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Climatic Resources

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Soil water and soil temperature patterns in the soil profile determine the overall biological response of plants, microbes, and other soil fauna. The impact of soil management practices on the soil microclimate depends primarily on how management practices affect the soil water and soil temperature patterns at the soil surface and within the soil profile throughout the day and across the year. As we begin to understand these interactions, the more opportunities we have to develop soil management practices that will have a positive impact on the soil. These impacts will improve plant production efficiency, decrease pressures from pests, and enhance the quality of the soil over time.

To understand how the soil microclimate is affected by soil management practices it is important to begin with an understanding of the physical processes that determine the temperature and water regimes in the soil profile. Manipulation of the soil surface by tillage, residue cover, cover crops, and the type of crop that is grown affects these dynamics of the energy balance, which defines the exchange of energy between the soil and the atmosphere. This process is relatively simple and is governed by the energy balance as shown in Eq. [1]:

$$R_n - G = H + \mathrm{LE} \qquad [1]$$

where R_n is the net radiation, G is the soil heat flux, H the sensible heat flux, and LE the latent heat flux with each parameter expressed in terms of watts per square meter (W m^{-2}).

Dissecting Eq. [1] into the components begins with the R_n component. This is the dominant parameter in the energy balance and is a function of the amount of sunlight and longwave radiation that impinges on the soil surface. Diagrammatically these components can be represented as shown in Fig. 11–1. Net radiation can be mathematically described as

$$R_n = (1 - \alpha)S_g + L_i - \varepsilon\sigma T_s^4 \qquad [2]$$

where α is the albedo of the surface which can be described as the reflectivity of the surface, S_g is the solar irradiance (W m^{-2}), L_i is the longwave irradiance from the sky, and ε is the emissivity of the soil surface, σ is the Stefan–Boltzman constant (5.67×10^{-8} W m^{-2} K^{-4}), and T_s is the surface temperature (K). Longwave radiation emitted from the atmosphere can be expressed in a similar form to the surface longwave in which the ε term is the emissivity of the atmosphere and the temperature term is expressed as the air temperature (T_a). Hatfield et al. (1983) compared a

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number of different approaches to estimating ε from the atmosphere and the necessary precautions to be followed in applying these approaches. All of the methods use an empirical combination of air temperature and relative humidity and are often developed for specific locations.

The albedo of the surface represents the reflectivity, which can be thought of as amount of light that is reflected back to the atmosphere; therefore, the higher the albedo, the more light that is returned and the brighter the surface appears. For example, a dark soil that is wet has a low albedo, and as the soil dries the albedo increases. Similarly, a dark soil covered with fresh crop residue will have a higher albedo than a bare soil surface. The albedo of the surface is variable and depends on the soil type, organic matter content of the surface soil, amount of crop residue, age of residue, crusting, tillage, and surface wetness. Given all of these variables that affect albedo, it is difficult to assume a constant value throughout a growing season. An example is shown in Fig. 11|2, which depicts the change in albedo over the course of a growing season. The presence of the residue material causes the albedo to be larger than the soil and during the season as the crop covers the soil surface the albedo increases with the presence of the crop. In a light-colored soil the growth of the crop actually decreases the albedo of the surface.

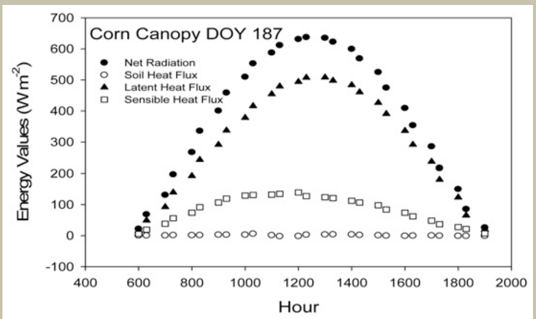

Fig. 11|1. Generalized description of the energy balance for a surface.

