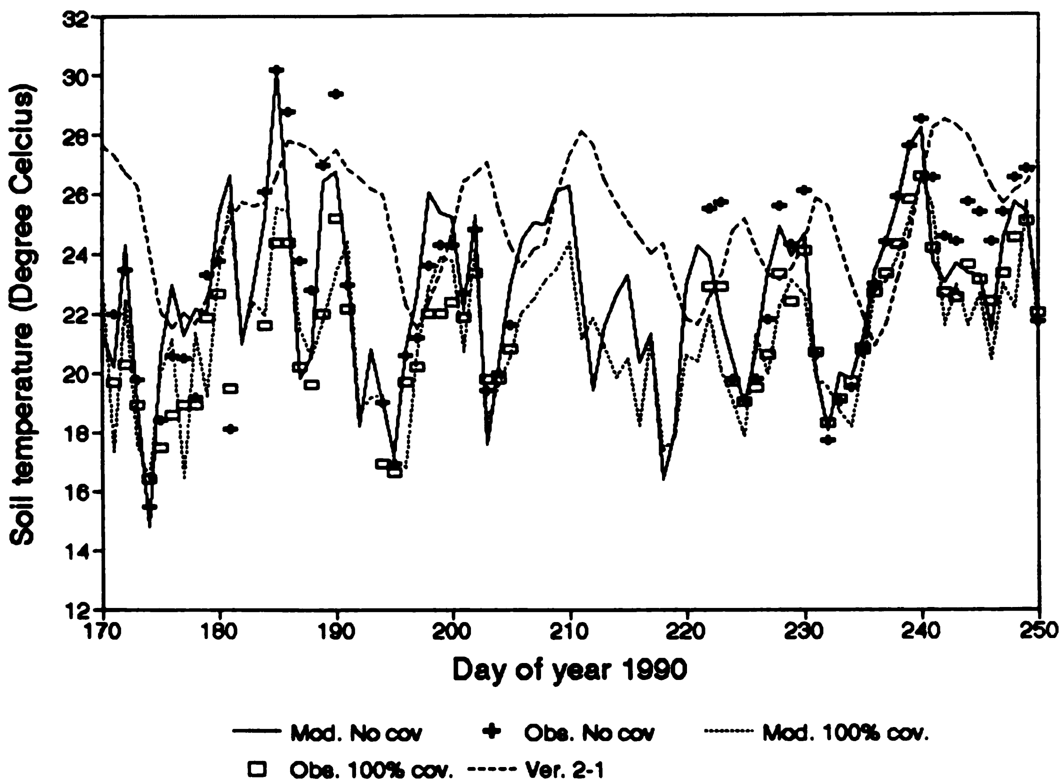

Figure 4.13: Observed and predicted daily average soil temperature at 2.5 cm at East Lansing, Michigan, 1990 for an uncovered and 100% covered soil surface.

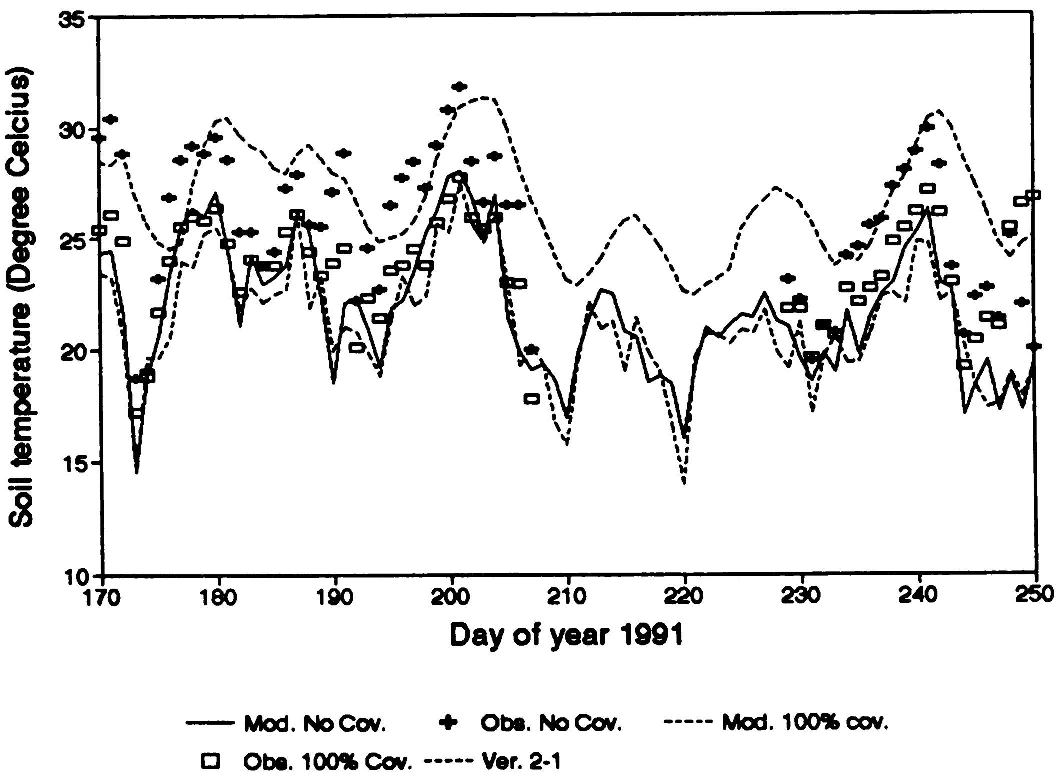

Figure 4.14: Observed and predicted daily average soil temperature at East Lansing Michigan, 1991 for an uncovered and 100% covered soil surface.

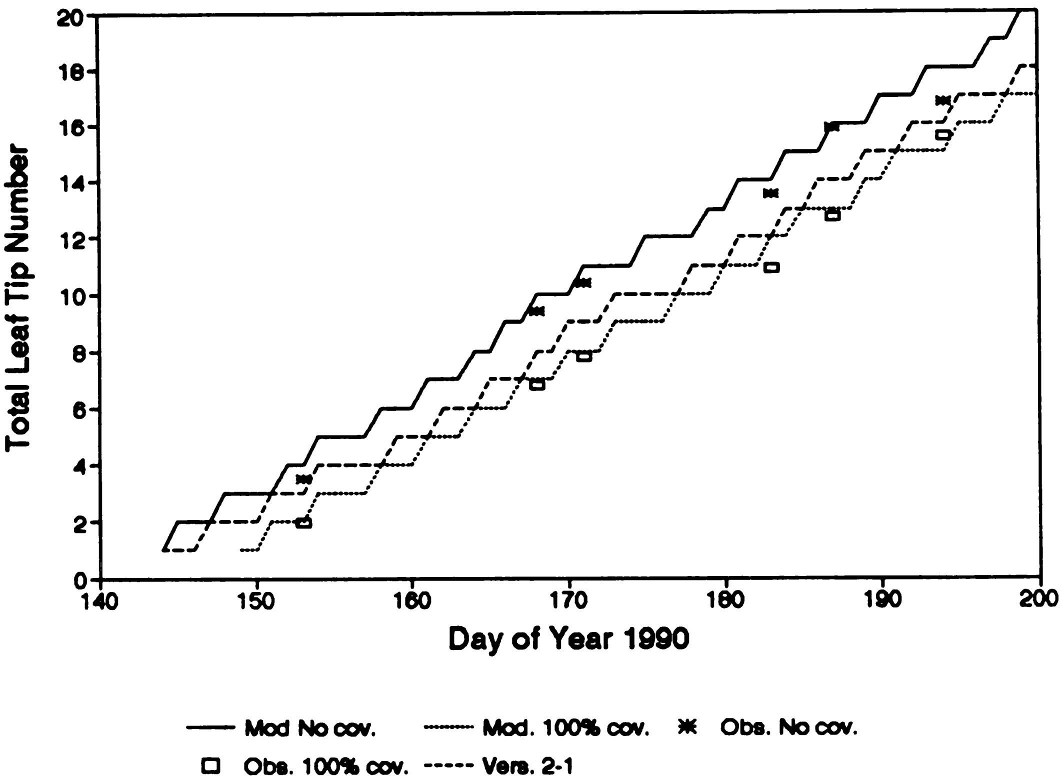

Figure 4.15: Observed and predicted leaf tip number at East Lansing, Michigan, 1990.

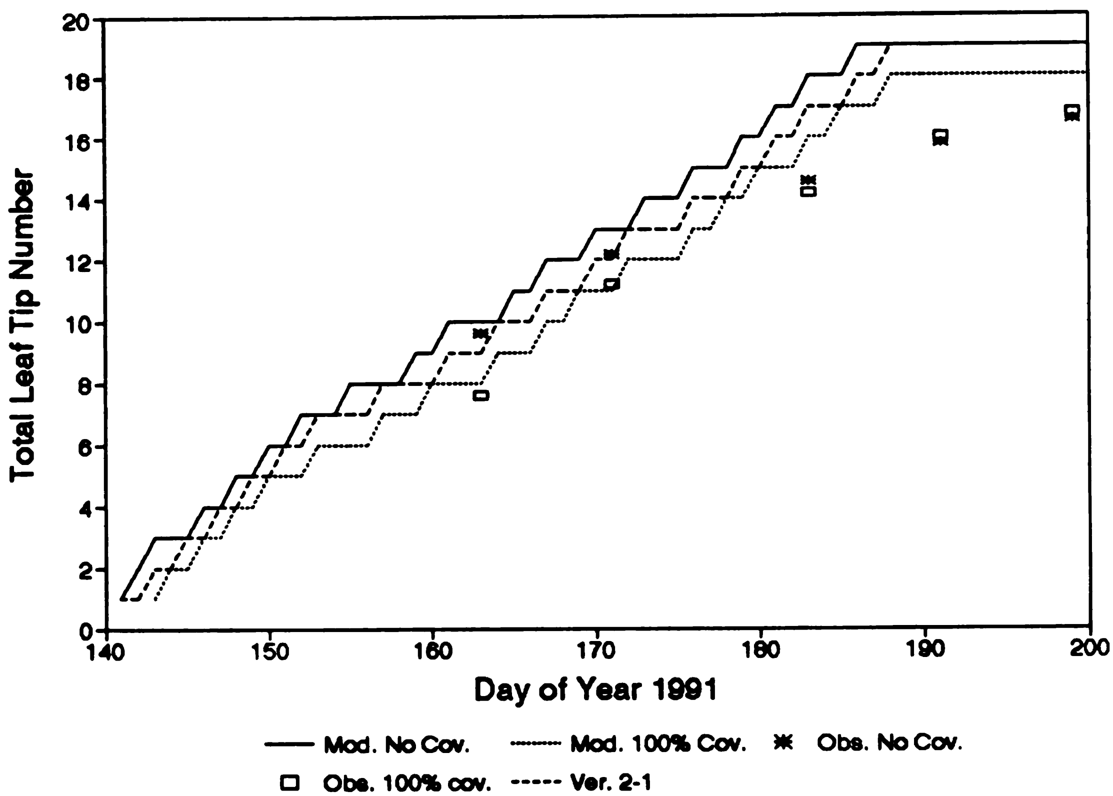

Figure 4.16: Observed and predicted leaf tip number at East Lansing, Michigan, 1991.

(Figure 4.15, 4.16). In 1991, the leaf appearance slowed at the end of the season, whereas the model kept a similar development for the final leaves appearance. Predicted final leaf number was higher on the no-residue cover treatment by one leaf and is due to a rounding error of the model.

Demonstration of the model of soil surface property dynamics

No complete data set with rainstorm intensity and surface properties were available to validate the model. The model was run for the 1990 data set for a bare fallow soil surface and a 100% residue cover surface (Figure 4.17). Two hypothetical tillage operations were considered: a moldboard plow on 11 January (beginning of the simulation) and a secondary tillage 10 May. Surface bulk density after tillage was assumed to be 1.2 g cm^{-3}, ponding capacity 1.5 cm, saturated water conductivity with macropores 10 for the first operation and 8 cm $hour^{-1}$ for the secondary tillage. The rapid changes in the curves are due to tillage operation. The curves move then slowly toward the settled values as cumulative rainfall intensity increases. The values are then reset back after the second tillage operation and then decrease. The model does not account for compaction from traffic because the CERES model does not include any spatial variability. Fast reconsolidation due to flooding or ponding water was not considered in this model.

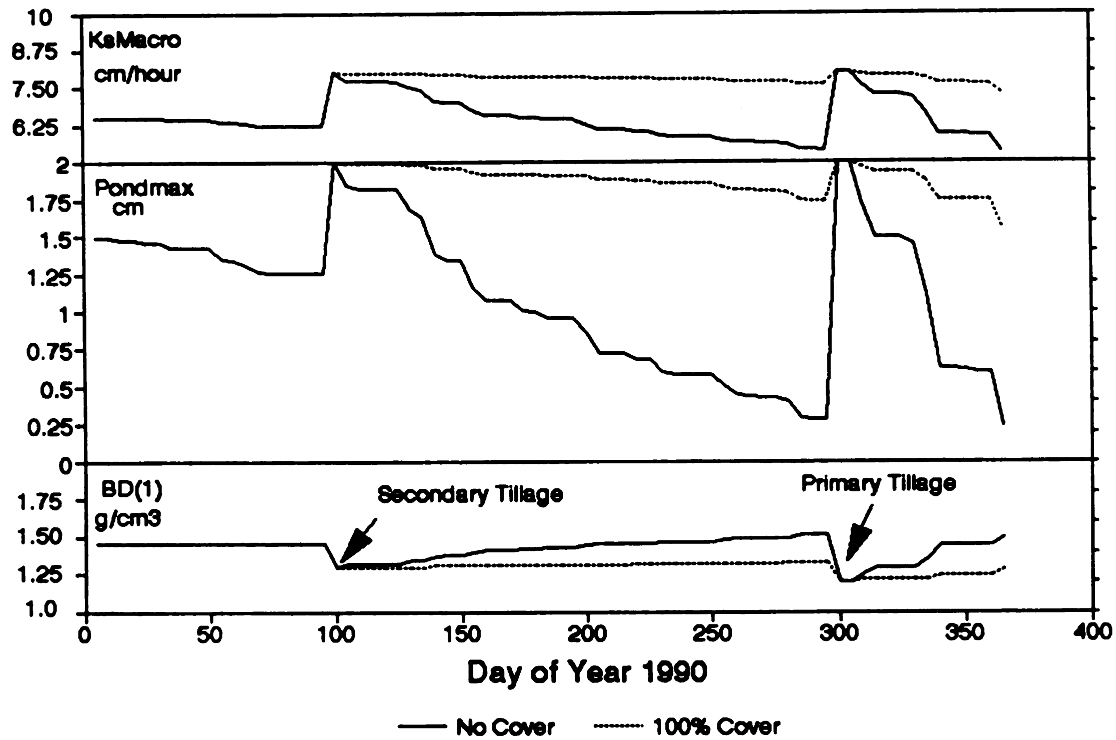

Figure 4.17: Predicted effect of a 100% residue cover on soil surface properties. Data set of 1990, East Lansing, Michigan, on a Conover soil.

Conclusion

The CERES model version 2.1 was modified to better predict residue cover effects on plant development and growth. The soil temperature model was modified to better predict temperature of the seed and meristem site for improved prediction of plant emergence and early development. Surface water conductivity and ponding capacity were dynamically modelled to account for changes of surface conditions due to precipitation intensities. Soil water evaporation was modified to account for surface ponding water evaporation and the impact of the residue cover on soil evaporation. These modifications logically improved the prediction of soil surface water balance of residue covered soil, and therefore, crop performance differences observed when a residue cover was present. Further validation for different crops would reinforce the model and more calibration will probably be needed for other climatic conditions.

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Chapter 5: Use of CERES-Till to evaluate conservation tillage strategies in four areas of Michigan

Abstract

The impact of residue cover on final yields is a complex interaction between climate, soil, and plant. Crop models including plant phenological development and soil environmental condition should help evaluate the consequences of conservation tillage on crop yield. A modified version of the CERES model that included tillage consequences on surface residue cover and soil surface condition was run using 30 years of weather data for four sites in Michigan. Three tillage systems were considered; conventional tillage, reduced tillage, and no-till. Four planting dates, from 30 April to 30 May, were also considered. The model results showed that a no-till system on rainfed maize crops improved returns and final yields by increasing the length of the vegetative stage and decreasing water stress at flowering and during the grain filling period. The model showed a decrease in water runoff in the conservation tillage strategies.

Introduction

Conservation tillage was partly designed to control soil erosion by keeping a sufficient residue cover on the soil surface. The adoption of conservation tillage has consequences other than reducing soil erosion. The existence of residue at the soil surface affects the soil's environment, thus the plant development and growth. Evaluation of conservation tillage consequences on final yield is difficult due to the interactions between delayed plant development caused by reduced soil temperature, increased soil surface water content, and climate. Thus, consequences of residue cover on maize growth makes it difficult to generalize the benefit of residue cover on yield for different climates and soil types. The use of a crop model based on phenological development that considers residue cover on soil environment should help assess the consequences of conservation tillage on crop production.

CERES-Till is a version of the CERES family of models (Jones and Kiniry, 1986; Ritchie *et al.*, 1989) that was designed to model tillage effect on residue cover and soil environment. It includes models of time-variant soil surface properties (hydraulic conductivity, ponding capacity, and bulk density), surface residue dynamics, soil temperature and plant development, and soil water evaporation. The simulation procedures are described in Chapter 4. The model was used to determine the consequences of conservation tillage adoption on economic return and environment in Michigan.

Methodology

Four study sites were chosen to contrast the spatial and temporal changes in maize yield for three different tillage systems with variation in weather. The sites were chosen for locations where sufficient information on soil and weather data was available. The prominent soil of each study area was used for the simulation. Table 5.1 gives the list of the four areas chosen, their geographical location, and the major soil type.

Table 5.1: Geographical location of the Michigan areas and their major soil type.

County	Longitude	Latitude	Soil Type	Code
Huron	83°00'	43°45'	Locke Sandy loam	HUMI
Tuscola	84°25'	43°30'	Tappan Loam	TUMI
Ingham	84°44'	42°43'	Capac Loam	MSUM
Kalamazoo	85°30'	42°20'	Kalamazoo Loam	KBSM

Soil profile information was obtained from the National Cooperative Soil Survey. Soil surface saturated conductivity was assumed to vary as described in Chapter 4, from 8 cm $hour^{-1}$ at time of tillage to 5 cm hr^{-1} for reconsolidated loam soils and 7 cm hr^{-1} for reconsolidated sandy loam soil. Maximum ponding capacity varied from 2 cm for moldboard plowing and 1 cm for chisel plow to 0 cm after reconsolidation. Residue cover slowed soil reconsolidation by intercepting rainfall kinetic energy, thus keeping soil ponding capacity and saturated hydraulic conductivity high. Ponding capacity was predicted from soil ponding capacity and residue cover. Residue was considered to increase soil ponding capacity by creating barriers to water movement over the surface. The increase in ponding capacity was correlated to the residue layer thickness calculated as described in Chapter 3. As seen in the previous chapters, conservation tillage impact on final yield varies from year to year depending on the climate. Using 30 years of weather data, the model was run for each area to investigate whether reduced tillage or no-till would provide an advantage to farmers with either increased revenue or decreased runoff. Air temperature and precipitation from historical data were used except for the Kalamazoo site where air temperature and precipitation were generated from weather at that site (WGEN, Richardson and Wright, 1984). Solar radiation was generated for all sites using a weather generator developed from actual weather data of the area (Richardson and Wright, 1984).

The three tillage systems considered were conventional tillage, reduced tillage, and no-till. Tillage sequences are detailed in Table 5.2. Time of tillage was deliberately fixed to reduce computing time. Nevertheless, tillage was delayed when the water content of the top five surface layers was above the drained upper limit.

The simulated planting date was varied from 30 April to 30 May with a 10 day increment to evaluate the consequences of variable planting dates on final

Table 5.2: Description of the three tillage systems compared for four Michigan sites.

Tillage operation	Date
Conservation tillage	
Moldboard plow 20 cm deep	16 November
Secondary tillage, disk 7.5 cm deep	30 April
Fertilizer application, 150 N Kg/ha	10 May
Planting	Variable
Reduced tillage:	
Chisel plow 15 cm deep	30 April
Fertilizer application, 150 N Kg/ha	10 May
Planting	Variable
No-Till	
Fertilizer application 150 N Kg/ha	10 May
Direct drill planting	Variable

yield for the three tillage strategies. Sowing was delayed if the minimum average temperature of the five days prior to the planting date was less than 5 ^{o}C, or if the water content of the top five layers was above the drained upper limit. No irrigation was applied. Table 5.3 describes the genetic parameters used to run the model where P1 is the thermal time (base 8 ^{o}C) from seedling emergence to the end of juvenile phase, P2 is the photoperiod sensitivity coefficient, P5 is the thermal time (base 8 ^{o}C) from silking to physiological maturity, G2 is the potential kernel number, and G5 is the potential kernel growth rate (refer to Jones and Kiniry, 1986).The three genotypes were determined for each part of Michigan's lower peninsula: south, center and north Michigan. They represent the class of hybrid usually grown in these regions.

Table 5.3: Genetic coefficient chosen to run CERES-Till for four Michigan sites.

Variety #	P 1	P 2	P 5	G 2	G 5	Site
70	220	0.75	740	610	8.5	Kalamazoo, Ingham
71	154	0.3	685	560	8.5	Tuscola
72	130	0.3	685	560	8.5	Huron

For each strategy, total cost including tillage operation, fertilizer and fertilizer application, seed cost, herbicide (conventional and reduced tillage received one spray of herbicide, no-till received two sprays), and harvest, were calculated using the program STEM (DeVuyst and Black, 1989). Cost of diesel fuel was \$ 1.00 gallon^{-1}, wage rate and fringe benefits \$ 5.00 hour^{-1}, annual interest rate 9%, nitrogen cost \$ 0.29 N kg^{-1}, and seed cost \$ 0.94 per 1000 seeds. Total costs for each tillage strategy are given in Table 5.4.

Net return was calculated from gross return minus the cost of drying when the harvest was delayed. The selling price of maize was assumed to be \$ 115.38 T^{-1}. Drying costs were estimated from the maturity date. When the length of the grain filling period was longer than 70 days, maize grain was

Table 5.4: Cost associated with each tillage system (\$ ha^{-1}).

Tillage operation	Cost (\$ ha^{-1})
Conservation tillage	
Moldboard plow 20 cm deep	24.33
Secondary tillage, disk 7.5 cm deep	11.20
Fertilizer application, 150 N Kg/ha	28.57
Planting	91.85
herbicide application	13.38
harvest	72.60
Interest cost	14.53
Gross cost	**256.46**
Reduced tillage:	
Chisel plow 15 cm deep	11.20
Fertilizer application, 150 N Kg/ha	28.57
Planting	91.85
herbicide application	13.38
harvest	77.43
Interest cost	11.83
Gross cost	**234.26**
No-Till	
Fertilizer application 150 N Kg/ha	28.57
Direct drill planting	88.10
herbicide application (x2)	26.76
harvest	77.43
Interest cost	11.25
Gross cost	**232.11**

assumed to be at 15% water content. When the length was between 55 days to 70 days, the grain water content was assumed to decrease linearly from 30% to 15%. The cost to bring maize grain from 30% water content to a 15% water content was estimated at \$ 4.65 T^{-1} (Rose *et al.*, 1980). For intermediate water content the cost was assumed to decrease linearly.

The outputs of the multiple year runs were: number of days from sowing to anthesis, number of days from anthesis to maturity, nitrogen and water deficit factors during the end of the vegetative period and during grain filling period, annual runoff (cm), grain yield (T ha^{-1}), and return (\$ ha^{-1}).

For each strategy and planting date, the average, standard deviation, minimum and maximum values were calculated for all the output variables of the models. Comparisons among treatments and planting dates were done using cumulative probability curves. Cumulative probability curves are interpreted by reading the probability of getting a value lower than a certain level read on the X axis. Strategy evaluation was done by using stochastic dominance analysis. Strategy A dominates strategy B in the sense of stochastic dominance if, in a cumulative probability graph, the outcomes or variables of interest are always higher than outcomes in a cumulative probability of strategy B. Details on the theory of stochastic dominance are available (Anderson *et al.* 1977). A software program was written to calculate statistical parameters, sort data (Press *et al.*, 1992), and draw curves from output values of the model using the Graflib software (Graflib, 1989).

For each site and tillage strategy the planting date that maximized average yield was determined. The maximum return condition for each tillage strategy was then compared to the others using stochastic dominance principles in terms of economic return, annual runoff, length of vegetative and reproductive stages, and water deficit factors during those stages.

Results

Yield and net return mean, standard deviation, and minimum and maximum values, are presented for each site in Tables 5.5, 5.7, 5.9, and 5.11. The average length of the vegetative and reproductive stages, as well as the standard deviation, minimum and maximum are presented for each site in Tables 5.6, 5.8, 5.10, and 5.12. The yield, return, and water deficits during vegetative growth and grain filling cumulative probability curves for the planting date of each tillage strategy with the highest return are plotted in Figures 5.1 to 5.8. The water deficit factor for the vegetative and reproductive stages represent the average daily relative water deficit factor (ratio of actual transpiration and potential transpiration) the plant experienced during each stage.