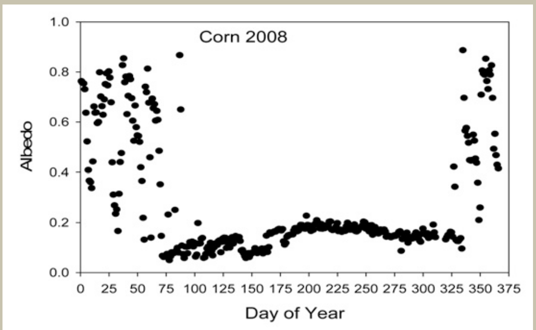

Fig. 11|2. Changes in albedo over a corn crop before planting until after harvest.

Solar irradiance is affected by a number of factors—the amount of sunlight that impinges on a surface depends on our location on the earth, the angle of the surface, and the time of year. Simply stated, the maximum solar energy is when the sun is directly overhead on a clear day, shining onto a level surface. The physics of this process are described in a number of textbooks (e.g., Monteith, 1973). There are physical equations that can be used to calculate the solar radiation impinging onto a surface on a clear day, and these are given in Ham (2005). There are actually two components of S_g, a direct and diffuse component. Direct sunlight is the direct beam of light from the sun, while diffuse is the amount of light that has been scattered by the atmosphere. The direct component is what causes a shadow, while the diffuse component allows us to have light in the shadow. On the soil surface, the direct component is a major energy source that impinges on the upper leaves of canopies or onto the surface, while the diffuse component is the energy that is present in the lower parts of the canopy or below the residue layer. The amount of direct and diffuse sunlight will vary throughout the year depending on the position on the earth, the slope, and cloudiness of the location.

Albedo and emissivity are dependent on parameters that are affected by soil management such as crop residue, surface drying, shape of the soil surface, or the soil organic matter content. As the albedo increases there is less energy that will be retained by the soil. If the emissivity increases, the amount of energy emitted from the soil surface will increase. There are large changes in the range of values induced by typical soil management practices, and albedo affects the energy available more than emissivity. The energy available in the solar radiation is larger than the longwave components during the day, while at night the longwave radiation is the only factor in the radiation balance (Fig. 11|3). These illustrations from measurements over a cropped field demonstrate that the magnitude of these values change throughout the day. These patterns change throughout the year, and in summer the incoming shortwave is the dominant component in the radiation balance. This changes during the winter period when the outgoing longwave component is the largest (Fig. 11|4). This is to be expected since the cooling that occurs during the winter period is due to the loss of energy from the surface. These values are for the central United States and will change as we move with latitude around the Earth. For example, near the equator the exchange of radiation would be fairly consistent throughout the year, but as one moves to more northerly or southerly latitudes, then the patterns in the radiation components will change.

An important part of the balance of longwave and shortwave radiation is the shape of the surface. In soil management, there are changes of the surface due to tillage, and these changes will affect the angle of the surface relative to the angle of the sun. This change only affects the direct beam of incoming shortwave radiation and not the diffuse shortwave or the longwave components. If there is a ridge created by tillage then the south side of the ridge would warm more quickly because of greater exposure to direct beam radiation. This would cause this surface to dry and warm more quickly than the north side of the ridge. In the southern hemisphere the opposite effect would be seen, with the north side of the ridge being that warmer side. One way of considering the impact of a sloping surface is to consider that having a south-facing slope with a 10° angle would have the same exposure to the sun as being 10° further south in latitude. There is little effect on the ongoing longwave caused by the fact that warmer surfaces would emit more radiation. As we change the slope of the soil surface in northern latitudes these areas would tend to warm more quickly in the spring because their surface is oriented more directly toward the sun. The details of this process are described in many microclimate books (Monteith, 1973; Rosenberg et al., 1983).

The radiation balance is a large part of the overall energy balance for a surface in which the available energy is partitioned into latent heat, sensible heat, and soil heat flux (Fig. 11|1). These data are for a typical day during the early spring in a northern latitude. There will be variation in these components caused by the cropping systems, tillage practice, locations, and time of year. To fully understand how soil management practices affect the energy balance it is important to briefly discuss each of the components.

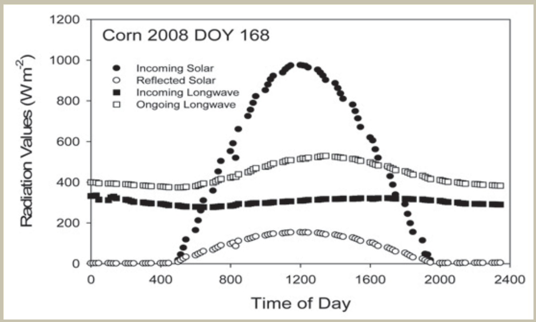

Fig. 11|3. Radiation balance for a typical summer day in central Iowa.

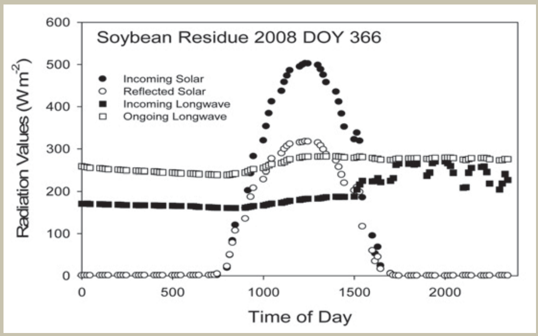

Fig. 11|4. Radiation balance for a typical winter day in central Iowa.

Soil Heat Flux

Soil heat flux (G) is simply the amount of energy that is exchanged between the soil and the atmosphere and has recently been discussed in detail by Sauer and Horton (2005). This process proceeds primarily by conduction and is described as

$$G = -\lambda \frac{\delta T}{\delta z} \qquad [3]$$

where λ is the thermal conductivity of the soil, *T* is the temperature of the soil layer, and *z* the depth of the soil layer. The factor in Eq. [3] that is affected most by soil management is the thermal conductivity of the soil layers, which depends on mineral composition of the soil, particle size, amount of organic matter, soil bulk density, and water content.

Tillage loosens the soil, which reduces the bulk density of the soil, which in turn reduces the thermal conductivity of the upper layers of the soil. Azooz et al. (1997) showed that the soil heat flux was lower in a tilled soil than a non-tilled soil because of the impact of increased air spaces in the upper layers on reducing the thermal conductivity. Adding residue onto the soil surface creates a layer with a lower thermal conductivity because of all of the air spaces in the residue layer. The change in the thermal conductivity of this layer reduces the energy that can be transported into the soil; thus, crop residue will reduce the soil heat flux. Sauer et al. (1997) found that corn residue on the surface had an albedo higher than bare soil, presented a barrier to water vapor movement from the soil to the atmosphere, and reduced the amount of energy that could be partitioned into soil heat flux. Soils with a large amount of residue cover tend to be cooler, wetter, and have a smaller soil heat flux than soils without residue cover.

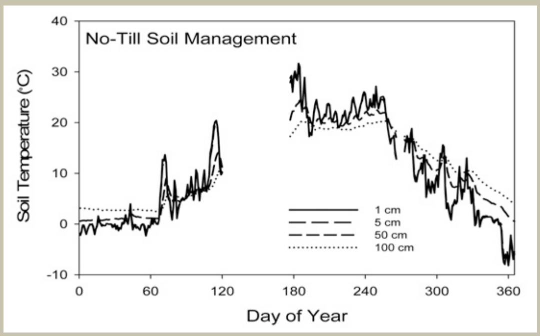

Fig. 11|5. Seasonal patterns in soil temperature throughout a year at multiple depths in the soil profile.