Huron site

Yields and net return information are presented in Table 5.5. On the conventional tillage strategy, yields were low, 3.42 T ha $^{-1}$, and slightly increased with late planting. The main reason for the yield increase was an extension of the grain filling stage and a small decrease in water stress in water deficit during that stage. Reduced tillage improved yields up to 4.21 T ha^{-1}. Planting dates had little effect on yield and return for the reduced tillage strategy. Planting date of 30 May (DOY 150) increased the length of the maturity stage decreasing the drying costs and improving the returns. The best return on the no-till strategy was reached for the planting date of 10 May (DOY 130) due to higher mid-range yields and longer vegetative stage.

Table 5.5: Yield (T ha^{-1}), return ($ ha^{-1}) for three tillage strategies and four planting dates at the Huron site.

TILLAGE	SOW	YIELD T HA^{-1} AVG	STD	MIN	MAX	RETURN $ HA^{-1} AVG	STD	MIN	MAX
Conventional	120	3.38	.98	1.93	6.19	120.32	110.27	-42.69	438.61
Conventional	130	3.42	1.02	1.93	6.19	125.74	114.43	-42.69	438.61
Conventional	140	3.43	1.03	1.93	6.19	127.10	115.91	-42.69	438.61
Conventional	150	3.46	1.06	1.93	6.19	129.92	119.28	-42.69	438.61
Reduced	120	4.19	1.14	2.40	7.43	233.43	127.62	33.78	602.34
Reduced	130	4.21	1.18	2.40	7.43	235.80	132.62	33.78	602.34
Reduced	140	4.21	1.19	2.40	7.43	235.88	132.87	33.78	602.34
Reduced	150	4.21	1.18	2.40	7.43	236.21	133.14	33.78	602.34
No-Till	120	4.70	1.28	2.71	8.38	293.11	144.22	70.50	708.81
No-Till	130	4.83	1.37	2.72	8.38	308.75	154.46	71.62	708.81
No-Till	140	4.74	1.35	2.71	8.38	298.63	151.65	70.50	708.81
No-Till	150	4.68	1.35	2.71	8.38	292.15	152.43	70.50	708.81

The no-till strategy was best when compared to the two other strategies (Figure 5.1). Residue cover maintained by reduced tillage and no-till increased yields for all planting dates (Table 5.5) by decreasing daily average water deficit by half during the vegetative growth. Another beneficial effect of the residue cover was to slow the vegetative stage for the No-Till strategy without reducing the length of the maturity stage (Table 5.6). Runoff was smaller on the reduced tillage and no-till strategies due to improved water infiltration. The decrease in runoff was larger on high runoff events due to increased water ponding capacity created by the residues.

Tuscola site

Yields and net return information are presented in Table 5.7. Due to its geographical location, north of mid-Michigan, crop failures (no yields) were important at the Tuscola sites, occurring 37% of the time. Late planting, 20 and 30 May (DOY 140, 150), increased average yield and returns. This indicates that a short season cultivar should be used. An alternate crop would likely be planted if the crop was killed by slow emergence. The late planting date, 30 May (DOY 150), gave the best yields and return due to higher yields in the colder years. Average yields and distribution were similar for all planting dates for the reduced tillage strategy. Although the yield did not vary much with the planting date, the best average return was reached for planting date of 10 May (DOY 130). No-till had the best return for the earliest planting date, 30 April (DOY 120), due to a

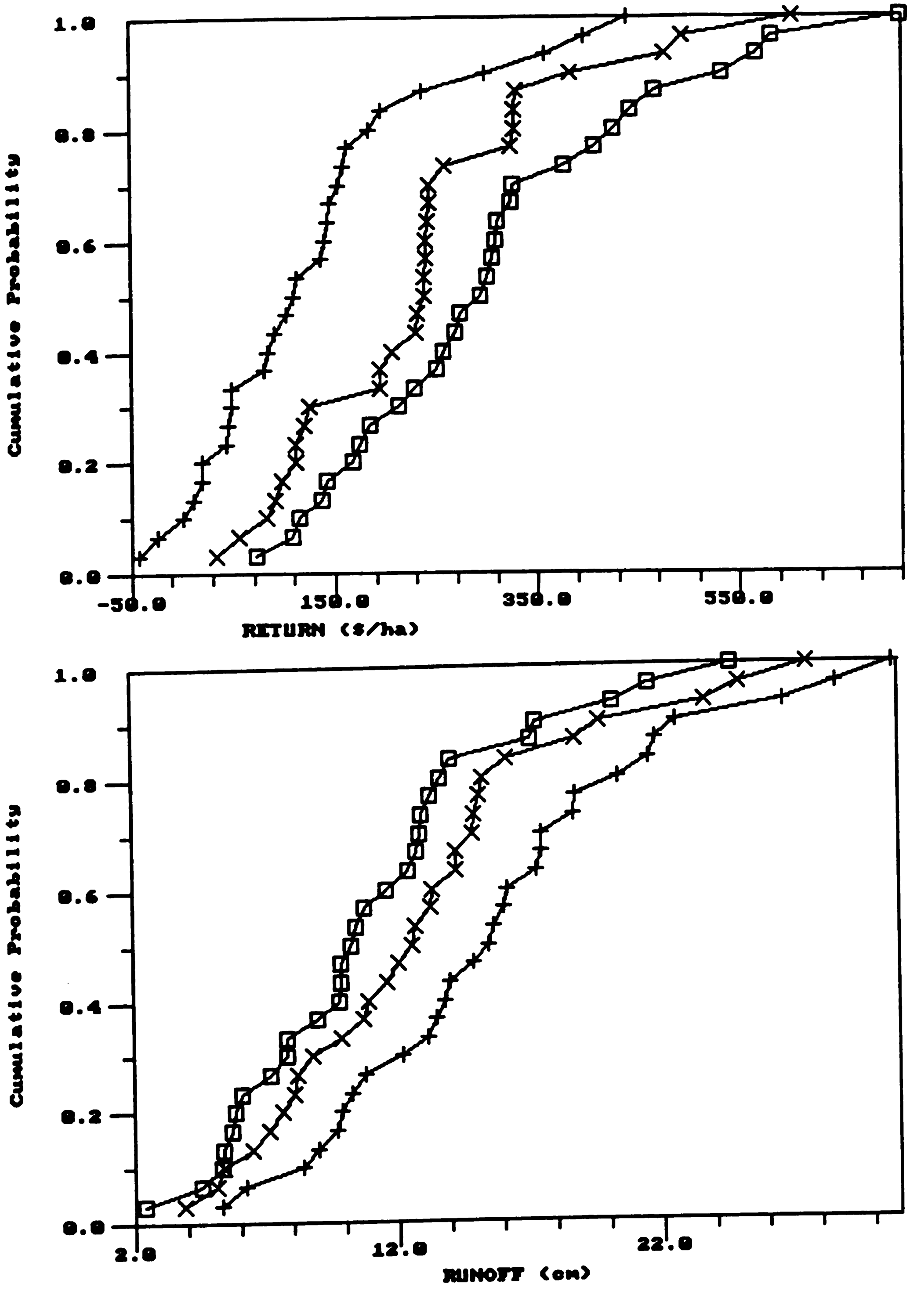

Figure 5.1: Cumulative distribution of economic return (\$ ha^{-1}) and annual runoff (cm) at the Huron site for the best planting dates for conventional tillage, reduced tillage, and no-till.

Table 5.6: Number of days from sowing to anthesis and anthesis to maturity for three tillage strategies and four planting dates at the Huron site.

TILLAGE	DOY	SOWING TO ANTHESIS AVG	STD	MIN	MAX	ANTHESIS TO MATURITY AVG	STD	MIN	MAX
Conventional	120	81.27	7.30	68.00	103.00	55.43	6.11	39.00	67.00
Conventional	130	80.47	8.04	66.00	103.00	55.57	6.27	39.00	67.00
Conventional	140	79.83	9.01	60.00	103.00	55.87	6.38	39.00	67.00
Conventional	150	80.40	10.53	55.00	103.00	56.50	6.21	43.00	69.00
Reduced	120	83.77	7.56	71.00	98.00	55.87	6.48	38.00	69.00
Reduced	130	82.33	8.31	66.00	98.00	56.03	6.58	38.00	69.00
Reduced	140	81.27	9.31	63.00	98.00	56.23	6.68	38.00	69.00
Reduced	150	80.53	10.36	56.00	98.00	56.70	6.60	38.00	69.00
No-Till	120	84.30	7.53	69.00	97.00	56.33	7.07	39.00	74.00
No-Till	130	85.37	10.00	64.00	102.00	56.87	6.52	45.00	69.00
No-Till	140	81.63	9.16	63.00	97.00	57.17	7.33	39.00	74.00
No-Till	150	81.07	10.13	57.00	97.00	57.03	7.08	39.00	74.00

better distribution of yields and a longer vegetative period in the warmer years.

Residue cover improved the average yield by decreasing the number of crop failures to 24%. Water conservation by the soil cover decreased water deficit during the vegetative and reproductive stages. Runoff was also decreased by the residue cover due to increased water infiltrability and ponding capacity.

Ingham site

Yield distribution was similar for all planting dates for the conventional tillage strategy (Table 5.9). Water deficit during the grain filling period was the main limiting factor on yield establishment and was not affected by planting time. Early planting, 30 April (DOY 120), improved returns on the best years by

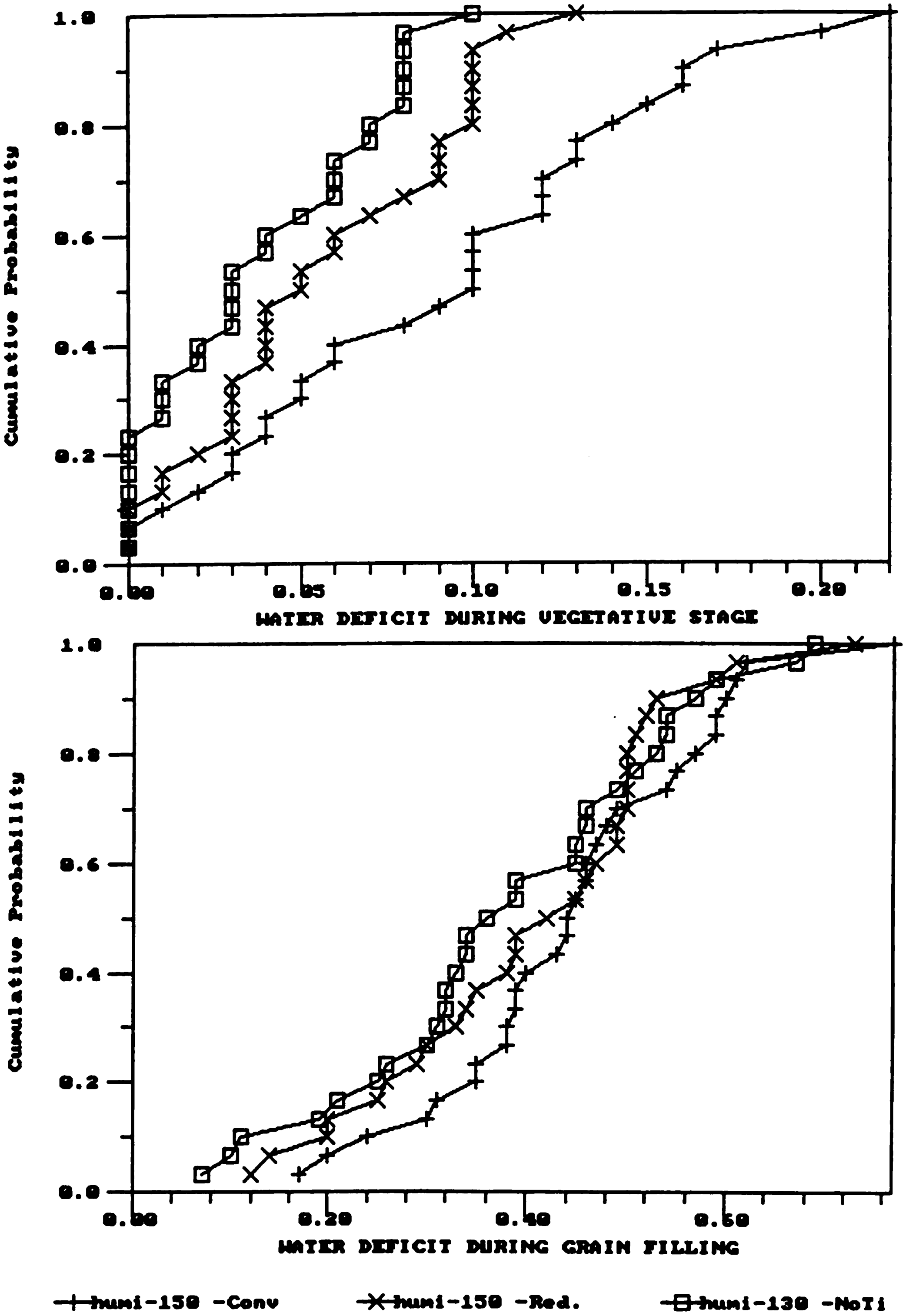

Figure 5.2: Water deficit during vegetative and reproductive stage for three tillage strategies at optimal planting date at the Huron site.

Table 5.7: Yield (T ha^{-1}), return (\$ ha^{-1}) for three tillage strategies and four planting dates at the Tuscola site.

TILLAGE	SOW	YIELD T HA-1 AVG	STD	MIN	MAX	RETURN \$ HA^{-1} AVG	STD	MIN	MAX
Conventional	120	3.70	2.62	.00	7.70	154.03	290.85	-256.40	596.22
Conventional	130	3.37	2.80	.00	7.93	117.96	310.11	-256.40	621.69
Conventional	140	3.85	2.61	.00	8.20	171.20	289.14	-256.40	654.13
Conventional	150	3.86	2.60	.00	7.85	173.33	289.52	-256.40	617.70
Reduced	120	4.38	2.69	.00	7.97	252.98	300.03	-234.20	648.32
Reduced	130	4.39	2.75	.00	9.17	253.62	305.64	-234.20	784.04
Reduced	140	4.37	2.71	.00	8.87	252.10	301.92	-234.20	750.72
Reduced	150	4.35	2.67	.00	8.41	250.42	297.36	-234.20	699.65
No-Till	120	4.64	2.85	.00	8.61	284.20	317.38	-232.10	721.29
No-Till	130	4.57	2.82	.00	8.86	276.51	314.02	-232.10	751.71
No-Till	140	4.52	2.76	.00	8.61	270.37	307.18	-232.10	723.95
No-Till	150	4.59	2.78	.00	8.54	278.79	310.62	-232.10	718.83

increasing the length of the vegetative stage (Table 5.8). Reduced tillage had the best return for the planting date of 10 May (DOY 130) due to a longer vegetative period. Planting dates of 10 and 20 May (130,140) increased yields on the no-till strategy by increasing the length of the vegetative period without decreasing the length of the grain filling period. Planting date of 10 May (DOY 130) had slightly higher mid-range yields.

Soil cover improved yields and returns by increasing plant water availability and decreasing water deficit during the vegetative and reproductive stages. The length of the grain filling period was unaffected by the tillage strategies. The decrease in runoff was more important during the years when runoff was large.

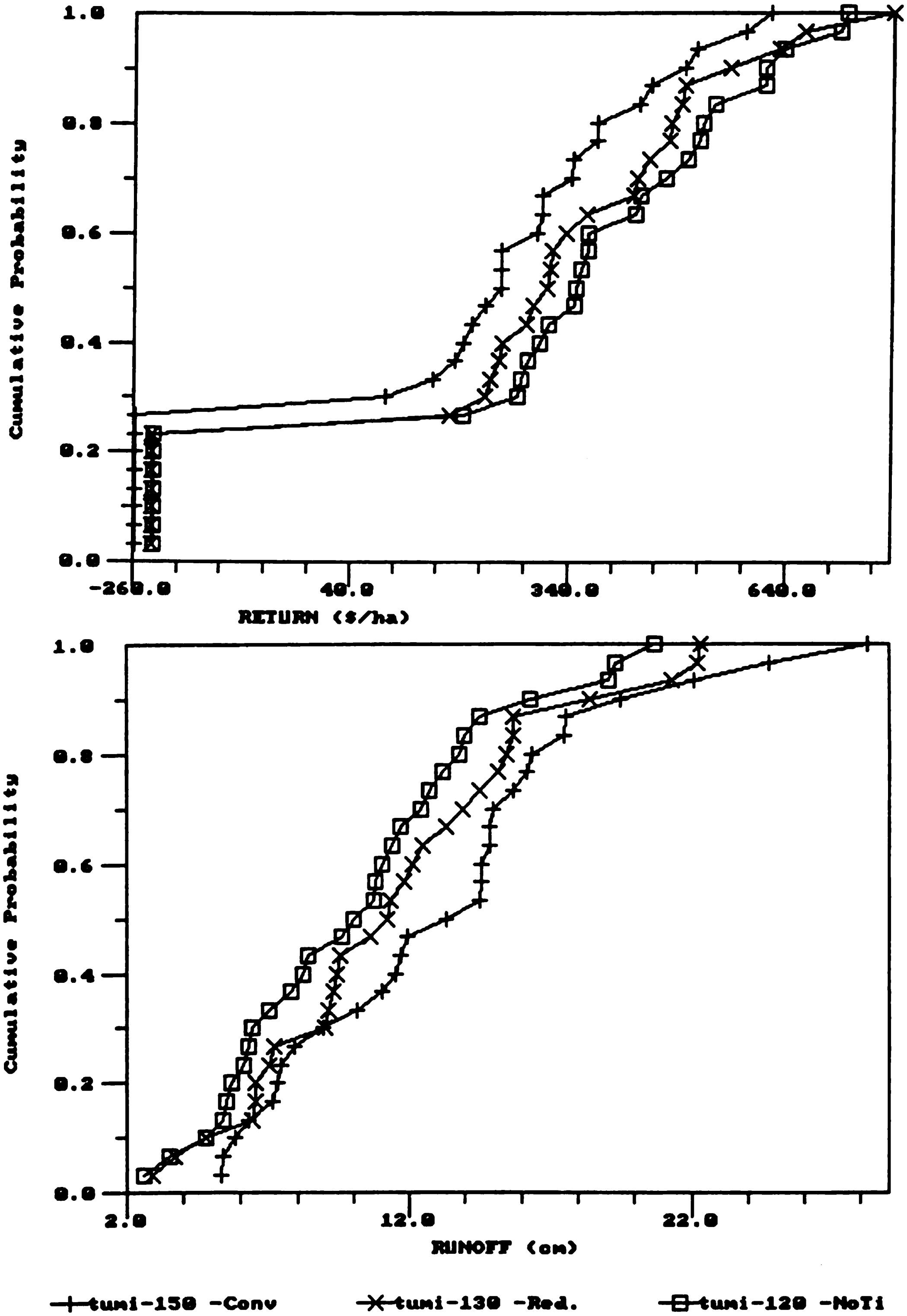

Figure 5.3: Cumulative distribution of economic return ($ ha^{-1}) and annual runoff (cm) at the Tuscola site for the best planting dates for conventional tillage, reduced tillage, and no-till.

Table 5.8: Number of days from sowing to anthesis and anthesis to maturity for three tillage strategies and four planting dates at the Tuscola site.

TILLAGE		SOWING TO ANTHESIS				ANTHESIS TO MATURITY			
	DOY	AVG	STD	MIN	MAX	AVG	STD	MIN	MAX
Conventional	120	79.70	5.86	70.00	92.00	42.33	19.01	12.00	64.00
Conventional	130	80.07	7.45	65.00	95.00	39.47	19.62	12.00	65.00
Conventional	140	77.90	7.64	61.00	92.00	43.57	18.44	12.00	68.00
Conventional	150	77.03	9.09	57.00	91.00	43.73	18.53	12.00	63.00
Reduced	120	82.57	6.61	70.00	95.00	44.53	17.51	13.00	65.00
Reduced	130	84.20	8.30	68.00	98.00	44.43	17.47	13.00	64.00
Reduced	140	80.60	8.70	63.00	95.00	44.90	17.84	13.00	65.00
Reduced	150	79.80	9.93	57.00	95.00	44.90	17.73	13.00	65.00
No-Till	120	83.37	6.77	72.00	96.00	44.60	17.44	13.00	62.00
No-Till	130	85.57	8.23	70.00	98.00	44.73	17.58	13.00	66.00
No-Till	140	82.67	9.00	66.00	96.00	44.63	17.63	13.00	64.00
No-Till	150	80.33	10.09	58.00	96.00	45.17	17.81	13.00	63.00

<u>Kalamazoo site</u>

Late planting decreased crop losses and improved high-range yields mostly because of a longer grain filling stage that increased kernel weight (Table 5.10). The best yield and return (Table 5.11) was reached for the planting date of 30 May (DOY 150). Reduced tillage had fewer crop failures. Late planting increased the length of the grain filling period, thus improving the middle range yields. The decrease in number low yields improved the average return for the planting date of 30 May (DOY 150). For the no-till strategy late planting improved low yields by increasing the length of the grain filling period. Best returns were obtained for the latest planting date 30 May (DOY 150).

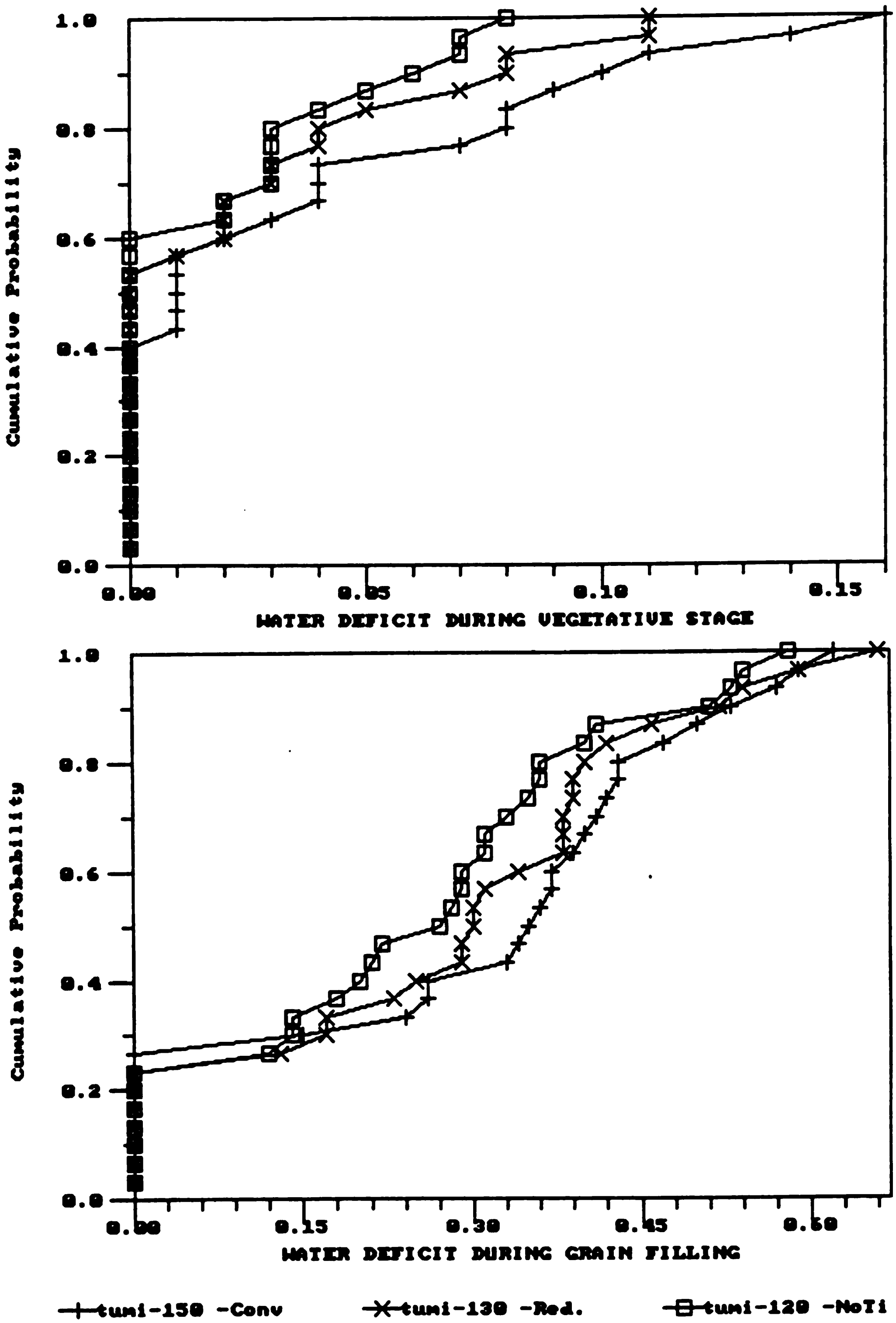

Figure 5.4: Water deficit during vegetative and reproductive stage for three tillage strategies at optimal planting date at the Tuscola site.