Soil Temperature

Soil heat flux provides the energy required to change the temperature of the soil. Soil temperature patterns are important for plant growth, biological activity, and water vapor exchange within the soil profile and between the soil surface and the atmosphere. Soil temperature is a soil parameter that is more often used to assess the impact of soil management practices because the question will be whether this change in practice will cause the soil temperatures to be either warmer or colder than what is optimum for plant growth and development. Soil temperatures are influenced by a number of factors, including meteorological conditions, soil surface conditions, type of crop, and growing season. Soil temperature patterns within the soil vary with time of day, time of year, and depth. Van Wijk and deVries (1966) were among the first to describe this process in detail and provided elaborate detail on the physics and mathematics of soil temperature patterns in soil. Soil temperatures within a field exhibit various patterns throughout the year, as shown in Fig. 11|5. The greatest variation over the year occurs in the upper layers of the soil profile and gradually diminishes with depth in the profile. At some depth, typically 2 m, there is no variation in soil temperature.

The effects of soil management on soil temperature have been extensively documented over the past 100 yr. For example, Burrows and Larson (1962) showed that corn residue reduced soil temperature and consequently corn growth. They found that plant height and plant biomass decreased as the amount of residue on the surface increases. Singh and Sandhu (1979) found a similar result in studies in India. Al-Darby and Lowery (1987) reported that soil temperatures at 5 cm were lower in no-till systems with undisturbed residue on the surface, and these lower temperatures affected emergence and growth of corn seedlings. Gupta et al. (1983) had previously reported that soil surface temperatures were lowest in no-till with surface residue and highest in no-till with the residue removed. Evaluation of the impact of residue on soil temperatures has to consider the annual changes in temperature. In comparing different tillage systems with and without corn residue, for example, fall plow, chisel-plow, and no-till, Benoit and van Sickle (1991) found that no-till with residue in Minnesota had the highest over-winter temperatures at the 5-, 10-, and 30-cm depths. They also found that the no-till with residue was the first soil to become frost free in the spring and had warmer temperatures until planting time. Earlier, Benoit et al. (1986) found that the reduced tillage systems with the residue increased the snow accumulation, which reduced the depth of the frost into the soil. Hatfield and Prueger (1996) compared continuous corn and corn–soybean rotations under no-till, chisel-low, and moldboard plow in central Iowa and found the largest effect of residue was in the fall after harvest when the no-till fields cooled more slowly than the tilled fields. They found that the diurnal temperature patterns were more affected by the presence of residue than the annual patterns. In a recent study, Dahiya et al. (2007) evaluated the effect of mulch on temperature patterns in a loess soil and found that tillage and mulch did not affect the soil thermal conductivity and changed the soil temperatures by less than 1.0°C.

The effect of crop residue and tillage of the surface on the soil temperature regimes with the soil profile is realized through changes in the soil thermal properties. Novak (2005) summarized the soil temperature regime as being affected by two major factors: those that affect the conduction of energy into the soil (Eq. [3]) and those that affect the volumetric heat capacity and soil thermal conductivity. The volumetric heat capacity of a soil is the sum of the individual heat capacities for the soil components weighted by their volumetric fraction. This can be expressed as a simple sum, as shown in Eq. [4]:

$$C = x_m M + x_{om} \mathrm{OM} + x_w W + x_a A \qquad [4]$$

where C is the soil heat capacity and x_m, x_{om}, x_w, and x_a are the fraction of the soil volume comprised of minerals, organic matter, water, and air, respectively. The specific heat values for the individual components are shown in Table 11|1. As the composition of the soil changes there are large impacts on the heat capacity of the soil. Likewise, there are large differences in the thermal conductivity values for the different soil fractions (Table 11|1). As the fractions change within the soil there are large effects on how quickly the soil changes temperature. As tillage affects the amount of air space in the soil or the addition of organic materials into the soil volume, these factors can have large impacts on the soil temperature patterns within the soil profile.

Table 11|1. Thermal properties of the soil components.