Table 5.9: Yield (T ha^{-1}), return (\$ ha^{-1}) for three tillage strategies and four planting dates at the Ingham site.

TILLAGE	SOW	YIELD T HA-1 AVG	STD	MIN	MAX	RETURN \$ HA^{-1} AVG	STD	MIN	MAX
Conventional	120	4.53	1.32	.00	7.59	253.01	148.16	-256.40	602.86
Conventional	130	4.52	1.31	.00	7.59	252.10	147.96	-256.40	602.86
Conventional	140	4.44	1.29	.00	7.59	243.43	145.81	-256.40	602.86
Conventional	150	4.38	1.29	.00	7.59	236.17	144.71	-256.40	602.86
Reduced	120	4.86	1.57	.00	7.59	311.59	176.99	-234.20	627.42
Reduced	130	4.87	1.56	.00	7.59	313.49	176.16	-234.20	627.42
Reduced	140	4.88	1.56	.00	7.59	314.46	175.94	-234.20	627.42
Reduced	150	5.03	1.52	.00	7.59	333.13	172.00	-234.20	627.42
No-Till	120	5.30	1.65	.00	8.15	365.39	186.38	-232.10	670.35
No-Till	130	5.35	1.64	.00	8.14	371.37	185.72	-232.10	669.24
No-Till	140	5.35	1.66	.00	8.15	370.79	188.04	-232.10	670.35
No-Till	150	5.25	1.57	.00	7.59	358.13	176.60	-232.10	627.16

Residue cover increased the length of the vegetative stage without decreasing the length of the grain filling period, thus increasing kernel weight and final yield. The main effect of the soil cover was to decrease water deficit intensity during the vegetative and reproductive period, thus increasing grain yield. Returns were the highest for the no-till strategy. Maximum runoff was decreased by half on the no-till strategy compared to the conventional tillage strategy. Runoff was always smaller on the reduced tillage and no-till strategies.

Table 5.10: Number of days from sowing to anthesis and anthesis to maturity for three tillage strategies and four planting dates at the Ingham site.

TILLAGE		SOWING TO ANTHESIS				ANTHESIS TO MATURITY			
	DOY	AVG	STD	MIN	MAX	AVG	STD	MIN	MAX
Conventional	120	92.59	8.52	76.00	111.00	60.72	7.15	47.00	73.00
Conventional	130	92.31	8.58	76.00	111.00	60.97	7.08	49.00	73.00
Conventional	140	89.86	9.47	69.00	111.00	60.69	6.83	51.00	74.00
Conventional	150	89.55	9.93	69.00	111.00	60.48	6.39	51.00	74.00
Reduced	120	84.45	10.24	71.00	102.00	59.93	6.59	48.00	74.00
Reduced	130	84.14	10.13	72.00	102.00	60.03	6.52	50.00	74.00
Reduced	140	83.55	10.34	71.00	102.00	59.97	6.40	50.00	74.00
Reduced	150	87.55	12.91	68.00	113.00	61.28	6.12	54.00	73.00
No-Till	120	91.24	11.87	71.00	114.00	60.83	6.56	49.00	73.00
No-Till	130	90.69	12.14	71.00	114.00	60.83	6.67	48.00	73.00
No-Till	140	90.14	12.52	71.00	114.00	60.97	6.47	52.00	73.00
No-Till	150	87.52	12.92	69.00	114.00	60.52	5.96	54.00	74.00

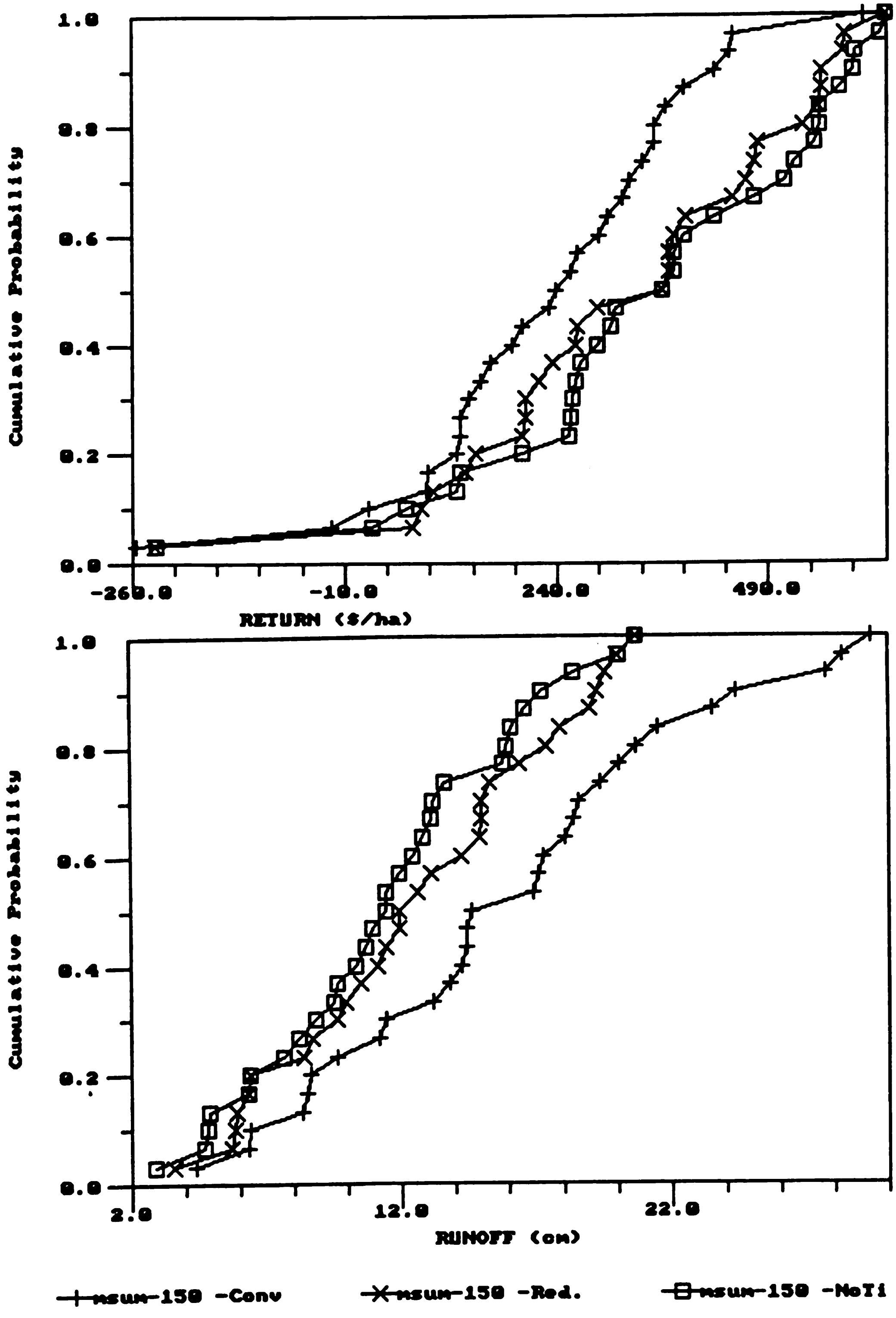

Figure 5.5: Cumulative distribution of economic return ($ ha^{-1}) and annual runoff (cm) at the Ingham site for the best planting dates for conventional tillage, reduced tillage, and no-till.

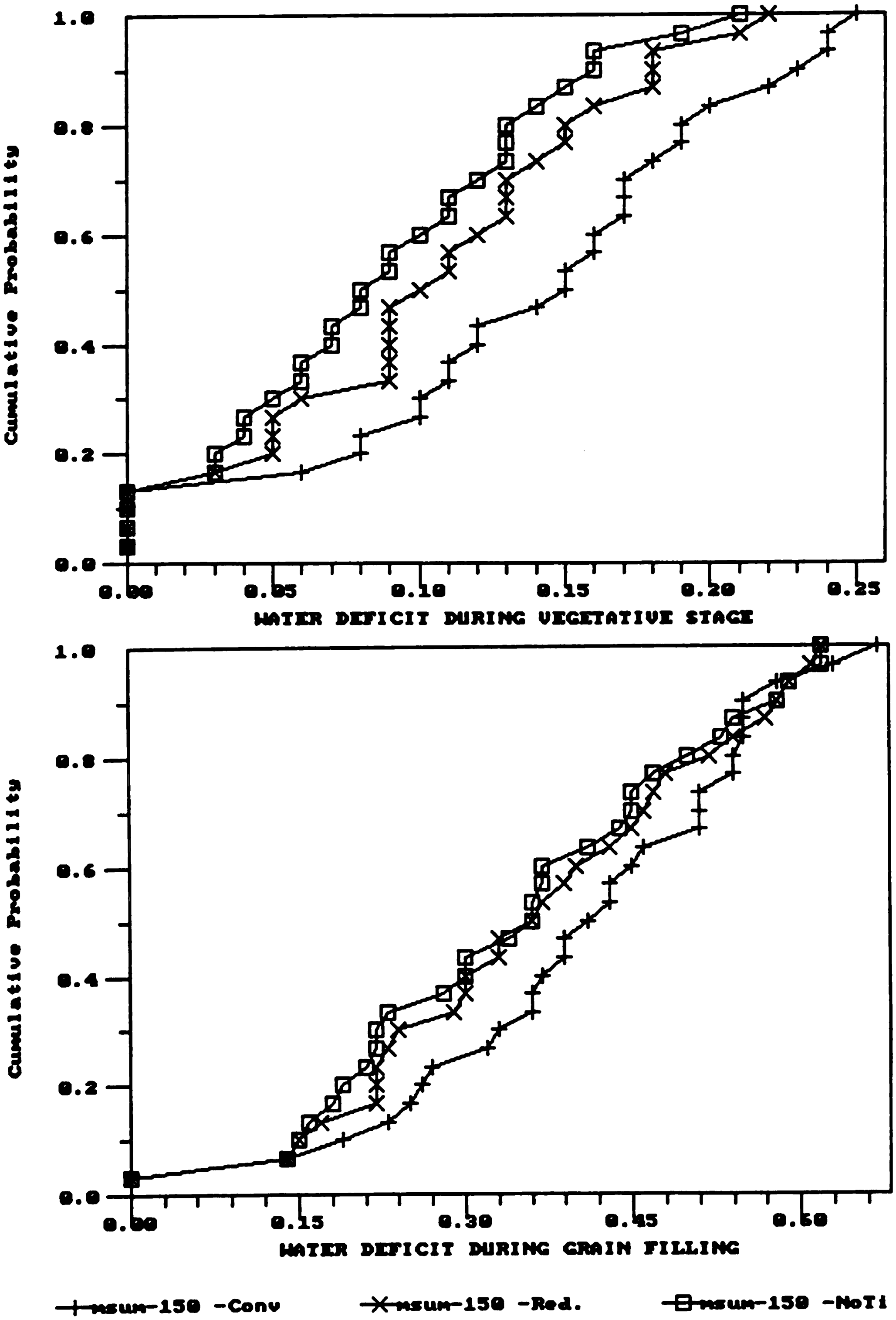

Figure 5.6: Water deficit during vegetative and reproductive stage for three tillage strategies at optimal planting date at the Ingham site.

Table 5.11: Yield (T ha^{-1}), return (\$ ha^{-1}) for three tillage strategies and four planting dates at the Kalamazoo site.

TILLAGE	SOW	YIELD T HA^{-1} AVG	STD	MIN	MAX	RETURN \$ HA^{-1} AVG	STD	MIN	MAX
Conventional	120	4.03	1.78	.00	7.46	191.88	198.41	-256.40	569.65
Conventional	130	4.00	1.78	.00	7.46	190.18	198.63	-256.40	569.65
Conventional	140	4.00	1.80	.00	7.46	190.55	201.20	-256.40	569.65
Conventional	150	4.17	1.70	1.30	7.64	210.78	190.30	-112.45	589.58
Reduced	120	5.38	1.92	1.48	9.09	366.69	216.24	-70.32	800.51
Reduced	130	5.34	1.90	1.48	8.98	363.00	214.09	-70.32	787.99
Reduced	140	5.47	1.94	1.48	8.54	378.23	219.47	-70.32	736.67
Reduced	150	5.49	1.93	1.48	8.54	380.96	217.64	-70.32	733.23
No-Till	120	6.00	2.04	1.58	10.13	438.60	230.58	-57.15	921.00
No-Till	130	5.96	1.95	1.58	9.10	433.75	219.59	-57.15	775.54
No-Till	140	6.11	2.04	1.58	9.30	452.19	230.79	-57.15	840.93
No-Till	150	6.14	2.09	1.58	9.18	456.12	237.37	-57.15	793.03

Discussion

Due to important water deficit during vegetative growth, planting dates had little effect on final yields. Late planting tended to increase final yield by increasing the length of the grain filling period, thus allowing increased dry matter accumulation. On the residue cover treatments, planting earlier than the conventional tillage strategy was required to ensure sufficient growing season before maturity. In some cases, late planting decreased the length of the vegetative period due to higher air temperature. This caused a longer grain filling period. Thus late planting improved yields for the reduced and no-till strategies at the warmest location (Kalamazoo site, Table 5.12).

Table 5.12: Number of days from sowing to anthesis and anthesis to maturity for three tillage strategies and four planting dates at the Kalamazoo site.

TILLAGE		SOWING TO ANTHESIS				ANTHESIS TO MATURITY			
	DOY	AVG	STD	MIN	MAX	AVG	STD	MIN	MAX
Conventional	120	89.97	12.20	70.00	120.00	52.93	10.24	7.00	69.00
Conventional	130	87.63	12.69	70.00	120.00	53.53	10.51	7.00	70.00
Conventional	140	86.40	13.20	69.00	120.00	54.93	11.50	7.00	70.00
Conventional	150	80.23	8.66	64.00	97.00	56.93	6.85	47.00	72.00
Reduced	120	90.80	10.04	72.00	111.00	55.63	5.50	48.00	70.00
Reduced	130	89.57	10.26	72.00	111.00	56.47	6.19	48.00	73.00
Reduced	140	89.53	13.97	69.00	123.00	57.20	6.90	48.00	73.00
Reduced	150	83.90	10.55	67.00	104.00	57.33	6.94	48.00	74.00
No-Till	120	92.03	9.59	73.00	112.00	56.03	5.59	48.00	70.00
No-Till	130	90.67	10.01	73.00	112.00	56.80	6.28	48.00	73.00
No-Till	140	87.73	10.88	69.00	112.00	57.80	7.14	48.00	73.00
No-Till	150	84.90	11.08	66.00	105.00	57.67	6.65	48.00	72.00

No-till always provided better yields and economic return for the four locations. No-till increased yield by increasing infiltration (reduced runoff), which diminished water deficit during the vegetative period and the grain filling period. Reduced tillage improved economic returns compared to conventional tillage by increasing yields and decreasing costs. The yield increase induced by the tillage strategies was larger than that caused by planting dates. The yield increase from conventional tillage to no-till varied from 18% at the Ingham site to 47% at the Kalamazoo site. The increase was highest on the sandy soil where there was higher rainfall. The Kalamazoo site was the most humid, 924 mm precipitation, followed by the Huron site, 743 mm (Table 5.12). Yields for all strategies increased when the temperature in the spring increased. The coldest site was the

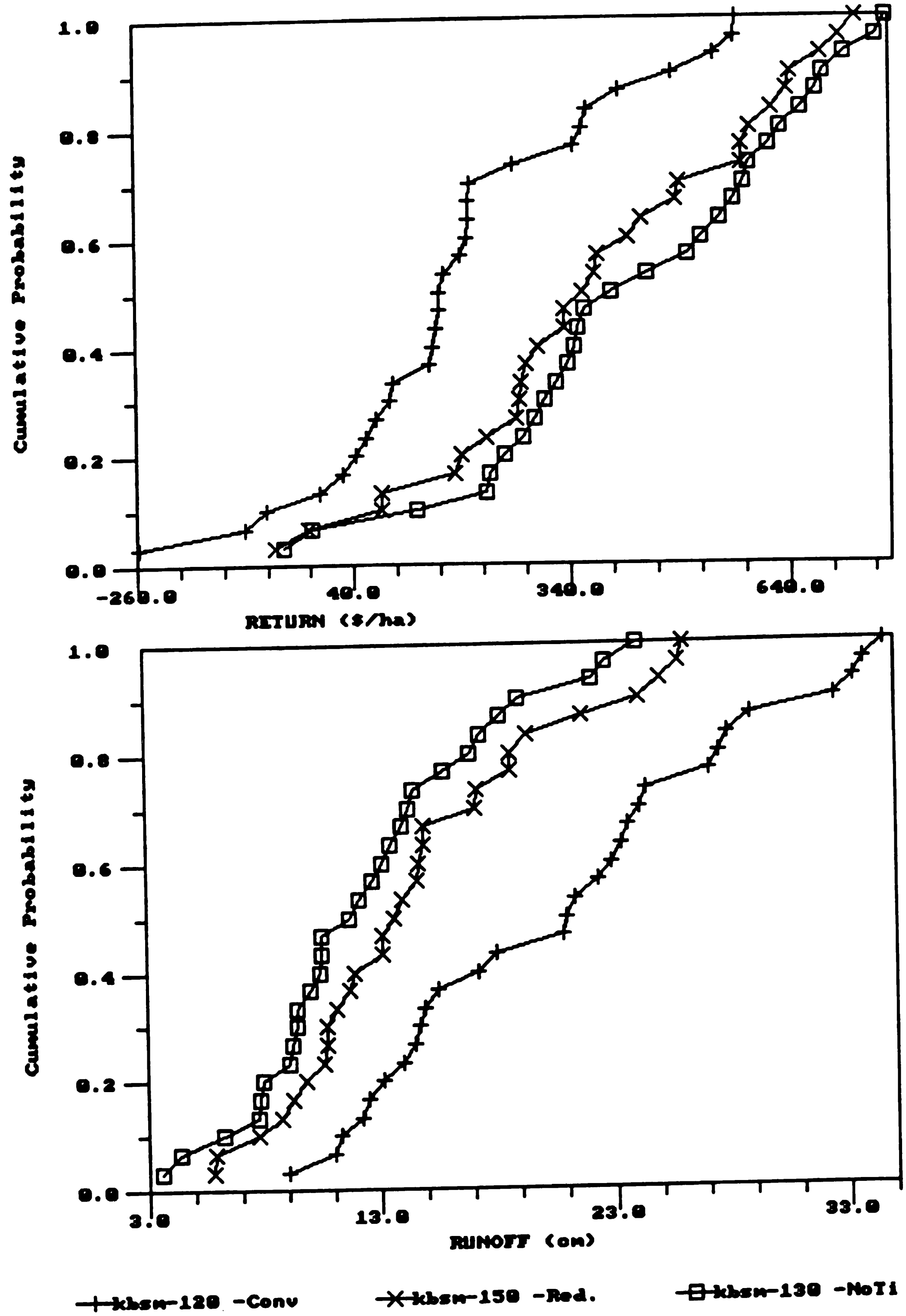

Figure 5.7: Cumulative distribution of economic return ($ ha^{-1}) and annual runoff (cm) at the Kalamazoo site for the best planting dates for conventional tillage, reduced tillage, and no-till.

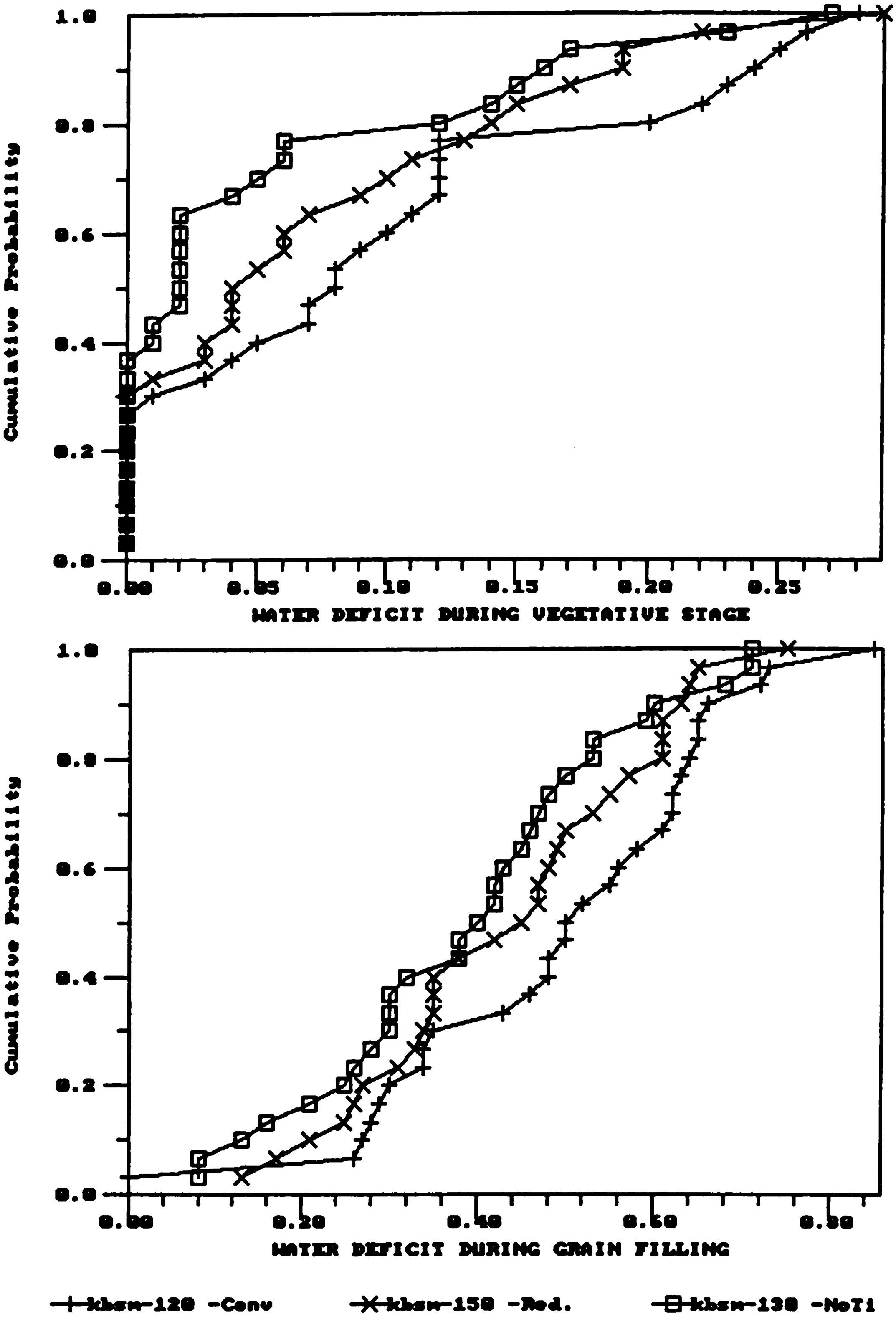

Figure 5.8: Water deficit during vegetative and reproductive stage for three tillage strategies at optimal planting date.

Huron site and the temperature increased from the coast to the inland locations at Tuscola, Ingham and Kalamazoo (Table 5.13).

Table 5.13: Five day average air temperature in the spring at the Huron, Tuscola, Ingham and Kalamazoo sites.

Date	April 30	May 05	May 10	May 15	May 20	May 25	May 30	June 04	June 09
Huron site									
Average	10.38	11.06	12.10	13.81	14.46	14.59	15.70	17.94	17.93
STD	3.21	3.90	2.77	3.94	3.72	2.85	1.96	3.15	3.07
Tuscola site									
Average	11.42	12.25	12.85	14.48	15.14	15.41	16.45	18.60	19.06
STD	3.39	4.11	2.94	3.75	3.69	2.58	1.96	2.90	2.94
Ingham site									
Average	11.81	12.27	13.47	14.78	15.70	16.22	16.63	19.17	19.60
STD	3.39	4.11	2.94	3.75	3.69	2.58	1.96	2.90	2.94
Kalamazoo site									
Average	13.10	14.15	14.67	16.66	17.29	17.33	17.98	19.09	20.76
STD	3.60	2.89	2.68	2.88	3.22	2.33	2.72	2.56	2.31

Runoff was decreased by the soil cover due to an increase in water infiltration and ponding capacity (Table 5.14). The model did not include any preferential flow that may happen on the conservation tillage system due to fauna activity and root channels. Preferential flow will improve water infiltration and move water faster downward the lower layers. Although the runoff was still high on the no-till strategy, soil erosion should be smaller due to the decrease in raindrop impact and the barrier to soil displacement created by the residue cover.

Table 5.14: Annual runoff (cm) at four sites for three different tillage strategies at the optimum yield.

TILLAGE	AVG	STD	MIN	MAX	DECREASE %
Huron site					
Conventional	15.90	6.26	5.30	30.80	
Reduced	12.93	5.81	3.90	27.60	19
No-till	11.06	5.25	2.40	24.90	30
Tuscola site					
Conventional	13.24	5.73	5.30	28.20	
Reduced	11.63	5.18	2.90	22.80	12
No-till	10.30	4.72	2.60	20.70	22
Ingham site					
Conventional	15.86	6.56	4.40	29.40	
Reduced	12.30	4.90	3.6	20.0	22
No-till	11.22	4.71	2.9	20.10	30
Kalamazoo site					
Conventional	20.90	7.49	9.0	34.60	
Reduced	14.67	5.69	5.80	26.00	30
No-till	12.60	5.18	3.60	24.00	40

These results are dependent on the model assumptions. The model does not predict crop losses due to pests and disease. No-till has been reported to increase the amount of pests in the crop and may be a constraint to no-till adoption.

Conclusion

The model showed that no-till would increase maize yield and economic return in Michigan for rainfed crops. The yield increase was mainly due to increased infiltration and reduced water deficit during vegetative and grain filling stages. Planting date had a small effect on final yield because of the dominant effect of the water deficit on yield. Comparison of model outputs to long term yield data is necessary before using the model for a wide selection of climates and soil types. The model showed a decrease in water runoff for the less tilled strategies due to higher saturated water conductivity and water ponding capacity. A model of particle detachment and preferential flow would also improve the model by allowing prediction of soil erosion.

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Conclusion and recommendations

The complexity of the interaction of crop residue cover and climate was illustrated in field experiments. Residue cover delayed maize development while the meristem was below ground, and thus its growth. The delay in plant development was still evident at harvest because of high water content of the grain. The length of the delay was linked to the spring air temperatures. Under high air temperatures, the delay was shorter due to rapid plant growth. Crop residue cover maintained high water content at the surface, thus kept root distribution near the surface. The root distribution pattern under a residue cover needs to be further investigated to better understand the consequences of water deficit later in the season.

Maize development prediction was improved by using soil temperature to calculate thermal time while the plant meristem was below ground. Although air temperature gave good correlation, phyllochron or base temperature had to be modified to get an accurate prediction. Soil temperature gave a better prediction because it used phyllochron and base temperature that has been confirmed by experimental data.

A model of tillage and residue cover effects on soil surface conditions was added to the CERES model. Surface bulk density, saturated hydraulic conductivity, and ponding capacity were time-variant adding a dynamic dimension to the model that is necessary to evaluate residue cover impact on water runoff.

Further work is needed to validate the model of surface properties and to include initial soil conditions effect on soil properties after tillage. The model prediction of chopped surface residue decomposition was an improvement but a standing crop residue model would be closer to field conditions.

Crop residue cover effects on maize development was an essential step toward no-till modelling. The modelling of maize growth response to no-till conditions needs to be validated to ensure that the model accurately predicts biomass, root distribution, and water uptake. The problems of pest damage that are encountered in no-till conditions is not included in the CERES model. A pest-weed model needs to be linked to the CERES models.

Model simulations of three tillage strategies, conventional, reduced tillage, and no-till, showed that no-till was the best tillage strategy for the four studied sites located in mid-Michigan. No-till had lower water deficit conditions during vegetative growth and higher net return due to higher final grain yield and lower costs. No-till considerably decreased runoff, especially in the high range where soil erosion is most likely to happen. A model of particle detachment linked to the water runoff model would allow prediction of soil loss and its impact on long-term soil productivity. The results found in these simulations must be validated with long-term yield data from several climates from cool temperate to tropical.

Appendix 1: Weather and soil data

SITE	YEAR	DOY	Solrad	Air temp. °C Max	Min	Rain cm
MSUM	90	91	14.41	10.6	5.6	5.3
MSUM	90	92	12.04	5.6	4.4	7.9
MSUM	90	93	10.81	3.9	-1.1	1.5
MSUM	90	94	18.82	10.0	-1.1	.0
MSUM	90	95	19.12	4.4	-1.1	.0
MSUM	90	96	19.33	3.3	-6.7	.0
MSUM	90	97	19.84	4.4	-7.2	.0
MSUM	90	98	13.95	11.7	-6.7	3.3
MSUM	90	99	14.11	17.2	7.2	11.2
MSUM	90	100	12.02	8.9	6.7	6.1
MSUM	90	101	11.49	3.9	-1.1	2.5
MSUM	90	102	20.33	5.0	-4.4	.0
MSUM	90	103	14.52	12.2	-2.2	5.8
MSUM	90	104	14.59	8.9	4.4	.5
MSUM	90	105	20.55	12.2	1.7	.0
MSUM	90	106	14.38	16.1	-1.1	3.8
MSUM	90	107	21.30	3.9	-1.1	.0
MSUM	90	108	21.55	13.3	-5.0	.0
MSUM	90	109	21.97	16.1	.0	.0
MSUM	90	110	15.56	15.0	10.0	14.7
MSUM	90	111	20.67	18.9	7.8	.0
MSUM	90	112	20.77	22.2	5.6	.0
MSUM	90	113	21.34	23.9	6.7	.0
MSUM	90	114	14.18	28.3	11.7	1.3
MSUM	90	115	20.59	30.0	16.7	.0
MSUM	90	116	19.58	29.4	16.1	.0
MSUM	90	117	19.58	28.9	15.6	.0
MSUM	90	118	19.83	27.2	15.0	.0
MSUM	90	119	20.15	22.2	12.2	.0
MSUM	90	120	20.95	26.1	10.0	.0
MSUM	90	121	21.69	15.0	4.4	.0
MSUM	90	122	23.21	17.8	2.2	.0
MSUM	90	123	23.71	17.2	4.4	.0
MSUM	90	124	17.34	9.4	8.9	19.3
MSUM	90	125	23.36	16.7	5.6	.0
MSUM	90	126	23.91	15.6	3.9	.0
MSUM	90	127	24.21	23.3	7.8	.0
MSUM	90	128	24.03	27.2	13.3	.0
MSUM	90	129	15.02	25.0	15.6	3.3
MSUM	90	130	13.73	10.0	9.4	1.0
MSUM	90	131	23.60	16.1	1.7	.0
MSUM	90	132	18.71	11.1	2.8	7.9
MSUM	90	133	25.18	17.8	7.8	.0
MSUM	90	134	18.52	16.7	5.0	.3
MSUM	90	135	18.88	21.1	10.0	14.7
MSUM	90	136	18.14	22.2	16.1	16.8
MSUM	90	137	15.35	16.1	12.8	.5
MSUM	90	138	24.01	14.4	7.8	.0
MSUM	90	139	18.79	12.9	4.4	9.9
MSUM	90	140	25.81	16.1	7.5	.0
MSUM	90	141	25.78	15.6	7.8	.0
MSUM	90	142	25.84	17.8	5.6	.0
MSUM	90	143	26.09	20.0	5.0	.0
MSUM	90	144	26.26	20.0	11.1	.0
MSUM	90	145	19.40	19.8	8.9	4.1
MSUM	90	146	19.62	21.3	10.3	4.3
MSUM	90	147	26.08	24.4	7.9	.0
MSUM	90	148	26.33	23.3	7.2	.0
MSUM	90	149	26.50	16.1	8.9	.0
MSUM	90	150	26.51	20.6	3.3	.0
MSUM	90	151	26.97	23.9	5.0	.0
MSUM	90	152	27.01	27.2	8.3	.0
MSUM	90	153	20.61	27.2	18.9	2.8
MSUM	90	154	25.10	24.4	15.6	.0
MSUM	90	155	25.36	17.8	5.0	.0
MSUM	90	156	20.90	18.9	3.9	.3
MSUM	90	157	27.39	25.6	13.3	.0
MSUM	90	158	20.31	25.6	12.2	15.0
MSUM	90	159	26.77	25.6	13.3	.0
MSUM	90	160	26.61	24.4	16.1	.0

SITE	YEAR	DOY	Solrad	Air temp. °C Max	Min	Rain cm	
MSUM	90	161	26.00	23.3	12.8	.0	
MSUM	90	162	19.93	25.0	11.7	.5	
MSUM	90	163	26.95	25.6	14.4	.0	
MSUM	90	164	19.83	32.2	17.8	17.5	
MSUM	90	165	18.02	26.7	18.9	1.0	
MSUM	90	166	25.36	27.2	13.9	.0	
MSUM	90	167	26.46	29.4	14.4	.0	
MSUM	90	168	26.62	32.2	19.4	.0	
MSUM	90	169	25.53	26.7	20.0	.0	
MSUM	90	170	25.22	25.0	10.6	.0	
MSUM	90	171	20.66	23.9	15.6	4.1	
MSUM	90	172	26.74	27.2	15.6	.0	
MSUM	90	173	26.60	20.0	18.3	.0	
MSUM	90	174	18.51	15.6	13.9	11.4	
MSUM	90	175	26.93	23.3	10.0	.0	
MSUM	90	176	27.32	27.2	6.7	.0	
MSUM	90	177	21.73	25.0	15.6	.8	
MSUM	90	178	20.56	26.7	13.3	10.7	
MSUM	90	179	27.04	23.9	17.8	.0	
MSUM	90	180	26.33	27.8	20.0	.0	
MSUM	90	181	25.56	30.0	18.3	.0	
MSUM	90	182	25.72	23.3	15.0	.0	
MSUM	90	183	26.57	26.7	11.1	.0	
MSUM	90	184	27.06	29.4	14.4	.0	
MSUM	90	185	26.85	34.4	22.2	.0	
MSUM	90	186	25.12	28.3	20.0	.0	
MSUM	90	187	25.18	22.2	13.3	.0	
MSUM	90	188	26.65	24.4	8.9	.0	
MSUM	90	189	20.97	33.3	15.6	.0	13.6
MSUM	90	190	26.59	30.0	21.7	.0	
MSUM	90	191	17.21	28.3	16.7	.0	13.3
MSUM	90	192	25.76	20.0	13.9	.0	
MSUM	90	193	26.41	23.3	15.6	.0	
MSUM	90	194	19.75	22.8	12.2	7.6	
MSUM	90	195	20.13	21.1	7.8	.8	
MSUM	90	196	20.82	24.4	13.9	8.2	10.2
MSUM	90	197	20.03	26.7	14.4	5.1	
MSUM	90	198	26.12	28.9	17.8	.0	
MSUM	90	199	18.59	30.0	17.8	2.5	
MSUM	90	200	18.06	30.0	17.2	14.0	
MSUM	90	201	18.11	24.4	18.9	12.7	
MSUM	90	202	24.80	27.8	17.8	.0	
MSUM	90	203	17.67	19.4	14.4	9.9	
MSUM	90	204	18.97	24.4	11.7	1.3	
MSUM	90	205	25.65	26.1	12.2	.0	
MSUM	90	206	25.57	28.3	12.8	.0	
MSUM	90	207	25.43	28.9	14.4	.0	
MSUM	90	208	25.19	28.9	14.4	.0	
MSUM	90	209	25.05	30.0	16.7	.0	
MSUM	90	210	24.64	30.0	17.8	.0	
MSUM	90	211	24.17	24.4	21.1	.0	
MSUM	90	212	23.31	21.7	12.2	.0	
MSUM	90	213	24.63	26.1	8.9	.0	
MSUM	90	214	24.86	27.2	11.1	.0	
MSUM	90	215	24.66	27.2	14.4	.0	
MSUM	90	216	24.29	21.7	18.9	.0	
MSUM	90	217	16.29	24.4	17.2	7.4	
MSUM	90	218	23.31	17.2	13.3	.0	
MSUM	90	219	17.36	22.2	10.0	8.6	
MSUM	90	220	23.99	27.2	8.9	.0	
MSUM	90	221	23.98	28.3	13.3	.0	
MSUM	90	222	23.57	27.8	13.3	.0	
MSUM	90	223	16.91	26.7	14.4	26.9	
MSUM	90	224	23.12	22.2	15.0	.0	
MSUM	90	225	22.92	20.0	16.1	.0	
MSUM	90	226	22.52	24.4	10.0	.0	
MSUM	90	227	22.92	27.2	14.4	.0	

SITE	YEAR	DOY	Solrad	Air temp. °C Max	Min	Rain cm
MSUM	90	228	22.56	28.3	17.8	.0
MSUM	90	229	21.69	27.2	16.7	.0
MSUM	90	230	14.42	29.4	19.4	5.8
MSUM	90	231	13.23	20.6	19.4	1.5
MSUM	90	232	20.58	19.4	13.9	.0
MSUM	90	233	21.44	22.2	14.4	.0
MSUM	90	234	21.39	21.1	17.2	.0
MSUM	90	235	20.73	22.8	17.8	.0
MSUM	90	236	20.32	26.7	16.7	.0
MSUM	90	237	20.26	28.3	16.7	.0
MSUM	90	238	20.09	30.0	17.8	.0
MSUM	90	239	19.69	31.7	21.1	.0
MSUM	90	240	18.86	31.7	23.3	.0
MSUM	90	241	18.13	27.8	15.6	.0
MSUM	90	242	19.19	26.7	16.7	.0
MSUM	90	243	19.11	28.3	15.0	.0
MSUM	90	244	19.21	27.2	16.7	.0
MSUM	90	245	18.81	27.8	15.0	.0
MSUM	90	246	18.84	25.0	15.0	.0
MSUM	90	247	18.71	30.0	15.0	.0
MSUM	90	248	18.50	28.9	22.2	.0
MSUM	90	249	9.17	33.3	18.9	39.9
MSUM	90	250	17.14	23.9	18.9	.0
MSUM	90	251	17.07	25.6	10.0	.0
MSUM	90	252	18.30	26.7	11.7	.0
MSUM	90	253	18.16	27.8	17.2	.0
MSUM	90	254	17.10	25.6	13.9	.0
MSUM	90	255	17.22	29.4	12.8	.0
MSUM	90	256	17.23	27.8	16.1	.0
MSUM	90	257	9.33	23.9	18.9	19.0
MSUM	90	258	8.29	17.8	10.0	14.2
MSUM	90	259	16.89	16.1	10.0	.0
MSUM	90	260	17.00	15.6	3.3	.0
MSUM	90	261	17.24	17.1	1.0	.0
MSUM	90	262	17.24	15.1	9.0	.0
MSUM	90	263	16.71	19.3	4.2	.0
MSUM	90	264	16.66	14.9	8.3	.0
MSUM	90	265	16.31	16.0	5.6	.0
MSUM	90	266	16.21	10.7	1.7	.0
MSUM	90	267	16.22	16.0	1.0	.0
MSUM	90	268	16.09	19.1	8.6	.0
MSUM	90	269	15.58	21.1	8.1	.0
MSUM	90	270	15.30	24.0	6.4	.0
MSU	90	271	15.09	27.2	8.3	0.0
MSU	90	272	14.78	27.8	11.1	0.0
MSU	90	273	14.19	16.7	10.0	0.0
MSU	90	274	14.08	16.1	4.4	0.0
MSU	90	275	14.49	16.7	2.2	0.0
MSU	90	276	14.45	20.6	5.0	0.0
MSU	90	277	7.64	23.3	10.0	19.1
MSU	90	278	13.46	18.3	10.0	0.0
MSU	90	279	13.13	27.2	8.9	0.0
MSU	90	280	12.98	28.9	15.6	0.0
MSU	90	281	5.01	16.1	7.8	4.3
MSU	90	282	5.81	8.9	6.1	25.1
MSU	90	283	6.13	7.8	5.6	37.6
MSU	90	284	6.13	11.7	3.3	10.4
MSU	90	285	12.75	14.4	-.6	0.0
MSU	90	286	12.73	14.4	-.6	0.0
MSU	90	287	12.59	16.7	2.8	0.0
MSU	90	288	5.75	20.0	5.6	7.9
MSU	90	289	11.88	15.0	3.3	0.0
MSU	90	290	11.85	18.3	5.0	0.3
MSU	90	291	4.92	19.4	8.3	5.8
MSU	90	292	4.31	15.6	.6	1.0
MSU	90	293	11.43	10.0	-1.1	0.0
MSU	90	294	11.38	16.7	5.0	0.0
MSU	90	295	4.34	15.6	5.0	1.0
MSU	90	296	10.61	13.3	-2.2	0.0
MSU	90	297	10.90	14.4	-2.2	0.0
MSU	90	298	4.22	13.3	.0	0.5
MSU	90	299	10.58	7.8	-3.9	0.0
MSU	90	300	10.53	10.0	-3.3	0.0
MSU	90	301	10.38	16.1	2.2	0.0
MSU	90	302	10.05	8.3	-4.4	0.0
MSU	90	303	10.07	11.7	-2.8	0.0
MSU	90	304	9.91	19.4	5.6	0.0
MSU	90	305	9.26	17.8	7.2	0.0
MSU	90	306	8.81	22.8	11.1	0.0
MSU	90	307	8.26	22.2	13.3	0.0
MSU	90	308	1.67	22.8	6.7	2.5
MSU	90	309	1.85	6.1	2.2	35.1
MSU	90	310	2.10	6.1	-.6	33.0
MSU	90	311	2.20	3.9	.6	1.3
MSU	90	312	8.58	4.4	-5.6	0.0
MSU	90	313	8.73	6.1	-4.4	0.0
MSU	90	314	8.61	8.3	-3.3	0.0
MSU	90	315	8.46	10.0	-3.3	0.0
MSU	90	316	1.74	3.9	-3.3	0.8
MSU	90	317	8.22	4.4	-3.9	0.0
MSU	90	318	8.12	4.4	-3.9	0.0
MSU	90	319	8.01	15.0	-1.1	0.0
MSU	90	320	7.75	20.6	11.7	0.0
MSU	90	321	6.72	16.1	-.6	0.0
MSU	90	322	7.21	6.7	-5.0	0.0
MSU	90	323	7.56	7.8	-2.2	0.0
MSU	90	324	7.38	11.7	-3.3	0.0
MSU	90	325	7.31	13.3	-3.3	0.0
MSU	90	326	1.38	17.2	6.1	6.4
MSU	90	327	1.37	8.3	2.2	1.3
MSU	90	328	6.56	8.3	-3.3	0.0
MSU	90	329	6.83	9.4	-3.3	0.0
MSU	90	330	6.83	6.7	-2.8	0.0
MSU	90	331	1.33	17.8	-1.7	10.7
MSU	90	332	1.32	18.3	16.1	55.1
MSU	90	333	1.31	7.8	-.6	0.8
MSU	90	334	6.10	1.7	-3.3	0.0
MSU	90	335	6.38	7.2	-1.7	0.0
MSU	90	336	6.29	8.3	-5.6	0.0
MSU	90	337	1.28	3.9	-5.6	124.5
MSU	90	338	1.27	3.3	-5.6	14.0
MSU	90	339	6.38	-3.3	-5.0	0.3
MSU	90	340	6.31	2.2	-3.3	0.0
MSU	90	341	6.15	3.3	-6.1	0.0
MSU	90	342	6.23	3.9	-3.3	0.0
MSU	90	343	6.06	6.1	-3.3	0.0
MSU	90	344	5.98	11.1	1.1	0.0
MSU	90	345	5.69	3.9	-.6	0.0
MSU	90	346	5.70	8.3	.6	0.0
MSU	90	347	5.60	11.7	.6	0.3
MSU	90	348	5.55	1.7	10.6	0.0
MSU	90	349	1.22	1.7	-6.7	1.0
MSU	90	350	1.21	3.3	-.6	7.1
MSU	90	351	5.62	3.9	-.6	0.0
MSU	90	352	1.21	5.0	1.1	3.8
MSU	90	353	5.45	2.8	-2.2	0.3
MSU	90	354	5.60	2.8	-2.8	0.0
MSU	90	355	5.66	6.7	1.1	0.0
MSU	90	356	5.46	12.2	2.2	0.0
MSU	90	357	1.21	.6	-8.9	120.7
MSU	90	358	1.22	-8.3	13.3	43.2
MSU	90	359	1.22	11.7	13.9	1.3
MSU	90	360	4.61	-7.2	18.3	0.0

SITE	YEAR	DOY	Solrad	Air temp. °C Max	Min	Rain cm
MSEL	91	91	19.94	3.9	-.6	.0
MSEL	91	92	18.93	8.3	-4.4	.0
MSEL	91	93	19.02	14.4	-2.2	.0
MSEL	91	94	12.59	19.4	1.7	12.4
MSEL	91	95	18.78	21.1	8.3	.0
MSEL	91	96	17.73	26.7	8.3	.0
MSEL	91	97	17.59	27.2	15.0	.0
MSEL	91	98	7.82	23.3	17.8	5.1
MSEL	91	99	6.70	15.6	11.7	17.3
MSEL	91	100	17.12	7.8	1.1	.0
MSEL	91	101	19.41	8.3	-3.3	.0
MSEL	91	102	20.49	10.0	-1.7	.0
MSEL	91	103	14.29	11.7	1.7	5.8
MSEL	91	104	14.13	13.9	4.4	10.2
MSEL	91	105	13.40	18.3	6.1	3.8
MSEL	91	106	20.05	13.3	5.0	.0
MSEL	91	107	20.39	13.9	2.2	.0
MSEL	91	108	21.13	13.9	.0	.0
MSEL	91	109	15.13	7.2	3.3	21.8
MSEL	91	110	15.06	7.2	1.1	2.0
MSEL	91	111	15.43	5.6	1.7	1.0
MSEL	91	112	22.05	15.0	2.2	.0
MSEL	91	113	15.70	16.1	5.0	14.0
MSEL	91	114	22.03	15.6	5.6	.0
MSEL	91	115	22.00	18.3	1.7	.0
MSEL	91	116	22.63	23.3	6.1	.0
MSEL	91	117	15.54	25.6	10.6	8.6
MSEL	91	118	13.78	23.9	12.8	.5
MSEL	91	119	12.75	24.4	13.3	1.3
MSEL	91	120	12.47	18.9	12.8	.5
MSEL	91	121	12.82	14.4	8.3	1.8
MSEL	91	122	22.30	12.8	7.2	.0
MSEL	91	123	22.97	13.9	1.7	.0
MSEL	91	124	23.88	18.3	4.4	.0
MSEL	91	125	23.94	15.6	3.9	.0
MSEL	91	126	24.10	7.8	6.1	.0
MSEL	91	127	24.13	12.8	4.4	.0
MSEL	91	128	17.96	15.6	1.1	1.3
MSEL	91	129	24.72	23.9	5.6	.0
MSEL	91	130	24.59	27.2	9.4	.0
MSEL	91	131	24.17	28.9	10.6	.0
MSEL	91	132	23.83	30.6	15.6	.0
MSEL	91	133	22.80	28.9	15.0	.0
MSEL	91	134	22.81	29.4	16.1	.0
MSEL	91	135	22.70	32.2	11.1	.0
MSEL	91	136	16.12	31.1	13.3	7.6
MSEL	91	137	23.74	24.4	18.9	.0
MSEL	91	138	22.71	15.6	6.1	.0
MSEL	91	139	25.37	22.2	6.1	.0
MSEL	91	140	25.67	25.6	6.7	.0
MSEL	91	141	25.78	29.4	10.0	.0
MSEL	91	142	25.64	31.1	13.9	.0
MSEL	91	143	24.73	28.3	16.1	.0
MSEL	91	144	16.03	27.2	18.9	14.0
MSEL	91	145	14.66	27.8	18.9	9.4
MSEL	91	146	23.41	27.2	20.6	.0
MSEL	91	147	23.14	29.4	21.1	.0
MSEL	91	148	23.03	32.2	19.4	.0
MSEL	91	149	14.26	32.8	21.1	7.6
MSEL	91	150	23.22	30.6	20.0	.0
MSEL	91	151	14.32	30.6	19.4	.8
MSEL	91	152	14.78	27.8	18.9	6.1
MSEL	91	153	15.27	21.1	16.7	4.8
MSEL	91	154	24.79	26.7	14.4	.0
MSEL	91	155	25.52	20.6	8.9	.0
MSEL	91	156	26.76	23.9	9.4	.0
MSEL	91	157	26.90	26.1	7.2	.0
MSEL	91	158	27.13	27.2	10.6	.0
MSEL	91	159	26.97	27.2	11.1	.0
MSEL	91	160	26.94	28.9	11.1	.0
MSEL	91	161	20.53	28.9	15.0	8.1
MSEL	91	162	19.40	25.0	17.8	30.7
MSEL	91	163	25.64	27.2	13.9	.0
MSEL	91	164	26.40	25.6	8.3	.0
MSEL	91	165	27.26	31.1	13.3	.0
MSEL	91	166	20.51	32.2	17.8	2.3
MSEL	91	167	25.94	26.7	19.4	.0
MSEL	91	168	25.39	28.3	12.8	.0
MSEL	91	169	26.78	29.4	16.1	.0
MSEL	91	170	26.39	30.6	15.0	.0
MSEL	91	171	26.57	31.1	15.0	.0
MSEL	91	172	19.70	31.1	15.6	5.6
MSEL	91	173	19.47	16.1	14.4	16.5
MSEL	91	174	26.91	23.3	9.4	.0
MSEL	91	175	27.37	26.7	9.4	.0
MSEL	91	176	27.45	29.4	14.4	.0
MSEL	91	177	27.08	32.2	16.1	.0
MSEL	91	178	26.64	31.7	20.6	.0
MSEL	91	179	25.46	31.1	20.0	.0
MSEL	91	180	25.31	32.2	21.7	.0
MSEL	91	181	24.88	28.9	19.4	.0
MSEL	91	182	17.29	28.9	15.6	6.1
MSEL	91	183	26.27	29.4	17.2	.0
MSEL	91	184	18.95	31.1	17.2	16.0
MSEL	91	185	26.06	27.8	17.2	.0
MSEL	91	186	26.07	28.3	17.8	.0
MSEL	91	187	25.91	33.3	15.6	.0
MSEL	91	188	19.44	31.7	22.8	29.5
MSEL	91	189	24.74	25.6	17.8	.0
MSEL	91	190	18.04	25.6	12.2	.3
MSEL	91	191	26.61	27.8	13.3	.0
MSEL	91	192	26.59	27.2	15.6	.0
MSEL	91	193	26.37	24.4	16.7	.0
MSEL	91	194	19.29	23.3	16.1	1.0
MSEL	91	195	26.04	26.1	15.6	.0
MSEL	91	196	26.09	28.9	11.1	.0
MSEL	91	197	26.37	30.6	13.9	.0
MSEL	91	198	26.16	30.6	19.4	.0
MSEL	91	199	25.17	32.2	18.9	.0
MSEL	91	200	24.87	32.8	23.3	.0
MSEL	91	201	23.77	33.3	22.2	.0
MSEL	91	202	23.68	31.1	22.8	.0
MSEL	91	203	14.99	32.2	21.1	9.7
MSEL	91	204	23.70	31.7	21.1	.0
MSEL	91	205	23.71	26.1	14.4	.0
MSEL	91	206	25.12	23.9	14.4	.0
MSEL	91	207	25.24	24.4	10.6	.0
MSEL	91	208	25.43	25.6	9.4	.0
MSEL	91	209	19.39	25.6	13.3	.3
MSEL	91	210	18.80	20.0	15.0	28.7
MSEL	91	211	24.84	23.3	14.4	.0
MSEL	91	212	24.73	27.8	11.1	.0
MSEL	91	213	24.82	28.9	14.4	.0
MSEL	91	214	18.07	31.7	16.1	8.9
MSEL	91	215	24.13	22.8	18.9	.0
MSEL	91	216	23.39	24.4	15.0	.0
MSEL	91	217	23.88	23.9	10.0	.0
MSEL	91	218	24.23	25.6	8.3	.0
MSEL	91	219	18.20	26.7	12.2	2.3
MSEL	91	220	17.64	16.7	16.1	43.9
MSEL	91	221	16.95	25.0	13.3	2.3
MSEL	91	222	23.46	26.7	12.8	.0
MSEL	91	223	23.37	27.2	11.1	.0
MSEL	91	224	23.35	27.8	12.2	.0