Component	Specific heat capacity	Thermal conductivity
	J kg^{-1} K^{-1}	W m^{-2} K^{-1}
Mineral	755	2.9
Organic matter	1920	0.25
Water	4200	0.57
Air	1000	0.025

Evapotranspiration

Evapotranspiration (ET) or latent heat of vaporization (LE in Eq. [1]) represents one of the largest components of the energy balance. For a crop with an adequate water supply in the middle of summer the total ET can be 6 to 7 and as high 10 mm d^{-1}. Soil management practices can have a large impact on ET, and in particular the evaporation of water from the soil surface. The presence of crop residue on the surface acts as a barrier to evaporation of water in the same way in which soil temperatures are affected by the residue. The presence of the residue acts as an entity in which the vapor diffusivity is quite low, slowing the transport of water vapor from the soil surface to the atmosphere.

There have been several different approaches to estimating ET from a surface, the most recognized of which is the Penman–Monteith equation (Penman, 1948; Monteith, 1964) given as

$$\mathrm{ET} = \frac{\Delta\left(R_n - G\right) + \dfrac{m\rho C_\rho\left[e^*(z) - e(z)\right]}{r_a}}{\Delta + \dfrac{\gamma\left(r_a + r_c\right)}{r_a}} \qquad [5]$$

where Δ is the slope of saturation vapor pressure curve, γ is the psychrometric constant, λ is the latent heat of vaporization, m is the ratio of the molecular weight of water vapor to that of air (0.622), ρ the density of air, C_ρ is the volumetric heat capacity of air, e^* is the saturation vapor pressure of the air, e is the actual vapor pressure of the air both at some height z above the surface, r_a is the aerodynamic resistance to water vapor transfer, and r_c the canopy resistance to water vapor transfer. The major variables in Eq. [5] that are affected by soil management are the r_a term, r_c, R_n, G, and e. These are driving variables for ET that need to be examined. There are several forms of ET equations, but this form allows an examination of the factors that are affected by soil management. The resistance terms can be considered analogous to electrical resistors that affect the current flow. In the natural environment, the r_a term describes the rate of air movement from the surface to the atmosphere and is dependent on the wind speed, the roughness of the surface, and the impact of atmospheric stability that is affected by the temperature gradients in the lower atmosphere. The r_c term is the effect of the canopy on the release of water vapor from the leaf to the atmosphere. To place this in perspective, consider that a lush canopy with adequate water will have a minimal resistance, while a water-stressed or canopy with a large amount of senesced leaves will have a maximum r_c value.

Tillage disturbs the soil surface and also disrupts the soil crust, which in turn increases the rate of soil water evaporation from the surface. This is partially due to the exposure of wet soil to dry air in the atmosphere and the adsorption of energy into the surface, which evaporates water. Burns et al. (1971) and Papendick et al. (1973) showed that tillage disturbance of the soil surface increased soil water evaporation amounts compared to untilled areas. Ritchie (1971) found that soil water evaporation is affected by soil water content of the surface and degree of plant cover on the surface. Tillage moves moist soil up to the surface, where losses to drying may offset increased infiltration rates. Hatfield and Prueger (unpublished data, 1999) observed that total soil water evaporation fluxes were 10 to 12 mm for a three-day period following each cultivation operation in the spring in Iowa. Total evaporation fluxes from no-tillage fields were less than 2 mm during this same time period. Aggressive field cultivation operations in the spring could reduce soil water availability in the seed zone by as much as 20 to 30 mm. To replace this soil water lost from the seed zone it is necessary to have timely precipitation events to ensure germination and emergence of the crop. In semiarid areas, soil profile water contents that are near field capacity at the onset of the growing season are critical to crop production. In a recent study in Kansas Klocke et al. (2009) found that surface residue reduced soil water evaporation. Soil water evaporation was reduced by nearly 50% compared to bare soil when either wheat or corn residue nearly covered the soil surface. When they changed the configuration of the surface residue so that there was only partial coverage then corn stover only had a slight impact on soil water evaporation rates. However, full surface coverage with residue reduced soil water evaporation by 50 to 65% compared to the bare soil surface. An interesting aspect of their study was that the suppression of soil water evaporation that led to greater soil water for the crop created an economic impact of \$365.00 ha^{-1}. Manipulating the soil surface either with tillage or crop residue will affect the soil water evaporation. The presence of moist soil at the surface creates a more favorable microclimate for biological activity within the soil and the presence of the residue reduces the impact of raindrops onto the soil surface, thus reducing the potential for erosion by maintaining a larger infiltration rate into the soil.