MSEL	91	225	23.16	28.3	12.8	.0
MSEL	91	226	22.95	27.8	13.3	.0
MSEL	91	227	22.76	29.4	13.9	.0
MSEL	91	228	22.55	30.0	16.1	.0
MSEL	91	229	15.11	25.0	19.4	2.8
MSEL	91	230	13.61	27.8	13.3	10.4
MSEL	91	231	15.16	23.3	15.6	5.1
MSEL	91	232	14.66	23.9	14.4	1.3
MSEL	91	233	21.53	26.1	8.9	.0
MSEL	91	234	21.86	28.3	13.9	.0
MSEL	91	235	21.47	25.0	13.3	.0
MSEL	91	236	21.29	27.8	13.9	.0
MSEL	91	237	20.98	30.6	12.8	.0
MSEL	91	238	20.93	32.2	12.8	.0
MSEL	91	239	20.76	31.7	17.8	.0
MSEL	91	240	19.70	33.3	17.2	.0
MSEL	91	241	19.39	33.9	19.4	.0
MSEL	91	242	11.08	32.2	19.4	2.5
MSEL	91	243	18.49	27.8	17.8	.0
MSEL	91	244	18.59	24.4	7.8	.0
MSEL	91	245	19.91	28.3	7.2	.0
MSEL	91	246	19.89	27.2	11.7	.0
MSEL	91	247	19.50	23.9	12.2	.0
MSEL	91	248	19.22	26.1	7.2	.0
MSEL	91	249	19.31	28.3	10.6	.0
MSEL	91	250	18.99	30.0	12.2	.0
MSEL	91	251	11.91	30.6	15.6	.3
MSEL	91	252	10.60	30.0	15.6	8.6
MSEL	91	253	17.38	25.0	18.9	.0
MSEL	91	254	16.67	21.1	9.4	.0
MSEL	91	255	11.12	20.0	11.1	.3
MSEL	91	256	17.68	22.2	13.9	.0
MSEL	91	257	10.10	25.6	12.8	2.0
MSEL	91	258	16.88	31.7	16.1	.0
MSEL	91	259	16.17	26.7	22.2	.0
MSEL	91	260	14.99	22.8	11.1	.0
MSEL	91	261	9.14	18.3	11.1	.5
MSEL	91	262	16.31	13.9	4.4	.0
MSEL	91	263	16.78	14.4	1.7	.0
MSEL	91	264	16.80	18.3	-1.7	.0
MSEL	91	265	16.80	18.3	-.6	.0
MSEL	91	266	16.60	16.1	6.7	.0
MSEL	91	267	9.62	10.6	2.8	.5
MSEL	91	268	9.56	13.3	.0	1.8
MSEL	91	269	15.93	11.7	3.9	.0
MSEL	91	270	15.61	12.2	.6	.0
MSEL	91	271	15.53	16.7	-3.3	.0
MSEL	91	272	15.51	17.8	-3.3	.0
MSEL	91	273	15.36	26.7	-.6	.0
MSEL	91	274	15.05	20.0	8.3	.0
MSEL	91	275	7.91	23.9	10.0	7.9
MSEL	91	276	7.05	22.2	12.8	23.1
MSEL	91	277	6.22	19.4	10.0	11.2
MSEL	91	278	6.35	14.4	10.0	3.6
MSEL	91	279	6.26	8.9	2.2	1.3
MSEL	91	280	13.65	12.2	2.2	.0
MSEL	91	281	13.54	20.6	1.7	.0
MSEL	91	282	13.38	22.2	3.9	.0
MSEL	91	283	6.57	16.7	5.0	1.0
MSEL	91	284	6.31	13.9	5.0	1.8
MSEL	91	285	12.65	12.8	5.0	.0
MSEL	91	286	5.87	12.8	-2.2	2.3
MSEL	91	287	6.07	10.6	-1.7	5.3
MSEL	91	288	12.47	7.2	3.3	.0
MSEL	91	289	12.14	13.3	-3.9	.0

LOCATION CONOVER MI+IN WI

E[illegible]lished Series
Re.. RWS-EPW-WEF
1/90

CONOVER SERIES

The Conover series consists of very deep, somewhat poorly drained soils formed in loamy glacial till on low parts of moraines and till plains. These soils have moderate or moderately slow permeability. Slopes range from 0 to 6 percent. Mean annual precipitation is about 33 inches, and mean annual temperature is about 48 degrees F.

TAXONOMIC CLASS: Fine-loamy, mixed, mesic Udollic Ochraqualfs

TYPICAL PEDON: Conover loam on a 2 percent convex slope in a cultivated field. (Colors are for moist soil unless otherwise stated.)

Ap--0 to 9 inches; very dark grayish brown (10YR 3/2) loam, grayish brown (10YR 5/2) dry; moderate fine granular structure; friable; about 5 percent gravel; many fine roots; slightly acid; abrupt smooth boundary. (7 to 10 inches thick)

Bw--9 to 11 inches; dark yellowish brown (10YR 4/4) loam; common medium distinct yellowish brown (10YR 5/6) and grayish brown (10YR 5/2) mottles; weak medium subangular blocky structure; friable; about 5 percent gravel; c[illegible]on fine roots; slightly acid; clear wavy boundary. (0 to 6 inches t[illegible]

Bt1--11 to 19 inches; yellowish brown (10YR 5/4) clay loam; common fine distinct grayish brown (10YR 5/2) mottles; moderate medium subangular blocky structure; firm; few distinct dark grayish brown (10YR 4/2) clay films on faces of peds and in pores; about 5 percent gravel; few fine roots; slightly acid; gradual wavy boundary.

Bt2--19 to 27 inches; brown (7.5YR 4/4) silty clay loam; common medium prominent yellowish brown (10YR 5/6) and distinct gray (10YR 6/1) mottles; moderate medium subangular blocky structure; firm; common distinct dark grayish brown (10YR 4/2) clay films on faces of peds and in pores; about 5 percent gravel; few fine roots; slightly acid; gradual wavy boundary. (Combined thickness of the Bt horizon ranges from 8 to 24 inches.)

Cg1--27 to 50 inches; light brownish gray (10YR 6/2) loam; common medium distinct yellowish brown (10YR 5/4) and faint gray (10YR 6/1) mottles; weak medium subangular blocky structure; firm; about 5 percent gravel; slight effervescence; mildly alkaline; gradual wavy boundary.

Cg2--50 to 60 inches; light brownish gray (10YR 6/2) loam; common medium prominent strong brown (7.5YR 5/6) and faint gray (10YR 6/1) mottles; massive; firm; about 5 percent gravel; slight effervescence; mildly alkaline.

T[illegible] LOCATION: Washtenaw County, Michigan; about 3 miles south and 1 1/2 [illegible] east of Chelsea; 1,860 feet north and 1,840 feet west of the s[illegible]heast corner of sec. 29, T. 2 S., R. 4 E.

RANGE IN CHARACTERISTICS: Solum thickness ranges from 24 to 40 inches and coincides with depth to effervescence. Rock fragments range from 0 to 10 percent throughout the solum. The reaction generally ranges from medium to slightly acid, but in some pedons the Ap and B horizons are neutral.

The Ap or A horizon has value of 2 or 3, and chroma of 1 or 2. It is loam, silt loam, or sandy loam. Some pedons have E horizons. If present, it has hue of 10YR, value of 5 or 6, and chroma of 2 or 3. It is 2 to 6 inches thick and has textures like the Ap or A horizon.

The Bw horizon has hue of 10YR or 7.5YR, value of 4 to 6, and chroma of 3 or 4. It is loam or silt loam.

The Bt horizon has colors similar to the Bw horizon. It is clay loam, silty clay loam, or loam. Some pedons have BC horizons of loam or clay loam up to 7 inches thick. Some pedons have secondary carbonates in the lower B horizon (Bk horizons) on the the underside of rock fragments.

The C horizon has value of 4 to 6, and chroma of 2 or 3. It is loam, silt loam, or clay loam. It is mildly or moderately alkaline.

COMPETING SERIES: These are the Beardstown, Cantril, Dundas, Manheim, Metamora, Monitor, Riceville, Romulus, Schley, and Skyberg series. Similar soils are the Blount, Capac, Crosier, Locke, and Macomb series. Beardstown, Cantril, Monitor, and Schley soils have thicker sola. In addition, Beardstown soils have C horizons formed in stratified loam or sandy loam outwash materials and the Schley soils formed in stratified sediments overlying glacial till at depths of 30 to 50 inches. Dundas soils have lower chromas in the B horizon and typically 2.5Y and 5Y hues in the B and C horizon. Metamora soils formed in sandy materials overlying calcareous loam till at depths of less than 40 inches. Manheim soils are darker colored throughout the profile. Riceville, and Skyberg soils do not have rock fragments in the upper part of the series control section. Romulus soils have hues redder than 7.5YR in upper part of the series control section, and finer-textured C horizons. Blount soils have lighter colored Ap horizons and are in a fine family. Capac and Crosier soils have lighter colored Ap horizons. Locke soils are coarse-loamy. Macomb soils have gravelly layers within the control section.

GEOGRAPHIC SETTING: Conover soils typically are on low parts of moraines and till plains. Slopes range from 0 to about 6 percent, and dominant slopes are from 1 to 4 percent. Mean annual precipitation is 29 to 37 inches, and mean annual temperature ranges from 46 to 51 degrees F.

GEOGRAPHICALLY ASSOCIATED SOILS: The poorly drained Brookston and well drained Miami soils are in a drainage sequence with the Conover soils, and they are the most common associates. The very poorly drained organic Carlisle soils are in depressions.

DRAINAGE AND PERMEABILITY: Somewhat poorly drained. Surface runoff ranges

USE AND VEGETATION: Largely under cultivation. Corn, beans, small grain, and legume-grass hay are the major crops. A small part is in forest. Native vegetation was hardwood forest.

DISTRIBUTION AND EXTENT: Southern Michigan, southern Wisconsin, and northern Indiana. The series is of large extent.

SERIES ESTABLISHED: Miami County, Ohio, 1916.

REMARKS: Diagnostic horizons and features recognized in this pedon are: ochric epipedon - the zone from the surface to 9 inches (Ap horizon); argillic horizon - the zone from 11 to 27 inches (Bt1 and Bt2 horizons); aquic soil moisture regime.

National Cooperative Soil Survey
U.S.A.

Table I.1: Conover loam volumetric water content at 3 different depth and different suction and bulk density at the Box Farm, East Lansing, Mich., USA.

Suction (kPa)	0.00	0.10	0.20	0.39	0.59	3.33	10.00	BD
				cm^3 cm^{-3}				g cm^{-3}
0-7.6	0.51	0.41	0.34	0.33	0.33	0.31	0.27	1.27
7.6-15.2	0.51	0.42	0.35	0.33	0.33	0.31	0.28	1.26
15.2-22.8	0.52	0.42	0.34	0.33	0.33	0.31	0.27	1.39

Appendix 2: Modified subroutines

```
      Program MAIN
C     C E R E S   G E N E R I C   N I T R O G E N   M O D E L
C     This is an effort to combine all the models into one generic
C     model.  All routines are generally the same except for some crop
C     specific ones (nfact,menu2,grosub).
C
C     This version includes changes for tillage simulation (in bold) developed by F. Dadoun
C
C     CERES MAIZE MODEL -
C     CERES WHEAT MODEL -
C     CERES SORGHUM MODEL
C     CERES PEARL MILLET MODEL
C     CERES BARLEY MODEL
C     CERES CEREAL GENERIC MODEL DEVELOPED BY SINGH,GODWIN AND HUMPRIES -IFDC
C     NITROGEN ROUTINES DEVELOPED BY GODWIN,JONES, ET AL
C
      INCLUDE 'gen1.blk'
      INCLUDE 'gen2.blk'
      INCLUDE 'gen3.blk'
      INCLUDE 'gen4.blk'
      INCLUDE 'Ntrc1.Blk'
      INCLUDE 'Ntrc2.Blk'
      INCLUDE 'comibs.blk'
      INCLUDE 'predob.blk'
      INCLUDE 'Nmove.Blk'
      INCLUDE 'Enviro.Blk'
      INCLUDE 'soilox.blk'
      INCLUDE 'nwatbal.blk'
      INCLUDE 'till.blk'
c
      LOGICAL iechon, filexist, Lrun, Lbegin, OUT5OPEN, FCROP, Update
      DIMENSION Store(12, 50)
      CHARACTER*1 iehvc, RESP2,ans
      CHARACTER*2 Cropa(6)
      CHARACTER*12 FFile1, FileC, FileD, drainfile,calcevfile, wtfile
      INTEGER ISWWT, DECTRT, UNTRT, DECEXP, UNEXP, ifs0, ifs1
      DATA Cropa/'MZ', 'WH', 'SG', 'ML', 'BA', 'FA'/
c
      OPEN (UNIT = 77, FILE = 'NBAL.OUT', STATUS = 'UNKNOWN')
      Update = .TRUE.
      POND = 0.0
10    ioutpt = .TRUE.
      Lbegin = .FALSE.
      OUT5OPEN = .FALSE.
      NSENS = 0
      NREP = 0
      NOUT0 = 40
      NOUT1 = 41
      NOUT2 = 42
      NOUT3 = 43
      NOUT4 = 44
      Nout5 = 45
      KOUTWA = 5
      KOUTGR = 5
      Koutnu = 5
      DRAINFILE = 'OUT7.MZ'
      CALCEVFILE = 'OUT6.MZ'
c
      INQUIRE (FILE = 'CROP.DAT', EXIST = FCROP)
      IF (FCROP) OPEN (UNIT = 2, FILE = 'CROP.DAT', STATUS = 'OLD')
      INQUIRE (FILE = 'BATCH.$$$', EXIST = filexist)
      IF (filexist) OPEN (5, FILE = 'BATCH.$$$', STATUS = 'OLD')
c
      OPEN (UNIT = NOUT0, FILE = 'SIM.DIR', STATUS = 'UNKNOWN')
      CALL Clear()
      write (6, 5000)
      READ (5, '(a1)') a
      if (a.eq.'y'.or.a.eq.'Y') then
         call clear
```

```
       open (unit=6,file='nul',status='old')
       write (*,*) " Program running, please wait, ......"
    endif
    IF (FCROP) THEN
       READ (2, *) NCROP
       IF (ncrop .EQ. 2.) THEN
          Ichoice = 5
       ELSE IF (ncrop .EQ. 5) THEN
          Ichoice = 1
       ELSE IF (ncrop .EQ. 6) THEN
          Ichoice = 4
       ELSE IF (ncrop .EQ. 10) THEN
          Ichoice = 3
       ELSE IF (ncrop .EQ. 12) THEN
          Ichoice = 2
       ELSE
          Ichoice = 7
       END IF
    END IF
    IF (.NOT. FCROP .OR. ICHOICE .EQ. 7) THEN
       DO WHILE (.TRUE.)
          CALL clear()
          write (6, 5010)
          READ (5, '(I2)') Ichoice
          CALL Selpro(1, 6, Ichoice, Index, Ierr)
          IF (Index .NE. 2) GOTO 20
       END DO
    END IF
20  Crop = Cropa(Ichoice)
    Runall = .FALSE.
30  Imulti = .FALSE.
    Runend = .FALSE.
    Imoutf = 1
    Iphout = .TRUE.
    Numy = 0
    Nrep = Nrep + 1
40  Iret = 0
    CALL Clear()
    CALL IPEXP()
    FileC = FileB
    WRITE (FileC(12:12), 5020)
    FileD = FileB
    WRITE (FileD(12:12), 5030)
    FFile1 = File1
    IF (Runend) GOTO 130
    Change = .FALSE.
    IF (nyr .GT. 1) THEN
       Imulti = .TRUE.
       write (6, 5040) nyr
    END IF
    IF (.NOT. Imulti) CALL Clear()
    IF (.NOT. runall) GOTO 180
    nsens = 0
50  IF (.NOT. Change) CALL IPTRT(update)
    IF (.NOT. Change) CALL IPSWIN()
    IF (Iswco2 .NE. 1) THEN
       IF (.NOT. Change) THEN
          TCHANGE = 0.
          Tchmin = 0.
          Rchange = 1.
          Schange = 1.
       END IF
    END IF
    IF (Nsens .NE. 2) GOTO 70
    CALL MENU(iret)
    Change = .TRUE.
    Ffile1 = File1
    IF (.NOT. Imulti) GOTO 70
60  DO WHILE (.TRUE.)
```

```
         write (6, 5050)
         IF (Imulti) write (6, 5060)
         write (6, 5070)
         READ (5, 5080, IOSTAT = ierr) NSENS
         CALL Selpro(0, 3, Nsens, Index, Ierr)
         IF (Index .NE. 2) THEN
            IF (Nsens .EQ. 0 .AND. Imulti) THEN
               Imulti = .FALSE.
               write (6, 5090)
            END IF
            IF (Nsens .EQ. 3) CALL ipmulti(iupdate)
            IF (NSENS .NE. 1) GOTO 50
            CALL IPFREQ()
         END IF
      END DO
      GOTO 50
70    IF (change) ffile1 = filelt
      IF (iret .EQ. 1) THEN
         CLOSE (11)
         GOTO 40
      END IF
      CALL IPWTH()
      IF (Runall) THEN
         Titler = ' '
      ELSE
         write (6, 5100)
         READ (5, 5110) TITLER
      END IF
      IF (TITLER .EQ. ' ') TITLER = TITLET
      ifirst = 1
      IF (Nrep .LE. 1) THEN
         ISWWT = 0
         write (6, '(A,/,2(28X,A,/))')
     1    '  ENTER WATER TABLE SWITCH: 0 = OFF', '1 = WT W/O CONTROL',
     2    '2 = CONTROLLED WT'
         READ (*, '(I1)') ISWWT
C     Open files to direct drain outputs from watbal and read water table depth:
         IF (ISWWT .GE. 1) THEN
            DECTRT = INT(NTRT/10) + 48
            UNTRT = NTRT - INT(NTRT/10)*10 + 48
            DECEXP = INT(NFEXP/10) + 48
            UNEXP = NFEXP - INT(NFEXP/10)*10 + 48
            WTFILE = 'WT'//CHAR(DECEXP)//CHAR(UNEXP)//CHAR(DECTRT)//CHAR
     1       (UNTRT)//'.MZO'
            OPEN (380, FILE = DRAINFILE, STATUS = 'UNKNOWN')
            OPEN (410, FILE = WTFILE, STATUS = 'UNKNOWN')
            RESP2 = 'N'
            WRITE (380, 5120) NREP, TITLER
            PRINT *
            write (6, '(A \)')
     1       ' WANT TO WRITE DAILY WATER TABLE RESULTS TO A  FILE? (Y/N)
     2 '
            READ (*, '(A1)') RESP2
            IF (RESP2 .EQ. 'Y' .OR. RESP2 .EQ. 'y') THEN
               OPEN (370, FILE = CALCEVFILE, STATUS = 'UNKNOWN')
               WRITE (370, 5120) NREP, TITLER
            END IF
         else
            cumdep = 0.0
            do i=1,nlayr
              cumdep = cumdep + dlayr(i)
            enddo
            depwt = cumdep
         END IF
         OPEN (UNIT = NOUT1, FILE = OUT1, STATUS = 'UNKNOWN')
         OPEN (UNIT = NOUT2, FILE = OUT2, STATUS = 'UNKNOWN')
         OPEN (UNIT = NOUT3, FILE = OUT3, STATUS = 'UNKNOWN')
         OPEN (UNIT = NOUT4, FILE = OUT4, STATUS = 'UNKNOWN')
         IF (OUT5 .NE. '      ') THEN
```

```
            OPEN (UNIT = NOUT5, FILE = OUT5, STATUS = 'UNKNOWN', RECL =
     1       270)
            OUT5OPEN = .TRUE.
         END IF
         WRITE (NOUT0, 5130) OUT1, OUT2, OUT3, OUT4, OUT5
      END IF
      IF (.NOT. OUT5OPEN .AND. OUT5 .NE. ' ') OPEN (UNIT = NOUT5, FILE
     1 = OUT5, STATUS = 'UNKNOWN', RECL = 270)
      INQUIRE (FILE = FileC, EXIST = filexist)
      IF (.NOT. filexist) FileC = '            '
      INQUIRE (FILE = FileD, EXIST = filexist)
      IF (.NOT. filexist) FileD = '            '
      WRITE (NOUT0, 5140) TITLER, FILEB, FILEC, FILED
      iechon = .TRUE.
      lrun = runall
      ihvon = .FALSE.
      IF (Lrun) ihvon = .TRUE.
      IF (Imulti) THEN
         IF (numy .NE. 0) iechon = .FALSE.
         ihvon = .FALSE.
         lrun = .TRUE.
      END IF
      IF (.NOT. lrun) THEN
         write (6, 5150)
         READ (5, 5160) iehvc
         IF (iehvc .EQ. 'Y' .OR. iehvc .EQ. 'y') ihvon = .TRUE.
      END IF
      DO WHILE (.TRUE.)
         READ (11,5280,IOSTAT=ifs0) IYR,DOY,SOLRAD,TEMPMX,TEMPMN,RAIN
         IF (ifs0 .LT. 0) GOTO 90
         IF (solrad.LE.0. .OR. rain.LT.0. .OR.
     1       tempmx.EQ.-99. .OR. tempmn.EQ.-99.)
     2   write (6, 5170) FFILE1, IYR, DOY, SOLRAD, TEMPMX, TEMPMN, RAIN
         IF (DOY .NE. Isim) GOTO 110
         Lbegin = .TRUE.
         TEMPMX = TEMPMX + TCHANGE
         TEMPMN = TEMPMN + TCHmin
         SOLRAD = SOLRAD*Schange
         RAIN = RAIN*Rchange
C***** zero out accumulators for multi-year run
         IF (imulti) THEN
            cet = 0.
            ntill = 1
            arunof = 0
            igsl = 0
            yield = 0.0
            biomas = 0.0
            abioms = 0.0
            gsrain = 0.0
            train = 0.0
            tlch = 0.0
            tnox = 0.0
            IF (numy .NE. 0) THEN
               CALL reinit()
               nrep = nrep + 1
            END IF
         END IF
         ifirst = 2
         if (update) then
           CALL PROGRI(update)
           CALL soltin()
           IF (ISWSWB .NE. 0) CALL SOILRI()
           IF (ISWNIT .NE. 0) THEN
              CALL SOILNI()
              CALL OMINIT(CEC)
              CALL NBAL(1)
           END IF
         else
           call progri(update)
```

```
      endif
      IF (Doy .EQ. Isim) BACKSPACE 11
      IF (numy .EQ. 0) THEN
         CALL echo(iechon)
         nline = 0
         IF (iphout) write (6, 5180)
      END IF
      IF (numy .EQ. 0 .AND. .NOT. iphout) THEN
         CALL Clear()
         IF (nline .EQ. 0) write (6, 5260)
         WRITE (nout1, 5260)
      END IF
80    continue
      READ (11,5280,IOSTAT=ifs1) IYR,DOY,SOLRAD,TEMPMX,TEMPMN,RAIN
      IF (ifs1 .EQ. 0) THEN
         IF ((solrad .LE. 0.0 .OR. rain .LT. 0.0 .OR. tempmx .EQ.
     1    -99.0 .OR. tempmn .EQ. -99.) .AND. iret .NE. 1) write (6,
     2    5170) FFILE1, IYR, DOY, SOLRAD, TEMPMX, TEMPMN, RAIN
         TEMPMX = TEMPMX + TCHANGE
         TEMPMN = TEMPMN + TCHmin
         SOLRAD = SOLRAD*Schange
         RAIN = RAIN*Rchange
         Tempm = (Tempmx + Tempmn)*0.5
         CALL mulche()                              !CERES-Till
         CALL solt()                                !CERES-Till
         IF (DOYX .EQ. 367) CALL CALDAT()
         IF (ISWSWB .NE. 0) CALL WATBAL(ISWWT)
         IF (ISWNIT .NE. 0) THEN
            CALL OMCYCLE(TCO2)
            CALL NTRANS()
         END IF
         IF ((DOY .gt. ISOW-5.and.doy.le.isow+20) .OR. ISTAGE .NE. 7)
     1        CALL PHENOL(iret, CUMDELAY,ratio)
         IF (ISTAGE .LT. 6 .AND. CROP .EQ. 'MZ') THEN
            CALL GROSUB(CUMDELAY,ratio)
         ELSE IF (ISTAGE .LT. 6 .AND. CROP .EQ. 'WH') THEN
            CALL WGROSUB()
         ELSE IF (ISTAGE .LT. 6 .AND. CROP .EQ. 'SG') THEN
            CALL SGROSUB()
         ELSE IF (ISTAGE .LT. 6 .AND. CROP .EQ. 'ML') THEN
            CALL MGROSUB()
         ELSE IF (ISTAGE .LT. 6 .AND. CROP .EQ. 'BA') THEN
            CALL WGROSUB()
         END IF
         Train = Train + Rain
         IF (istage.ge.3.and.Istage .Le. 6) THEN
             Igsl = Igsl + 1
             Gsrain = Gsrain + Rain
         END IF
         IF (iret .EQ. 1 .AND. EOF(11)) GOTO 100
         IF (ISWNIT .NE. 0) CALL NWRITE()
         CALL WRITE()
         GOTO 80
      END IF
90    IF (iret .EQ. 1) GOTO 100
      READ (FFile1(11:12), 5190) Kyr
      Kyr = Kyr + 1
      IF (Kyr .GT. 99) Kyr = 10
      WRITE (FFile1(11:12), 5190) Kyr
      INQUIRE (FILE = FFile1, EXIST = filexist)
      IF (filexist) THEN
         OPEN (11, FILE = FFile1)
         READ (11, 5200) LAT, XLONG, PARFAC, PARDAT
         IF (LBEGIN) GOTO 80
         GOTO 110
      END IF
C
      WRITE (nout1, 5290)
      write (6, 5290)
```

```
100      Lbegin = .FALSE.
         IF (OUT5 .NE. ' ') CALL FOUT5()
         IF (ISWNIT .NE. 0) CALL NBAL(3)
         IF (.NOT. imulti) GOTO 140
         numy = numy + 1
         nline = nline + 1
         CALL Phasei(CUMDELAY)
         Iret = 0
         Store(1, numy) = yield
         Store(2, numy) = biomas*10.
         Store(3, numy) = abioms*10.
         Store(4, numy) = totnup
         Store(5, numy) = Tlch + Tnox
         Store(6, numy) = Igsl
         Store(7, numy) = gsrain
         STore(8, numy) = Si1(1)
         Store(9, numy) = Si1(5)
         Store(10, numy) = Si3(1)
         Store(11, numy) = Si3(5)
         Store(12, numy) = numy
         IF (nline .GE. 22) nline = 0
         IF (.NOT. iphout) THEN
            IF (nline .EQ. 0) write (6, 5260)
            write (6, 5270) numy, (Store(j, numy), j = 1, 12)
         END IF
         IF (Float(Ny/15) .EQ. 15 .AND. .NOT. iphout) THEN
            CALL Clear()
            write (6, 5220)
            READ (5, '(a1)') a
         END IF
         IF (numy .EQ. nyr) GOTO 120
110      CONTINUE
      END DO
120   CALL Psort(Store, 12, Numy)
      CALL Clear()
      write (6, 5210)
      WRITE (nout1, 5210)
      write (6, 5260)
      WRITE (Nout1, 5260)
      DO ny = 1, numy
         write (6, 5270) ny, (store(j, ny), j = 1, 12)
         IF (Float(Ny/15) .EQ. 15) THEN
            CALL Clear()
            write (6, 5260)
            write (6, 5220)
            READ (5, '(a1)') a
         END IF
         WRITE (Nout1, 5270) ny, (store(j, ny), j = 1, 12)
      END DO
      write (6, 5220)
      READ (5, '(a1)') a
      GOTO 140
130   Nrep = Nrep - 1
140   DO WHILE (.NOT. Runall)
         IF (FCROP) THEN
            write (6, 5240)
         ELSE
            write (6, 5230)
         END IF
         READ (5, '(i2)', IOSTAT = ierr) igo
         CALL selpro(0, 4, igo, index, ierr)
         IF (index .EQ. 2) GOTO 160
         IF (igo .EQ. 0) igo = 1
         IF (FCROP .AND. IGO .EQ. 3) IGO = 4
         IF (igo .NE. 2) GOTO 150
         IF (Imulti) THEN
            write (6, 5250)
         ELSE IF (Runend) THEN
            write (6, 5300)
```

```
         ELSE
            CALL disout()
         END IF
      END DO
      GOTO 160
150   CONTINUE
      IF (igo .EQ. 4) GOTO 190
      write (6,*) ' Do You want to reset soil parameter (Default, y)'
      read (*,'(a1)') ans
      ntill = 1
      if ((ans.eq.'n'.or.ans.eq.'N').or.(imulti.and.iupdate.eq.2)) then
         update= .false.
      else
         update=.true.
      endif
      IF (igo .EQ. 3) GOTO 170
160   CLOSE (11)
      GOTO 30
170   CLOSE (11)
      GOTO 10
180   filelt = ffile1
      GOTO 60
190   ENDFILE (NOUT0)
      ENDFILE (NOUT1)
      ENDFILE (NOUT2)
      ENDFILE (NOUT3)
      ENDFILE (NOUT4)
      IF (OUT5 .NE. ' ') ENDFILE (NOUT5)
      CLOSE (NOUT0)
      CLOSE (NOUT1)
      CLOSE (NOUT2)
      CLOSE (NOUT3)
      CLOSE (NOUT4)
      IF (OUT5 .NE. ' ') CLOSE (NOUT5)
      CLOSE (24)
      STOP
C
5000  FORMAT (///, 20x, 'Welcome to the C E R E S Model Version 1.99',
     1 //, 20x,
     2 'Incorporates  new  menu structure, includes soil stresses', /,
     3 20x, '(water, nitrogen and oxygen), and surface residue        '
     4 , /, 20x,
     5 'supports  multi-year  and   multi-treatment                ', /,
     6 20x, 'simulation and also provides output support              '
     7 , /, 20x, '       for IBSNAT graphics and DSSAT', /
     7 , /, 20x, ' To turn screen OFF press Y',/////,
     8 ' Press Enter to Continue')
5010  FORMAT (///,
     1 '  Which of the following models do you want to run :', //, 20x,
     2 '  1.        Maize  ', /, 20x, '  2.        Wheat  ', /, 20x,
     3 '  3.        Sorghum ', /, 20x, '  4.        Millet  ', /, 20x,
     4 '  5.        Barley ', /, 20x, '  6.        Fallow ', //////,
     5 '  Please enter your choice:')
5020  FORMAT ('C')
5030  FORMAT ('D')
5040  FORMAT (' Multiple Year Run ', i5, ' Years')
5050  FORMAT (/, 2X, 'RUN-TIME OPTIONS: ', //2X, '0)   RUN SIMULATION '
     1 , /2X, '1)   SELECT SIMULATION OUTPUT FREQUENCY'/2x,
     2 '2)   MODIFY SELECTED MODEL VARIABLES INTERACTIVELY.'//)
5060  FORMAT (2X, '3)   RUN MULTI-YEAR SIMULATION')
5070  FORMAT (//2X, '<=== CHOICE? [ DEFAULT = 0 ]')
5080  FORMAT (I2)
5090  FORMAT (' Single season simulation only')
5100  FORMAT (/, T21, '<=== ENTER UP TO HERE RUN IDENTIFIER, ',
     1 '<cr> FOR NONE.')
5110  FORMAT (A20)
5120  FORMAT (1X, 'RUN  ', I2, 8X, A20)
5130  FORMAT (1X, 4(A7, ','), A7)
5140  FORMAT (1X, A20, 21X, A12, 1X, A12, 1X, A12)
```

```
5150  FORMAT (' Do you want post harvest comparison with observed data'
     1 , /, '  displayed on the screen (Y/N) ? ')
5160  FORMAT (a)
5170  FORMAT (2x, ' Please correct your weather file - ', A12, '.', /,
     1 2x, 'Missing solar radiation, temperature or rainfall data.', /
     2 /, 2X,
     3 'Year   Day   Solar Rad.   Max. Temp.   Min. Temp.   Rain', /,
     4 3x, i2, 4x, i3, 6x, f5.2, 2(8x, f5.1), 4x, f5.1, //, 2x,
     5 ' <Ctrl> <Break> to change missing values. ')
5180  FORMAT (/, 15X, 'SIMULATION HAS BEGUN....PLEASE WAIT.'/10X,
     1 'DON''T TOUCH THE TERMINAL UNTIL IT PROMPTS YOU.')
5190  FORMAT (I2.2)
5200  FORMAT (4X, 2(1X, F6.2), 2(1X, F5.2))
5210  FORMAT (' Simulation Outputs sorted according to yield')
5220  FORMAT (' Press Enter to Continue')
5230  FORMAT (' Simulation complete for this treatment.', /,
     1 ' Do you want to :', /,
     2 ' 1  Return to Experiment and Treatment Menu', /,
     3 ' 2  Display Detailed Outputs on Screen', /,
     4 ' 3  Choose another crop', /, ' 4  Quit', //,
     5 '    Input a number (default is 1)')
5240  FORMAT (' Simulation complete for this treatment.', /,
     1 ' Do you want to :', /,
     2 ' 1  Return to Experiment and Treatment Menu', /,
     3 ' 2  Display Detailed Outputs on Screen', /, ' 3  Quit', //,
     4 '    Input a number (default is 1)')
5250  FORMAT (' Option not available under Multiple Year Setting')
5260  FORMAT (2x, '#', 3X, 'GRAIN', 2X, 'MATURE', 2X, 'ANTHES', 5X, 'N'
     1 , 5X, 'N', 2X, 'E-M', 3X, 'E-M', 2(3X, 'WAT'), 2(3X, 'NIT'), 1X,
     2 'YR', /, 6X, 'YIELD', 2(1X, 'BIOMASS'), 1X, 'UPTAKE', 2X, 'LOSS'
     3 , 1X, 'DAYS', 2X, 'RAIN', 2(1X, 'STRS1', 1x, 'STRS5'))
5270  FORMAT (1x, i2, 3f8.0, 2f6.0, f5.0, f6.0, 4f6.1, 1x, f3.0)
5280  FORMAT (5x, i2, 1x, i3, f6.2, 2(1x, f5.1), 1x, f5.1, 1x, f6.2)
5290  FORMAT (6X, 'END OF WEATHER DATA')
5300  FORMAT (' Option not available under Multi-Treatment Setting')
      END



    CALEO - Subroutine to calculate potential ET
      Subroutine CALEO

      INCLUDE 'GEN2.BLK'
      INCLUDE 'GEN3.BLK'
      INCLUDE 'GEN4.BLK'
      INCLUDE 'NTRC2.BLK'
      include 'Till.blk'
      include 'Nwatbal.blk'
c
      real mulchalb
      data iidoy /0/
C
      TD = 0.60*TEMPMX+0.40*TEMPMN
c calculation of albedo
      CANCOV = 1 - EXP(-0.75*LAI)
      mulchalb = 0.3
      IF (ISTAGE .LE. 6) THEN
         IF (ISTAGE .GE. 5) THEN
           ALBEDO=0.23+(LAI-4)**2/160
         ELSE
           albedo=cancov*0.23+mulchcov*(1-cancov)*mulchalb+
     &             (1-mulchcov)*(1-cancov)*salb
         END IF
      ELSE
         albedo=(1-mulchcov)*salb+mulchcov*mulchalb
      END IF
*     EEQ is in MJ/day -- AG
      EEQ = SOLRAD*(4.88E-4 - 4.37E-4 * ALBEDO) * (TD + 29.0)
```

```
      IF (TEMPMX.GT.35.) THEN
         EO = EEQ*((TEMPMX-35.)*0.05+1.1)
       ELSE IF (TEMPMX.LT.5.0) THEN
         EO = EEQ*0.01*EXP(0.18*(TEMPMX+20.))
       ELSE
         EO = EEQ*1.1
      END IF
c  Reducing factor due to canopy
      IF (LAI.GT.1.) THEN
         Ec = EXP(-0.4*LAI)/1.1
      ELSE
         Ec = (1.-0.43*LAI)
      END IF
c  Reducing factor due to mulch
       Rm = 1 - 0.807*mulchcov
       xmass = mulch
       Athick = 1.5
       surf = 1
       Rm = min(exp(-0.5*mulchthick),1-0.807*mulchcov)
c  Corrected soil potential evaporation.  Rm is used only on the water that is not ponding
c  and not held in the residues so that they will dry
      if ((mulchsw-0.01+pond).gt.Eo*Ec) then
         Eos = Ec*Eo
      else
         Eos = (Eo*Ec - (mulchsw-0.01+pond))*Rm +  (mulchsw -0.01+pond)
      endif
      RETURN
      END



      Subroutine DYNTILL(wat,time)
c
c  Dynamic changes of soil properties with tillage events and rainstorms
c  Tillage events reset values to default depending on Tillage type
c  Rainfall affect parameters depending on intensity
      real rstl,time,kechge,xbd(4),xpondmax,xksmacro(4)
      Include 'till.blk'
      Include 'gen1.blk'
      Include 'gen3.blk'
      Include 'gen4.blk'
      Include 'ntrc2.blk'
      Include 'Nwatbal.blk'
c  Initialize surface properties after tillage
      if (doy.eq.isim) then
        xpondmax = pondmax
        do l=1,4
          xbd(l) = bd(l)
          xksmacro(l) = ksmacro(l)
          sumke(l) = 0
        enddo
      endif
      if (doy.eq.doytill(ntill)) then
        l = 1
        depth = 0.0
        do while(depth.le.deptill(ntill))
          Xksmacro(l) = tillconsat(ntill)
          ksmacro(l) = Xksmacro(l)
          if (ksmacro(l).lt.ksmtrx(l)) then
            ksmacro(l) = ksmtrx(l)
            xksmacro(l) = ksmtrx(l)
          endif
          xbd(l) = tillbd(ntill,l)
          bd(l) = xbd(l)
          depth = depth + dlayr(l)
          sumke(l) = 0
          l = l+1
        enddo
```

```
          Xpondmax = tillpond(ntill)
          pondmax = Xpondmax
        endif
c  Cumulative counter for rainfall intensity
        if (wat.gt.0.0) then
          cancov = 1 - exp(-.75*lai)
          soilcov = cancov + mulchcov*(1-cancov)
          rainint = (3.812+0.812*log10(wat*.01/(time*24)))*wat*.01
c  Surface Bulk density
          depth = 0
          do l=1,4
            depth = depth + dlayr(l)/2
            As = 0.205*OC(l)
            Rstl = 5. * (1 - As)
            sumke(l) = sumke(l) + (1-soilcov)*exp(- .15*depth)*rainint
            Kechge = exp(-Rstl*sumke(l))
            bd(l) = stlbd(l)+(Xbd(l)-stlbd(l))*kechge
            ksmacro(l) = ksmtrx(l)+(Xksmacro(l)-ksmtrx(l))*kechge
            sat(l) = 0.85*(1 - bd(l)/2.66)
            if (sw(l).gt.sat(l)) then
              pond = pond + (sw(l) - sat(l))*dlayr(l)
              sw(l) = sat(l)
            endif
c  Surface conductivity and ponding capacity equations
            if (l.eq.1) then
              pondmax = stlpond+(Xpondmax-stlpond)*kechge
              if (pond.gt.pondmax) then
                runoff = runoff + pond - pondmax
                pond = pondmax
              endif
            endif
            depth = depth + dlayr(l)/2
          enddo
        endif
        return
        end



        Subroutine IPNIT(update)
C          This module will first read variables from File4 and
C       check for existing treatment number choice and issue the
C       appropriate message.  Secondly, the variables from File7
C       will be read and echoed, giving the user an option to
C       change Fday, AFERT, DFERT or IFTYPE.
C
        INCLUDE 'Comibs.Blk'
        INCLUDE 'Ntrc2.Blk'
        INCLUDE 'Ntrc1.Blk'
        INCLUDE 'GEN1.blk'
        INCLUDE 'GEN3.blk'
        INCLUDE 'till.blk'
        Logical out,update
        INTEGER ifs0, ifs1, ifs2, ifs3
        INTEGER Trtno, dout
        REAL defpond(13), defdep(13), defbd(13), defconsat(13)
        CHARACTER*1 Ans
        CHARACTER*2 Yr
        DATA defpond/2, 2, 2, 2, 1, 1, 1, 1, 1, 1, 1, 1, 1/
        DATA defdep/30, 15, 15, 15, 15, 15, 15, 10, 10, 5, 5, 5, 5/
        DATA defbd/1.2, 1.2, 1.2, 1.2, 1.2, 1.2, 1.2, 1.2, 1.2, 1.2, 1.2,1.2, 1.2/
        DATA defconsat/10, 10, 10, 10, 10, 10, 10, 10, 10, 10, 10, 10, 10/
C        FILE4 SECTION
        TrtNo = 0
        Ierror = 0
        OPEN (32, FILE = File4, STATUS = 'Old')
        DO while (trtNo.ne.NTRT)
           READ (32, 5050, IOSTAT = ifs0) Insts, Sites, Yr, Exptno,
```

```
     1    Trtno, rMulch, rScn, rRoot, Am
          IF (ifs0 .LT. 0) then
             GOTO 30
          elseIF (ifs0 .GT. 0) then
             Ierror = 1
             GOTO 30
          endif
          if (trtno.ne.ntrt) then
            dout = 0
            dowhile (dout.ne.-1)
              read (32,5000) dout
            enddo
          endif
       END DO
       i = 0
       out=.false.
       DO WHILE (.not. out)
          i = i + 1
          READ (32, 5000) doytill(i), codtill(i), deptill(i), fractill
     1     (i), tillpond(i), tillconsat(i), (tillbd(i, j), j = 1, 4)
          IF (doytill(i) .NE. -1) THEN
             DO WHILE (codtill(i) .LE. 0 .OR. codtill(i) .GT. 13)
                write (6, *)
     1           ' ERROR IN TILLAGE CODE FILE 4, Please correct'
                write (6, *) ' Enter new value and correct file later'
                READ (*, '(i2)') codtill(i)
             END DO
             IF (tillpond(i) .EQ. 0) tillpond(i)  = defpond(codtill(i))
             IF (tillconsat(i).EQ.0) tillconsat(i)= defconsat(codtill(i))
             IF (deptill(i).eq.0)    deptill(i)   = defdep(codtill(i))
             DO j = 1,4
               IF (tillbd(i,j) .EQ. 0) tillbd(i,j) = defbd(codtill(i))
             END DO
          else
             out = .true.
          END IF
       END DO
       sumke = 0
       IF (stlxks .EQ. 0) stlxks = 0.1
       IF (stlpond .EQ. 0) stlpond = 0.01
       IF (stlbd(j) .EQ. 0) stlbd = 1.4
       ntill = 1
       if (update) then
         scn = rscn
         root = rroot
         mulch = rmulch
         d1 =  - 0.1395*alog(scn) + 0.8664
         kl = 2.96
         kr = 0.035*d1 - 0.0013
         mulchr = mulchr + mulch*(1 - d1)
         mulchl = mulchl + mulch*(d1)
       endif
       pondmax = stlpond
30     IF (TrtNo .EQ. Ntrt) THEN
          DO WHILE (straw .LT. 0.0 .OR. sdep .LT. 0.0 .OR. scn .LE. 0.0
     1     .OR. root .LE. 0.)
            write (6, 5010) FILE4
            READ (5, 5020) ANS