Another form of a mulch on the surface is that of a dust mulch, in which a layer of dry soil occurs over a moist soil. The changes that occur in this layer serve to reduce the diffusivity of water vapor through the dust and which creates a situation in which the dust acts as barrier for evaporation. The presence of a layer of different diffusivity materials will alter the evaporation rate. In a similar fashion, adding residue to the surface also reduces the evaporation rate of water from the soil.

Soil Management Impacts on the Soil Microclimate

Soil management impacts can be detected in the soil through the effects on the factors that make up the soil microclimate, including the radiation balance, the thermal properties of the soil or crop residue, and the effect of the residue on heat or water vapor exchanges. The processes are governed by the available energy from solar radiation, which is dependent on the location and time of year. We can substantially alter the soil microclimate by how we shape the surface with tillage, remove or incorporate crop residue, or change crop cover during the season. All of these factors are interrelated. The challenge is to determine how to best manage the soil and crop system for a particular location to maximize crop production efficiency, minimize negative environmental impacts, and ensure that positive impacts on the soil increase with time. Evaporation from the surface is affected by different soil management practices. Tillage will temporarily increase soil water evaporation, dry the soil, and cause the soil temperature to rise more than if the soil had not been tilled. There would also be a change in the distribution of water content and soil temperature with depth in the soil profile between the tilled and un-tilled fields. Leaving residue on the surface will alter the radiation balance of the soil, thereby affecting the amount of energy available for heating the soil and evaporating water. Residue management on the soil surface can be effectively used as a method to alter soil water and soil temperature profiles.

Climatic Resources

Decisions about the proper management of the soil that are based on understanding and utilizing the soil microclimate require information about the general climatic conditions for a location. There are various sources of this information; these data often are available from meteorological agencies of a country (Leemans and Cramer, 1991; Lieth, 1972). However, there are some worldwide databases that are maintained by the Food and Agriculture Organization (FAO) that are available through FAOClim2-Net. This database covers monthly data for 28,100 stations and includes up to 14 observed and computed agroclimatic parameters. There are long-term averages for the period from 1961 through 1990 and time series for rainfall and temperature. These data can be retrieved by geographic area, time period, and parameter, and data can be downloaded in different formats for use with different analysis packages. The variables available in this database include maximum air temperature, minimum air temperature, mean air temperature, mean nighttime air temperature, mean daytime air temperature, total daily rainfall, dew point temperature, relative humidity, actual vapor pressure, potential evapotranspiration using the Penman–Monteith equation, wind speed, global solar radiation, sunshine fraction, and sunshine hours. This would be a rich database for the assessment of the climate at any given location.

Challenges

There are many challenges in the assessment of soil management impacts on the soil microclimate, but the principles that affect these changes are relatively simple to understand, and the framework is contained in the energy balance for a given surface. Altering the surface with any soil management practices—tillage and residue management are the primary methods—changes the radiation balance through the albedo, the soil heat flux, and soil water evaporation rate. One challenge is to determine how these factors affect the development of the crop and the associated biological systems in the soil, including the microbes, weeds, pathogens, and insects. The primary challenge for those who manage the soil is to understand these dynamics and their impact on all of the biological systems so that soil management practices can be effectively used to enhance the growing conditions for the crop and diminish the negative impacts of pests on the economic crop.

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