            IF (.NOT. (ANS .EQ. 'Y' .OR. ANS .EQ. 'y')) GOTO 40
            CALL menu4()
          END DO
          GOTO 50
40        IF (straw .LT. 0.) Straw = 800.
          IF (sdep .LT. 0.) Sdep = 30.
          IF (scn .LE. 0.) Scn = 75.
          IF (root .EQ. 0.) root = 500.
50        CLOSE (32)
C      FILE7 SECTION
          TrtNo = 0
```

```
         OPEN (33, FILE = File7, STATUS = 'Old')
         DO K = 1, 10000
            DO WHILE (.TRUE.)
               READ (33, 5060, IOSTAT = ifs1) TrtNo, Inste, Sitee, Yr,
     1          ExptNo
               IF (ifs1 .LT. 0) GOTO 100
               IF (ifs1 .GT. 0) GOTO 90
               IF (TrtNo .EQ. Ntrt) GOTO 70
               DO M = 1, 10000
                  READ (33, 5070, IOSTAT = ifs3) Mday
                  IF (ifs3 .LT. 0) GOTO 100
                  IF (ifs3 .GT. 0) GOTO 90
                  IF (Mday .LT. 0) GOTO 60
               END DO
               GOTO 80
60             CONTINUE
            END DO
70          DO J = 1, 10000
               READ (33, 5070, IOSTAT = ifs2) Fday(J), Afert(J), Dfert
     1          (J), Iftype(J)
               IF (ifs2 .LT. 0) GOTO 100
               IF (ifs2 .GT. 0) GOTO 90
               IF (Fday(J) .LT. 0) GOTO 100
               IF (Iftype(J) .EQ. 17) Iftype(J) = 12
               IF (Crop .EQ. 'BA') THEN
                  IF (Dfert(J) .EQ. 0.0) Dfert(J) = 0.1
               END IF
            END DO
80          CONTINUE
         END DO
90       Ierror = 1
         TrtNo =  - 99
100      IF (TrtNo .EQ. Ntrt) THEN
            J = J - 1
            Nfert = J
            DO WHILE (.TRUE.)
               Icount = 0
               DO K = 1, Nfert
                  IF (Afert(K) .LT. 0.0) Icount = Icount + 1
                  IF ((Afert(K) .NE. 0.0) .AND. (Dfert(K) .LE. 0.0))
     1             Icount = Icount + 1
               END DO
               IF (Icount .LE. 0) GOTO 110
               write (6, 5030) File7
               READ (5, 5040) ANS
               IF (.NOT. (ANS .EQ. 'Y' .OR. ANS .EQ. 'y')) GOTO 120
               CALL menu(iret)
            END DO
110         CLOSE (33)
            RETURN
120         CLOSE (11)
            CLOSE (33)
         ELSE IF (Ierror .EQ. 1) THEN
            write (6, 5130) File7
            CLOSE (11)
         ELSE
            write (6, 5080) Ntrt, File7
            CLOSE (11)
         END IF
      ELSE IF (Ierror .EQ. 1) THEN
         write (6, 5130) File4
         CLOSE (32)
         CLOSE (11)
      ELSE
         write (6, 5080) Ntrt, File4
         CLOSE (32)
         CLOSE (11)
      END IF
      STOP
```

```
C
5000  FORMAT (5x, i3, 3(1x, i3), 7(2x, f5.2))
5010  FORMAT (/, ' Error! MISSING VALUES OR VALUES OUT OF RANGE IN: ',
     1 A12, /, 10x, 'DEFAULT VALUES WILL BE USED BY THE MODEL Unless ',
     2 /, '  you type Y to correct crop residue parameters ', /,
     3 '  interactively for this run : ')
5020  FORMAT (1a)
5030  FORMAT (/, ' Error! Missing values found in ', A12, '.', /, /,
     1 ' Type Y to correct it interactively for this run', /,
     2 ' Or program will stop to allow modification  : ')
5040  FORMAT (1a)
5050  FORMAT (4(a2),1x,I2, 3(1x, F5.0),1X,F7.5)
5060  FORMAT (I2, 1x, 3(A2), a2)
5070  FORMAT (I4, 2(1x, F5.1), 1x, I2)
5080  FORMAT (3x, '***** TREATMENT NO. ', I2, ' MISSING IN FILE ', A,
     1 '   ', /, ' Program will stop and allow modification of file.')
5090  FORMAT (A1)
5100  FORMAT (///, 15x,
     1 'FERTILIZER APPLICATION DATA FOR TREATMENT NO. ', I2, ' ')
5110  FORMAT (/, 20x, 'DAY', 5X, 'AMOUNT', 5X, 'DEPTH', 5X, 'TYPE', /,
     1 20X, '---', 5X, '------', 5X, '-----', 5X, '----')
5120  FORMAT (20x, I3, 6x, F5.0, 5x, F5.0, 6x, I2)
5130  FORMAT (3x, '**** READ ERROR ENCOUNTERED ON INPUT FILE ', A,
     1 '   ', /, 3x,
     2 'Program will stop to allow checking of File Formats.')
      END


      Subroutine IPSOIL
c     Soil Selection
      INTEGER ifs0
      INCLUDE 'comibs.blk'
      INCLUDE 'GEN1.blk'
      INCLUDE 'GEN3.blk'
      INCLUDE 'ntrc1.blk'
      INCLUDE 'ntrc2.blk'
      INCLUDE 'NWATBAL.BLK'
      INCLUDE 'till.blk'

      DO WHILE (.TRUE.)
         OPEN (12, FILE = FILE2, STATUS = 'OLD')
         DO WHILE (.TRUE.)
            READ (12, 5000, IOSTAT = ifs0) IDUMSL, PEDON, TAXON
            IF (ifs0 .LT. 0) GOTO 20
            READ (12, 5010) SALB, U, CN2, TAV, AMP, DMOD, SWCON1,
     1       swcon2, swcon3, RWUMX, PHFAC3, stlpond
            J = 0
            cumdep = 0.0
            DO WHILE (.NOT. (J .EQ. 20 .AND. idumsl .EQ. isoilt))
               J = J + 1
               READ (12, 5030) DLAYR(J), LL(J), DUL(J), SAT(J), SWINIT
     1          (J), WR(J), stlBD(J), OC(J), Dnh4(j), Dno3(j), PH(J),
     2          KSMACRO(j), sand(j), rok(j), KSMTRX(J), rwucon(j)
               IF (SAT(J) .LE. DUL(J)) SAT(J) = DUL(J) + 0.001
               cumdep = cumdep + dlayr(j)
               IF (DLAYR(J) .LE. 0.0) GOTO 10
               BD(J) = STLBD(J)
            END DO
            IF (Dlayr(J) .NE. -1.0) THEN
               J = 21
               write (6, 5020)
            END IF
10          NLAYR = J - 1
            depmax = cumdep + 1
            IF (IDUMSL .EQ. ISOILT) GOTO 40
         END DO
20       write (6, 5040) ISOILT, FILE2
```

```
          READ (5, 5050) ANS
          IF (.NOT. (ans .EQ. 'Y' .OR. ans .EQ. 'y')) GOTO 30
          CLOSE (12)
          CALL menu2()
          DSFILE =  - 1
       END DO
30     CLOSE (12)
       CLOSE (11)
       STOP
40     CLOSE (12)
       RETURN
5000   FORMAT (1X, I2, 1X, A12, 1X, A60)
5010   FORMAT (F6.2, 1x, F5.2, 7x, (1x, F6.2), 2(1x, F5.1), 1x, F3.1,
      1 1x, E9.2, 1x, F6.1, 2(1x, F5.2), 1x, F4.2, 2(1x, f5.2))
5020   FORMAT (
      1 '  Maximum number of 20 soil layers needed by model have  been re
      2ached.'
      3 , /, '   Modification of File 2 may be required.')
5030   FORMAT (1x, F5.0, 5(1x, F6.3), 2(1x, F5.2), 4(f5.1), 2(1X, F5.2),
      1 1X, F5.1, 1x, f5.2)
5040   FORMAT (/, ' Error! SOIL NO ', I3, ' NOT FOUND IN FILE :', A12,
      1 /T8, 'Type Y to correct file interactively for this run', /T8,
      2 'Or program will stop to allow modification : ')
5050   FORMAT (1a)
       END



       Subroutine MULCHE
C
       Include 'GEN1.blk'
       Include 'GEN3.blk'
       Include 'GEN4.blk'
       Include 'till.blk'
       Include 'ntrc2.blk'
       Include 'Nwatbal.blk'
       logical tilltime
       REAL *4 td,tempfac,mdecomp,watfac
c  Add residues to the soil when tillage occurs
       mulchsat = 3.85e-5*mulch
       IF (DOY.EQ.DOYTILL(ntill)) then
         if (tilltime()) then
           call omupdate(.true.,mdecomp)
           call dyntill (0.0,0.0)
           mdecomp = 0.0
           pmulchl = mulchl
           pmulchr = mulchr
           mulch = mulchr + mulchl
           ntill = ntill + 1
         else
           doytill(ntill) = doytill(ntill) + 1
         endif
       ENDIF
C TEMPERATURE FACTOR FOR DECOMPOSITION
       TD = 0.60*TEMPMX + 0.40*TEMPMN
       if (td.lt.0) then
           tempfac = 0.0
       elseif (td.lt.20) then
           tempfac = 0.05 * TD
       elseif (td.lt.35) then
           tempfac = 1.0
       elseif (td.lt.60) then
           tempfac = 2.4 - 0.04*TD
       else
           tempfac = 0.0
       endif
C      MOISTURE FACTOR FOR DECOMPOSITION
        if (mulchsw.gt.0.01.and.mulchsat.gt.0.01) then
```

```
          watfac = 1 - alog(mulchsw/mulchsat)/alog(0.01/mulchsat)
        else
          watfac = 0.01
        endif
C  MULCH DECOMPOSITION
      pmulchr = mulchr
      pmulchl = mulchl
      mulchr = pmulchr*exp(-0.0053 *amin1(tempfac,watfac))
      mulchl = pmulchl*exp(-.296*amin1(tempfac,watfac))
      IF (MULCHR.LT.0.5) MULCHR = 0.0
      IF (MULCHL.LT.0.5) MULCHL = 0.0
      mulch = mulchr + mulchl
C  FERTILISATION from mulch occurs when rain flushes down OM (begining of day)
      IF (rain .NE. 0.0) THEN
         call omupdate(.false.,mdecomp)
         MDECOMP = 0.0
      ENDIF
      MDECOMP = MDECOMP + pmulchr + pmulchl - MULCH
c  Mulch residue cover and thickness
      mulchcov = 1 - exp(-Am *mulch)
      mulchsat = 3.85e-5*mulch
      Mulchthick = 0
      Athick = 1.5
      do while (surf.gt.0.01)
         xmass = xmass - surf/Am
         surf = surf*(1-exp(-Am*xmass/surf))
         Mulchthick = Mulchthick + surf*Athick
      enddo
      RETURN
      END



      Subroutine OMINIT(CEC)
c
c  Subroutine to initialize soil organic matter pools
c  and decay constants
c
      Include 'OMATTER.BLK'
      Include 'GEN3.BLK'
      Include 'NTRC2.BLK'
      Real Cec(*),Wrn(21),Ligmul
c Rate constant and initial c/n ratio
       data rate /.027,.00082,.0018,.00055,0.0/
       data (somcn(i),i=2,5) /150,8.5,10,10/
       data Porghum /0.54/
       data Ligmul /0.1/
c    Distribute root residue across depths and into FOM and FON pools, shoot residues are distributed
c    at time of tillage in OMUPDAT
      RNKG=ROOT*0.01
      WSUM=0.0
      DEPTH=0.0
      DO 200 L=1,NLAYR
           DEPTH=DEPTH+DLAYR (L)
           WRN(L)=EXP(-3.0*DEPTH/DEPMAX)
           WSUM=WSUM+WRN(L)
 200  CONTINUE
      DO 300 L=1,NLAYR
           FOM(L)=ROOT*WRN(L)/WSUM
           FON(L)=RNKG*WRN(L)/WSUM
  300 CONTINUE
      Do 700 l=1,Nlayr
           TOTC=OC(L)*1.E03*BD(L)*DLAYR(L)
           Ligf=fom(l)*0.4*ligmul
           presd=0.85-0.018*ligf/fon(l)
           soc(l,1)=fom(l)*presd*0.40
           soc(l,2)=fom(l)*0.4-soc(l,1)
           soc(l,3)=0.03*Totc
```

```
          soc(l,4)=0.67*Totc
          soc(l,5)=Totc-soc(l,3)-soc(l,4)
          son(l,3)=soc(l,3)/somcn(3)
          son(l,4)=soc(l,4)/somcn(4)
          son(l,5)=soc(l,5)/somcn(5)
          son(l,2)=soc(l,2)/somcn(2)
          son(l,1)=fon(l)-son(l,2)
          somcn(1)=soc(l,1)/son(l,1)
          ybiocn(l)=somcn(3)
          Pcorg=(29.0+0.1*CEC(l))/100
700   CONTINUE
      Return
      End



      Subroutine OMupdate(till,mferti)
c
c     Subroutine to update soil Organic matter at time ot tillage
c     and when the solutes from the surface residue decomposes are flushed in the profile
      Include 'OMATTER.BLK'
      Include 'GEN3.BLK'
      Include 'NTRC2.BLK'
      Include 'till.blk'
      Real Ligmul,add(21),mferti
      logical till
       data rate /.027,.00082,.0018,.00055,0.0/
       data (somcn(i),i=2,5) /150,8.5,10,10/
       data Porghum /0.54/
       data Ligmul /0.1/
c     Distribute shoot residue across depths and into FOM and FON pools
      IF (TILL) THEN
        STRAW = MULCH*fractill(ntill)*0.01
        SNKG=STRAW*SCN*0.01
        MULCHl = MULCHl*(1 - fractill(ntill)*0.01)
        MULCHr = MULCHr*(1 - fractill(ntill)*0.01)
        sdep = deptill(ntill)
        DEPTH=0.0
        IOUT=1
        i = 1
        DO WHILE (STRAW.GT.0.0.AND.I.le.NLAYR.and.IOUT.eq.1)
          HOLD=DEPTH
          DEPTH=DEPTH+DLAYR(I)
          IF (SDEP.LE.DEPTH) THEN
             FR=(SDEP-HOLD)/SDEP
             IF(I.EQ.1) FR=1
             IOUT=2
          ELSE
             FR=DLAYR(I)/SDEP
          ENDIF
          ADD(I)=STRAW*FR
          FOM(I)=FOM(I)+ADD(I)
          FON(I)=FON(I)+ADD(I)*0.40/SCN
          i = i + 1
        ENDDO
      ENDIF
      Do 700 l=1,Nlayr
        TOTC=OC(L)*1.E03*BD(L)*DLAYR(L)
        Ligf=fom(l)*0.4*ligmul
        presd=0.85-0.018*ligf/fon(l)
        if (l.eq.1.and.mferti.ne.0.0) then
          soc(l,1)=soc(l,1) + 2/7*mferti*presd*0.40
          soc(l,2)=soc(l,2) + 2/7*mferti*0.4*(1-presd)
          FOM(1)=FOM(1)+2/7*mferti
          FON(1)=FON(1)+2/7*mferti*0.40/SCN
        elseif (l.eq.2.and.mferti.ne.0.0) then
          soc(l,1)=soc(l,1) + 5/7*mferti*presd*0.40
          soc(l,2)=soc(l,2) + 5/7*mferti*0.4*(1-presd)
```

```
        FON(2)=FON(2)+5/7*mferti
        FON(2)=FON(2)+5/7*mferti*0.40/SCN
      endif
      soc(l,1)=soc(l,1) + add(l)*presd*0.40
      soc(l,2)=soc(l,2) + add(l)*0.4*(1-presd)
      add(l) = 0.0
      son(l,2)=soc(l,2)/somcn(2)
      son(l,1)=fon(l)-son(l,2)
      somcn(1)=soc(l,1)/son(l,1)
      ybiocn(l)=somcn(3)
700     CONTINUE
      do l=1,nlayr
        add(l) = 0.0
      enddo
    Return
    End



    Subroutine PONDING (PINF,RUNOFF)

c   PONDING - Program to determine ponding based on rainfall intensity and  a function for hydraulic
       conductivity.  In the context of the model it calculates the daily amounts of infiltration
       runoff and chances to the height of the ponded water
c   Created by:   J.T. Ritchie, I. White, and B. Baer  Febuary 1991
c   Modified by:  A. Gerakis and B. Baer              June 1991

    Include 'till.blk'
    Include 'gen3.blk'
    Include 'gen1.blk'
    Include 'Ntrc2.blk'
    Include 'Nwatbal.blk'
    INTEGER  J,NUMSTEPS
    REAL     PINF,INFILT,HOUR,MAXRAIN,RUNOFF,
   3         PIP,RAINDUR,TIME,TIMESTEP,TPAMT,PPRECIP,TRUNOFF

    PARAMETER (HOUR = 1.0 / 24.0)
    NUMSTEPS = 10
    TIME=0.0
C   Create rainstorm triangle.  Base = Length of the storm, Height = Maximum rain rate (cm/day).  (A
   RAINDUR = ((PRECIP - 1.0) * 0.5) * HOUR + HOUR
    IF (RAINDUR .GT. 1.0) THEN
       RAINDUR = 1.0
    ENDIF
    TIMESTEP = RAINDUR/NUMSTEPS
    MAXRAIN = 2.0 * (PRECIP/RAINDUR)
    RUNOFF = 0.0
    INFILT = 0.0
    IF ((MAXRAIN .LT. KSMTRX(1)) .AND. (POND .EQ. 0.0)) THEN
       PINF = PRECIP
    ELSE IF (PRECIP.GT.0.0) THEN
       PINF = 0.0
       DO 200, J = 1,NUMSTEPS
          TIME = TIME + TIMESTEP
          TRUNOFF = 0.0
          PPRECIP = RAINFUNC (RAINDUR,MAXRAIN,TIME,TIMESTEP)
          TPAMT=TPFUNC (KSMTRX(1),SAT(1),SW(1),PINF,PPRECIP,TIMESTEP)
          call dyntill(pprecip,timestep/hour)
          IF ((PPRECIP .LT. TPAMT) .AND. (POND .EQ. 0.0)) THEN
             INFILT = PPRECIP
          ELSE
             IF (TPAMT .GT. (KSMACRO(1)*TIMESTEP)) THEN
                INFILT = TPAMT
             ELSE
                INFILT= TPAMT + ((KSMACRO(1)*TIMESTEP)-TPAMT) *
   1                                          (POND/PONDMAX)**2
             ENDIF
```

```
            POND = POND + PPRECIP - INFILT
            IF (POND .GT. PONDMAX+mulchthick) THEN
               TRUNOFF = POND - PONDMAX - mulchthick
               POND = PONDMAX + mulchthick
            ELSE IF (POND .LT. 0.0) THEN
               INFILT = INFILT + POND
               POND = 0.0
            ENDIF
         ENDIF
         PINF = PINF + INFILT
         RUNOFF = RUNOFF + TRUNOFF
200   CONTINUE
      ELSE
         PINF = 0.0
      ENDIF
      PIP = 0.0
      IF (POND .GT. 0.0) THEN
         PIP = (0.2 * KSMTRX(1) + 0.8 * KSMACRO(1)) * (1.0 - TIME)
         IF (PIP .GT. POND) THEN
            PINF = PINF + POND
            POND = 0.0
         ELSE
            PINF = PINF + PIP
            POND = POND - PIP
         ENDIF
      ENDIF
      RETURN
      END


      Subroutine PROGRI(update)
C
C     ********** Subroutine TO READ AND INITIALIZE SOIL INFORMATION ****
C
      Include 'gen1.blk'
      Include 'gen2.blk'
      Include 'gen3.blk'
      Include 'gen4.blk'
      Include 'Ntrc1.Blk'
      Include 'comibs.blk'
      Include 'predob.blk'
      Include 'soilox.blk'
      Panwt=0.
      PTF=0.
      S1=SIN(LAT*0.01745)
      C1=COS(LAT*0.01745)
      IF(IIRR.EQ.4) then
        ISWSWB=0
        ISWNIT=0
      Endif
      XPLANT=PLANTS
      DO 10 I=1,8
        TMFAC(I)=0.931+0.114*I-0.0703*I**2+0.0053*I**3
10    CONTINUE
      ISTAGE=7
      IGSL=0
      xstage=0.1
      IF(CROP.EQ.'WH'.OR.CROP.EQ.'BA') THEN
        TBASE=2.
        SENTIL=0.
        SENLF=0.
        HI=0.
        SWDF3=2.0
      ELSE
        TBASE=10.
        SWDF3=1.0
      ENDIF
```

```
LN=0.
LAI=0.
SWDF1=1.0
SWDF2=1.0
TRWU=0.0
ICSDUR=0
ndef1=1.0
NDEF2=1.0
NDEF3=1.0
NDEF4=1.0
Anfac=0.
Nfac=1.
JHEAD=0
KHEAD=0
ioutwa=0
ioutgr=0
ioutnu=0
if (.not.update) then
   SNOW=0.
   AEP=0.
   AET=0.
   AEO=0.
   ASOLR=0.
   ATEMX=0.
   ATEMN=0.
   APRECP=0.
endif
TLCH=0.0
arunof = 0.0
ATLCH=0.0
ATANC=0.0
RANC=0.0
vanc=0.
vmnc=0.
tmnc=0.
rcnp=0.
tcnp=0.
TANC=0.044
IF(CROP.EQ.'WH'.OR.CROP.EQ.'BA') THEN
  TANC=0.045
  RANC=0.045
  LIF1=1.0
  LIF2=1.0
ELSEIF(CROP.EQ.'SG') THEN
  TANC=0.050
ENDIF
IF(ISWNIT.NE.1) TANC=0.0
ATMIN=0.0
TMIN=0.0
ATNOX=0.0
TNOX=0.0
stovN=0.0
ROOTN=0.0
GRAINN=0.0
GNP=0.0
TNUP=0.0
NHDUP=0
xgnp=0.0
xptn=0.0
aptnup=0.0
gnup=0.0
totnup=0.0
If(iswswb.eq.0) Koutwa=0
If(Imoutf.le.1)then
  call clear
  call opseas
Endif
DOYX=367
CUMDTT=0.
```

```
      SUMDTT=0.
      DTT=0.
      CRAIN=0.
      PRECIP=0.
      Do 200 I=1,6
          Si1(i)=0.0
          Si2(i)=0.0
          Si3(i)=0.0
          Si4(i)=0.0
          Si5(i)=0.0
200   Continue
      RETURN
      END



      Subroutine SOILNI
C
      Include 'gen1.blk'
      Include 'gen3.blk'
      Include 'gen4.blk'
      Include 'Ntrc1.Blk'
      Include 'Ntrc2.Blk'
      Include 'Nmove.Blk'
      Include 'comibs.blk'
C*****Subroutine INITIALIZES SOIL NITROGEN PARAMETERS
      IF(DMOD.EQ.0.)DMOD=1.
      CTNUP=0.0
      Iuon=.false.
      do 100 I=1,nlayr
           Urea(I)=0.0
           IF (BD(I).EQ.0.) BD(I)=1.2
           IF (PH(I).EQ.0.0) PH(I)=7.0
  100 CONTINUE
C*****CALCULATE N CONTRIBUTIONS
  600 TIFOM=0.0
      TIFON=0.0
      DO 700 I=1,NLAYR
           HUM(I)=OC(I)*1.E03*BD(I)*DLAYR(I)/0.58
           TIFOM=TIFOM+FOM(I)
           TIFON=TIFON+FON(I)
  700 CONTINUE
      DMINR=8.3E-05
      IF(DMOD.NE.0.) DMINR=DMINR*DMOD
      do 800 l=1,nlayr
           fac(l)=1.0/(bd(l)*1.e-01*dlayr(l))
           IF(NO3(L).LT.0.25) NO3(L)=0.25
           IF(NH4(L).LT.0.50) NH4(L)=0.50
           SNO3(L)=NO3(L)/fac(l)
           SNH4(L)=NH4(L)/fac(l)
           NHUM(L)=OC(L)*DLAYR(L)*BD(L)*1.E02-(SNO3(L)+SNH4(L))
           fpool(l,1)=fom(l)*0.20
           fpool(l,2)=fom(l)*0.70
           fpool(l,3)=fom(l)*0.10
  800 CONTINUE
C*********** INITIALIZE NITRIFICATION ROUTINE
      DO 1400 L=1,NLAYR
           CNI(L)=0.1
           WFY(L)=(SW(L)-LL(L))/DUL(L)
           IF (SW(L).GT.DUL(L)) WFY(L)=1.0-((SW(L)-DUL(L))
     1                   /(SAT(L)-DUL(L)))
           IF (WFY(L).LT.0.0) WFY(L)=0.0
           TFY(L)=0.0009766*ST(L)*ST(L)
           IF (ST(L).LT.5.0) TFY(L)=0.0
           phn(l)=1.0
           if(ph(l).lt.6.0)phn(l)=(ph(l)-4.5)/1.5
           if(ph(l).gt.8.0)phn(l)=9.0-ph(l)
           if(phn(l).lt.0.)phn(l)=0.
```

```
 1400 CONTINUE
      RETURN
      END


      Function TILLTIME
c
c   Function to decide when tillage is to occur
c   Tillage occurs when the top five layers are
c   near drained upper limit
c
c   Programmer F. Dadoun
c
     Include 'Gen3.blk'
      Logical Tilltime
      tilltime = .false.
      if (sw(1).le.dul(1)+0.01) then
         if (sw(2).le.dul(2)+0.01) then
            if (sw(3).le.dul(3)+0.01) then
               if (sw(4).le.dul(4)+0.01) then
                  if (sw(5).le.dul(5)+0.01) then
                     tilltime = .true.
                  endif
               endif
            endif
         endif
      endif
      return
      end


      Subroutine SOLT
C
C *** Subroutine to calculate daily average soil temperature at the
C     center of each soil layer.
C
       INclude 'comibs.blk'
       INCLUDE 'gen1.blk'
       INCLUDE 'gen2.blk'
       INCLUDE 'gen3.blk'
       INCLUDE 'gen4.blk'
       INCLUDE 'ntrc2.blk'
       Include 'Till.blk'
C
       real      zd(15),mulchalb,mthick, otempmn
C
      XI = float(DOY)
      ALX = (XI - HDAY) * 0.0174
      ATOT = ATOT - TMA(2)
      DO 100 K = 2,2,-1
         TMA(K) = TMA(K-1)
  100 CONTINUE
      mulchalb = 0.3
      ff = (sw(1) - 0.03)/(dul(1) - 0.03)
      salbedo = salb*(1 - 0.45*ff)
      IF (ISTAGE .LE. 6) THEN
         IF (ISTAGE .GE. 5) THEN
           ALBEDO=0.23+(LAI-4)**2/160
         ELSE
           CANCOV = 1 - EXP(-0.75*LAI)
           albedo=cancov*0.23+mulchcov*(1-cancov)*mulchalb+
     &              (1-mulchcov)*(1-cancov)*salbedo
         END IF
      ELSE
           albedo=(1-mulchcov)*salbedo+mulchcov*mulchalb
      END IF
```

```
      TA = TAV + AMP*COS(ALX)/2.
      TMA(1) = tempmn + (mulchcov+salbedo)*(otempmn-tempmn)/2
     &      + (1-albedo)*(TEMPMX - TEMPMN)*SQRT(SOLRAD * .03)
      otempmn = tempmn
      ATOT = ATOT + TMA(1)
      DT = tma(1) - TA
      DO L = 1, NLAYR
         IF (l .GT. 1) THEN
            AW = (AW + (SW(L) - ll(l))*DLAYR(L))
         ELSE
            aw = sw(1)*dlayr(1)
         END IF
         ALL = (ALL*(L-1) + LL(L))/L
         ABD = (ABD*(L-1) + BD(L))/L
         WW(L) = ((1-ABD/2.66) - ALL*ABD)
         WC = AW/(WW(L)*(z(l) + dlayr(l)*5))
         F = EXP(B(L)*((1. - WC)/(1. + WC))**2)
         DD = F*DP(L)
         IF (l .EQ. 1) dd1 = dd
         ZD(L) =  - Z(L)/DD
         if (l.eq.1) then
            zdchk = -(z(1)+15)/dd1
            STchk = (TAV + (AMP/2.*COS(ALX + zdchk) + DT)*EXP(zdchk))
         endif
         ST(L) = (TAV + (AMP/2.*COS(ALX + ZD(l)) + DT)*EXP(ZD(l)))
      END DO
      RETURN
      END



       Subroutine UPFLOW (AD,DLAYR,EOS,ES,LL,NLAYR,POND,SW,DUL)
c   Subroutine to simulate water redistribution in the profile
c   following evaporation
c
      Include 'Till.blk'
      include 'Nmove.blk'
      Real Ad(3),Dlayr(*),Dsw(3),Sw(*),Ll(*),dul(*),Eos, Es,Diff,pond
      Integer L,Nlayr,K,M
C     Evaporate water from ponding (if exists) and alter ponding amount
      IF(POND.GT.0.0) THEN
         ES=EOS
         IF(POND.GT.EOS)THEN
            POND=POND-EOS
         ELSE
c  Evaporates water from residues  and top two layers
          if ((mulchsw-0.01).gt.(eos-pond)) then
            mulchsw = mulchsw - (EOS - pond)
            pond = 0.0
          else
            SW(1)=SW(1)-0.30*(EOS-(pond+mulchsw-0.01))/DLAYR(1)
            SW(2)=SW(2)-0.70*(EOS-(pond+mulchsw-0.01))/DLAYR(2)
            mulchsw = 0.01
            POND=0.0
          endif
         END IF
      ELSE
c     Compute Maximum water loss from top three layers as a function
c     of their moisture contents
         if (mulchsw-0.01.ge.eos) then
            es = eos
            mulchsw = mulchsw - eos
         else
          do j=1,3
             Ad(j)=(0.109+0.469*(LL(j)-0.35)**2) *LL(j)
          enddo
         IF (SW(1).GT.DUL(1) - 0.02) THEN
            DSW(1) = (SW(1) - 0.02 - AD(1)) * 0.80
```

```
         ELSE
            Dsw(1)=0.5*(0.5+Eos-mulchsw+0.01)*(Sw(1)-Ad(1))**1.4
         ENDIF
         IF (SW(2).GT.DUL(2) - 0.02) THEN
            DSW(2) = (SW(2) - 0.02 - AD(2)) * 0.12
         ELSE
            Dsw(2)=0.075*(Sw(2)-Ad(2))**1.4
         ENDIF
         IF (SW(3).GT.DUL(3) - 0.02) THEN
            DSW(3) = (SW(3) - 0.02 - AD(3)) * 0.032
         ELSE
            Dsw(3)=0.04*(Sw(3)-Ad(3))**1.4
         ENDIF
         Es=Dsw(1)*2.0+Dsw(2)*5.0+Dsw(3)*8.0+mulchsw-0.01
c       Ensure ES does not exceed EOs - if so scale back DSW
         If(Es.Gt.Eos)Then
           Do L=1,3
              Dsw(L)=Dsw(L)*(Eos-mulchsw+0.01)/(Es-mulchsw+0.01)
           Enddo
           Es=Eos
         Endif
         mulchsw = 0.01
c        Compute a temporary change in water content of layer 3
         Sw(3)=Sw(3)-Dsw(3)
         Flowu(2)=0.0
c        Calculate diffusivities and fluxes for layers 4 to Nlayr
       if(sw(3).lt.dul(3)) then
         Do L=3,Nlayr-1
             K=L-1
             M=L+1
             Diff=0.5*Exp(40.0*((Sw(M)-LL(M))+
     &              (Sw(L)-Flowu(K)/Dlayr(L)-LL(L)))/2.0)
             If(Diff.Gt.50.0)Diff=50.0
             Flowu(L)=(Sw(M)-dul(m)-sw(l)+Flowu(K)/Dlayr(L)+dul(l))
     &                 *Diff/(Dlayr(L)+Dlayr(M))/2.0
             if (flowu(l).lt.0.0) flowu(l) = 0.0
            Sw(L)=Sw(L)-Flowu(K)/Dlayr(L)+Flowu(L)/Dlayr(L)
         Enddo
         Flowu(Nlayr)=0.0
         Sw(Nlayr)=Sw(Nlayr)-Flowu(Nlayr-1)/Dlayr(Nlayr)
       else
         do l=3,nlayr
            flowu(l) = 0.0
         enddo
       endif
c        Compute moisture content and Flows in top three layers
         Flowu(2)=Dsw(3)*8.0
         Flowu(1)=Flowu(2)+Dsw(2)*5.0
         flowu(0)=flowu(1)+dsw(1)*2.0
         Sw(2)=Sw(2)-Dsw(2)
         Sw(1)=Sw(1)-Dsw(1)
       endif
      ENDIF
      Return
      End


      Subroutine WATBAL (ISWAT)

      Include 'GEN1.BLK'
      Include 'GEN2.BLK'
      Include 'GEN3.BLK'
      Include 'GEN4.BLK'
      Include 'NMOVE.BLK'
      Include 'NTRC1.BLK'
      Include 'NTRC2.BLK'
      Include 'COMIBS.BLK'
      Include 'ENVIRO.BLK'
```

```
      INCLUDE 'NWATBAL.BLK'
      INCLUDE 'SOILOX.BLK'
      Include 'till.blk'
      Integer EVFLAG, K,L,M
      REAL Albedo, Eeq, Error, Flown(0:20), Leftwat,Overflow, Pinf, Snomlt, Td, Tprecp,
     2     Tratio, Tswy, oprecip

      DEPIR=0.
      DRAIN = 0.0
      EO = 0.0
      EP = 0.0
      ES = 0.0
      ET = 0.0
      EOS= 0.0
      EOP= 0.0
      ERROR = 0.0
      EVFLAG = 0
      ICSDUR=ICSDUR+1
      IDRSW = .FALSE.
      IOFF=0.
      OVERFLOW = 0.0
      PINF = 0.0
      PRECIP=0.
      RAIN = RAIN / 10.0
      RUNOFF = 0.0
      WTLAYR = NLAYR + 1
      DO 602 L=1,NLAYR + 1
         FLOWD(L)=0.
         FLOWU(L)=0.
         FLOWN(L)=0.
602   CONTINUE
```

If IIRR = 1, no irrigation. If IIRR = 2 or 3, call irrige. If IIRR = 4, watbal is not called (water non-limiting)

```
      IF (IIRR.EQ.2.OR.IIRR.EQ.3) THEN
          CALL IRRIGE
      ENDIF
      DEPIR = DEPIR / 10.0
      PRECIP=RAIN+DEPIR
      SWDEF=0.
      IF (TEMPMX.LE.1..OR .SNOW.NE.0.) THEN
        CALL SNOWFALL (TEMPMX, PRECIP, RAIN, SNOMLT, SNOW)
      ENDIF
      TPRECP=PRECIP
c Add water from precipitation to residues
      if (precip.gt.0.0 .and.precip.gt.(mulchsat - mulchsw)) then
         precip = precip - (mulchsat - mulchsw)
         mulchsw = mulchsat
      elseif (precip.gt.0.0) THEN
         mulchsw = mulchsw + precip
         precip = 0.0
      endif
```

If w.t. switch is 1,   call water table routine to find out the depth of the water table. If switch is 2, read file.

```
      IF (ISWWT.EQ.1) THEN
        CALL WATABLE (DEPWT, DL1, DL2, EVFLAG, NLAYR, SAT, SW,
     1               TRUDEPWT, WTCHANGE, WTLAYR)
      ELSEIF (ISWWT.EQ.2) THEN
        READ (410, 1325)  WTLAYR
1325    FORMAT ( 5X, I2)
        DO 125 M = NLAYR, WTLAYR, -1
           SW(M) = SAT(M)
125     CONTINUE
        K = WTLAYR-1
        DO 905 WHILE ((K.GE.1).AND.(SW(K).EQ.SAT(K)) )
           WTLAYR = K
```

```
          K = K - 1
905     CONTINUE
        DEPWT = DL1(WTLAYR)
        TRUDEPWT = DEPWT
      ENDIF
c Calculate potential evapotranspiration:
      CALL CALEO
```

If there has been any precip or if water remains in the pond call the ponding routine. When it rains, water either infiltrates, ponds or runs off.

```
      If(Pond.Gt.0.0.or.Precip.Gt.0.0)Then
          CALL PONDING (PINF,RUNOFF)
      Endif
c DRAINAGE calculates soil water content at equilibrium, downward flows, and backs up the water if
        there is a restricting layer   or water table in the profile

      Call Drainage (Dlayr,Dul,Sat,Sw,Flowd,Ksmacro,Overflow,
     &              Wtlayr,Nlayr,pinf,Idrsw,iswwt)
c  If there has been overflow generated by backup add this to the pond
      Pond=Pond+Overflow
      If(Pond.gt.Pondmax+mulchthick)Then
         Runoff=Runoff+Pond-Pondmax-mulchthick
         Pond=Pondmax+mulchthick
      Endif
      arunof = arunof + runoff
      Drain=Flowd(Amin1(Wtlayr-1,Nlayr))
      IF (ISWNIT.NE.0.AND.IDRSW) THEN
        CALL NFLUXD (Sat,Dul,Sw,Nlayr,Dlayr,Flowd,Swcon,SNo3,NNout)
      ENDIF
      IF (ISWNIT.NE.0.AND.IUON.AND.IDRSW) THEN
        CALL NFLUXD (Sat,Dul,Sw,Nlayr,Dlayr,Flowd,Swcon,Urea,NNout)
      ENDIF
```

Call water table routine to find out the new depth of the w.t.

```
      IF (ISWWT.GE.1) THEN
        CALL WATABLE (DEPWT, DL1, DL2, EVFLAG,NLAYR, SAT, SW,
     1              TRUDEPWT, WTCHANGE, WTLAYR)
      ENDIF
```

Calculate soil evaporation and water redistribution:

```
      Call Upflow (Ad,Dlayr,Eos,Es,LL,Nlayr,pond,Sw,dul)
      IF (ISWNIT.NE.0) THEN
        CALL NFLUXU (Nlayr,Sw,Dlayr,Sno3,Flowu,NNout)
      ENDIF
      IF (ISWNIT.NE.0.AND.IUON) THEN
        CALL NFLUXU (Nlayr,Sw,Dlayr,Urea,Flowu,NNout)
      ENDIF
      CES=CES+ES
      TLCH = TLCH + NNOUT(NLAYR)
      IF (ISWWT.GE.1) THEN
```

Call water table routine to find out the new depth of the w.t.

```
      CALL WATABLE (DEPWT, DL1, DL2, EVFLAG, NLAYR, SAT, SW,
     1              TRUDEPWT, WTCHANGE, WTLAYR)
      ENDIF
      IF (ISWWT.EQ.2) THEN
         IF (RWTLAYR.LT.WTLAYR) THEN
            DO 1000 L = RWTLAYR,WTLAYR
            SUBIRR = SUBIRR+(SAT(L)-SW(L))*DLAYR(L)
            IF ((SAT(L)-SW(L)) .LT. 0.0) THEN
                write (6,*) 'Problem with WT in WATBAL(266)'
            ENDIF
            SW(L)=SAT(L)
```

```
1000        CONTINUE
         ELSEIF (RWTLAYR.GT.WTLAYR) THEN
            CALL DRAINAGE(Dlayr,Dul,Sat,Sw,Flowd,Ksmacro,Overflow,
     &                 Wtlayr,Nlayr,Winf,Idrsw,iswwt)
            DRAIN = FLOWD(RWTLAYR-1)
         ENDIF
         WTLAYR = RWTLAYR
         IF (SUBIRR .GE. DRAIN) THEN
            SUBIRR = SUBIRR - DRAIN
            DRAIN = 0.0
         ELSE
            DRAIN = DRAIN - SUBIRR
            SUBIRR = 0.0
         ENDIF
      ENDIF
        DEPWT = DL1(WTLAYR)
      IF (RESP2.EQ.'Y'.OR.RESP2.EQ.'y') THEN
         IF (ISWWT.EQ.0) THEN
            WRITE (370, '(/,A, I3,A, F9.4,A, F9.4)' ) ' DOY = ', DOY,
     1' DEPWT = ',DEPWT, ' TRUDEPWT = ', TRUDEPWT
         ENDIF
         WRITE (370, 1210)'DEPTH','FLOWD','FLOWU','SW(L)','SAT(L)'
         DO 1150 L = 2, NLAYR
         IF (ISWWT.EQ.0) THEN
            WRITE(370, 1201) DL1(L), FLOWD(L), FLOWU(L), SW(L), SAT(L)
         ELSE
            WRITE(370, 1200) DL1(L), FLOWD(L), FLOWU(L), SW(L), SAT(L)
         ENDIF
1150     CONTINUE
1210     FORMAT (A5,A9,1X,A9,4X,A6,3X,A8)
1201     FORMAT (F4.0, 4(1X, F9.4) )
1200     FORMAT (F4.0, 4(1X, F9.4))
      ENDIF
```

Calculate water deficit for automatic irrigation.

```
      If(Iirr.eq.3)Then
         CALL WATDEF (ATHETA, CUMDEP, DLAYR, DSOIL, DUL, LL,
     1               NLAYR,SW,SWDEF)
      Endif
      PESW = 0.0
      DO 300, L = 1,NLAYR
         PESW = PESW + ((SW(L) - LL(L)) * DLAYR(L))
300   CONTINUE
      IF (ISTAGE.GE.6) THEN
        ET=ES
        CET=CET+ET
        CRAIN=CRAIN+PRECIP
      ELSE
2800    IF (GRORT.GT.0.0) THEN
            CALL ROOTGROW (CROP, ISTAGE, DTT, GRORT, ISWNIT, L1, PHINT,
     2                     PLANTS, RNFAC, SWDF, ISWWT)
        ENDIF
3300    Continue
```

Estimate plant water uptake,water deficit and water filled por

```
        Call Wuptake(Eop,tratio,potrwut)
        CALL WSTRSS (CSD1, CSD2, EP, EOP, POTRWUT, SWDF1, SWDF2)
        ET = ES + EP
3800    CEP=CEP+EP
        CET=CET+ET
        CRAIN=CRAIN+PRECIP
      ENDIF
      Do L=1,Nlayr
        Flown(L)=Flowd(L)-Flowu(L)
      Enddo
      RETURN
      END
```

Appendix 3: Input files to run CERES

Input file structure is described in:

IBSNAT Project. 1989. Technical report 5, Decision Support System for Agrotechnology Transfer (DSSAT), Documentation for IBSNAT crop model input and outputs files, version 1.1, University of Hawaii, Honolulu, Hawaii, USA.

MZEXP.DIR: Directory of files for each experiment

```
MSEL8801.MZA MSEL8801.MZB MS91.MZ MS92.MZ MS93.MZ MS94.MZ
MSEL9001 MSU East-Lansing, Michigan 1990         MSEL0112.W90 SPROFILE.mz2
MSEL9001.MZ4 MSEL0000.MZ5 MSEL9001.MZ6 MSEL9001.MZ7 MSEL9001.MZ8 GENETICS.MZ9
MSEL9001.MZA MSEL9001.MZB OUT1.MZ OUT2.MZ OUT3.MZ OUT4.MZ OUT5.MZ OUT5.MZ
MSEL9101 MSU East-Lansing, Michigan 1991         MSEL0110.W91 SPROFILE.mz2
MSEL9001.MZ4 MSEL0000.MZ5 MSEL9001.MZ6 MSEL9001.MZ7 MSEL9101.MZ8 GENETICS.MZ9
MSEL9001.MZA MSEL9001.MZB OUT1.MZ OUT2.MZ OUT3.MZ OUT4.MZ OUT5.MZ OUT5.MZ
```

WTH.DIR: Daily weather data

```
MSEL 1988 MSU East-Lansing, Michigan        01/01/88 12/31/88 MSEL0112.W88
MSEL 1990 MSU East-Lansing, Michigan        01/01/90 12/31/90 MSEL0112.W90
MSEL 1991 MSU East-Lansing, Michigan        01/01/91 10/01/91 MSEL0110.W91
```

SPROFILE.MZ2: File 2, soil profile properties

```
 42              CONOVER
   .13  9.00     .15  78.00   9.9  27.5 1.0   .27E-02   58.0  6.68   .03       01.53 02.55
    2.   .072   .211   .356   .211  1.000  1.54  1.24  2.4  3.1  5.6  5.5   .10   .00   5.0  0.40
    5.   .072   .211   .356   .211  1.000  1.54  1.24  2.4  3.1  5.6  5.5   .10   .00   5.0  0.40
    8.   .072   .211   .356   .211   .950  1.54  1.24  2.4  3.1  5.6  5.5   .10   .00   5.0  0.40
   11.   .103   .237   .347   .237   .791  1.57  1.01  2.4  3.1  6.0  5.4   .10   .00   5.0  0.35
   14.   .181   .302   .317   .302   .371  1.68   .33  2.3  3.1  7.7  5.2   .10   .00   5.0  0.30
   17.   .178   .298   .313   .298   .222  1.70   .27  2.3  3.0  8.1  5.2   .10   .00   5.0  0.20
   20.   .176   .295   .310   .295   .062  1.71   .21  2.4  3.1  8.1  5.2   .10   .00   5.0  0.15
   23.   .150   .272   .303   .272   .019  1.71   .20  2.3  3.1  8.2  5.2   .10   .00   5.0  0.15
   25.   .149   .270   .302   .270   .006  1.71   .20  2.3  3.1  8.2  5.2   .10   .00   5.0  0.10
   -1.   .000   .000   .000   .000   .000   .00   .00   .0   .0   .0  5.0
```

FILE 4: Soil nitrogen dynamics

```
MECP9001 01 9999.   75   500.
      11  01  20 100  15.00  15.00   1.2   1.2
     130  01  10   0  10.00   8.00   1.2   1.2
      -1  -1  -1  -1
MECP9001 02 9999.   75   500.
      11  01  20  73  15.00  15.00   1.2   1.2
     130  01  10   0  10.00   8.00   1.2   1.2
      -1  -1  -1  -1
MECP9001 03 9999.   75   500.
      11  01  20  47  15.00  15.00   1.2   1.2
     130  01  10   0  10.00   8.00   1.2   1.2
      -1  -1  -1  -1
MECP9001 04 9999.   75   500.
      11  01  20   0  15.00  15.00   1.2   1.2
     130  01  10   0  10.00   8.00   1.2   1.2
      -1  -1  -1  -1
```

```
MECP9005 05 9999.   75   500.
      11  01  20 100  15.00  15.00   1.2   1.2
     130  01  10   0  10.00   8.00   1.2   1.2
      -1  -1  -1  -1
MECP9006 06 9999.   75   500.
      11  01  20  73  15.00  15.00   1.2   1.2
     130  01  10   0  10.00   8.00   1.2   1.2
      -1  -1  -1  -1
MECP9007 07 9999.   75   500.
      11  01  20  47  15.00  15.00   1.2   1.2
     130  01  10   0  10.00   8.00   1.2   1.2
      -1  -1  -1  -1
MECP9008 08 9999.   75   500.
      11  01  20   0  15.00  15.00   1.2   1.2
     130  01  10   0  10.00   8.00   1.2   1.2
      -1  -1  -1  -1
```

File 5: Soil profile initial condition

```
01 MSEL9001
    2.   .174  2.9  1.0  6.0
    5.   .174  2.9  1.0  6.0
    8.   .174  2.9  1.0  6.0
   11.   .174  2.4   .9  6.0
   14.   .169  1.7   .8  6.1
   17.   .164  1.9   .7  6.1
   20.   .154  1.3   .6  6.1
   23.   .131   .9   .5  6.8
   34.   .116   .8   .5  7.4
   -1.   .000   .0   .0   .0
02 MSEL9001
    2.   .174  2.9  1.0  6.0
    5.   .174  2.9  1.0  6.0
    8.   .174  2.9  1.0  6.0
   11.   .174  2.4   .9  6.0
   14.   .169  1.7   .8  6.1
   17.   .164  1.9   .7  6.1
   20.   .154  1.3   .6  6.1
   23.   .131   .9   .5  6.8
   34.   .116   .8   .5  7.4
   -1.   .000   .0   .0   .0
03 MSEL9001
    2.   .174  2.9  1.0  6.0
    5.   .174  2.9  1.0  6.0
    8.   .174  2.9  1.0  6.0
   11.   .174  2.4   .9  6.0
   14.   .169  1.7   .8  6.1
   17.   .164  1.9   .7  6.1
   20.   .154  1.3   .6  6.1
   23.   .131   .9   .5  6.8
   34.   .116   .8   .5  7.4
   -1.   .000   .0   .0   .0
04 MSEL9001
    2.   .174  2.9  1.0  6.0
    5.   .174  2.9  1.0  6.0
    8.   .174  2.9  1.0  6.0
   11.   .174  2.4   .9  6.0
   14.   .169  1.7   .8  6.1
   17.   .164  1.9   .7  6.1
   20.   .154  1.3   .6  6.1
   23.   .131   .9   .5  6.8
   34.   .116   .8   .5  7.4
   -1.   .000   .0   .0   .0
05 MSEL9001
    2.   .174  2.9  1.0  6.0
    5.   .174  2.9  1.0  6.0
    8.   .174  2.9  1.0  6.0
   11.   .174  2.4   .9  6.0
   14.   .169  1.7   .8  6.1
```

```
   17.   .164  1.9    .7  6.1
   20.   .154  1.3    .6  6.1
   23.   .131   .9    .5  6.8
   34.   .116   .8    .5  7.4
   -1.   .000   .0    .0   .0
06 MSEL9001
    2.   .174  2.9   1.0  6.0
    5.   .174  2.9   1.0  6.0
    8.   .174  2.9   1.0  6.0
   11.   .174  2.4    .9  6.0
   14.   .169  1.7    .8  6.1
   17.   .164  1.9    .7  6.1
   20.   .154  1.3    .6  6.1
   23.   .131   .9    .5  6.8
   34.   .116   .8    .5  7.4
   -1.   .000   .0    .0   .0

07 MSEL9001
    2.   .174  2.9   1.0  6.0
    5.   .174  2.9   1.0  6.0
    8.   .174  2.9   1.0  6.0
   11.   .174  2.4    .9  6.0
   14.   .169  1.7    .8  6.1
   17.   .164  1.9    .7  6.1
   20.   .154  1.3    .6  6.1
   23.   .131   .9    .5  6.8
   34.   .116   .8    .5  7.4
   -1.   .000   .0    .0   .0
08 MSEL9001
    2.   .174  2.9   1.0  6.0
    5.   .174  2.9   1.0  6.0
    8.   .174  2.9   1.0  6.0
   11.   .174  2.4    .9  6.0
   14.   .169  1.7    .8  6.1
   17.   .164  1.9    .7  6.1
   20.   .154  1.3    .6  6.1
   23.   .131   .9    .5  6.8
   34.   .116   .8    .5  7.4
   -1.   .000   .0    .0   .0
08 MSEL9001
    2.   .174  2.9   1.0  6.0
    5.   .174  2.9   1.0  6.0
    8.   .174  2.9   1.0  6.0
   11.   .174  2.9   1.0  6.0
   14.   .174  2.7   1.0  6.0
   17.   .172  2.1    .8  6.1
   20.   .166  1.8    .7  6.1
   23.   .159  1.6    .6  6.1
   34.   .142  1.1    .5  6.5
   -1.   .000   .0    .0   .0
```

File 6: Irrigation management data

```
01 MECP9001
  -1  -1
02 MECP9001
  -1  -1
03 MECP9001
  -1  -1
04 MECP9001
  -1  -1
05 MECP9001
  -1  -1
06 MECP9001
  -1  -1
07 MECP9001
  -1  -1
08 MECP9001
  -1  -1
```

File 7: Nitrogen Fertilizer data

```
01 MECP9001
 146 183.5   5.0  5
  -1  -1.0  -1.0 -1
02 MECP9001
 146 183.5   5.0  5
  -1  -1.0  -1.0 -1
03 MECP9001
 146 183.5   5.0  5
  -1  -1.0  -1.0 -1
04 MECP9001
 146 183.5   5.0  5
  -1  -1.0  -1.0 -1
05 MECP9001
 146 183.5   5.0  5
  -1  -1.0  -1.0 -1
06 MECP9001
 146 183.5   5.0  5
  -1  -1.0  -1.0 -1
07 MECP9001
 146 183.5   5.0  5
  -1  -1.0  -1.0 -1
08 MECP9001
 146 183.5   5.0  5
  -1  -1.0  -1.0 -1
```

File 8: Crop management data

```
MSEL9001 01 FALLOW , NO RESIDUE COVER                         42   70
 001 270    7.25  0.711  5.00 01 01   0.95  1.50    0.40  95.00 00
MSEL9001 02 FALLOW , 30% RESIDUE COVER                        42   70
 001 270    7.25  0.711  5.00 01 01   0.95  1.50    0.40  95.00 00
MSEL9001 03 FALLOW , 50% RESIDUE COVER.                       42   70
 001 270    7.25  0.711  5.00 01 01   0.95  1.50    0.40  95.00 00
MSEL9001 04 FALLOW , 100% RESIDUE COVER.                      42   70
 001 270    7.25  0.711  5.00 01 01   0.95  1.50    0.40  95.00 00
MSEL9001 05 CROP, NO RESIDUES COVER                           42   70
 001 128    7.25  0.711  5.00 01 01   0.95  1.50    0.40  95.00 00
MSEL9001 06 CROP, 30% RESIDUE COVER                           42   70
 001 128    7.25  0.711  5.00 01 01   0.95  1.50    0.40  95.00 00
MSEL9001 07 CROP, 50% RESIDUE COVER.                          42   70
 001 128    7.25  0.711  5.00 01 01   0.95  1.50    0.40  95.00 00
MSEL9001 08 CROP, 100 % RESIDUE COVER.                        42   70
 001 128    7.25  0.711  5.00 01 01   0.95  1.50    0.40  95.00 00
```

File 9: Genetic coefficients

```
  70 PIO 3475         180.00 0.5000 685.0  584.00  9.300
```