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Crop Residue Effects on Surface Radiation and Energy Balance – Review

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With 6 Figures

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Summary

Crop residues alter the surface properties of soils. Both shortwave albedo and longwave emissivity are affected. These are linked to an effect of residue on surface evaporation and water content. Water content influences soil physical properties and surface energy partitioning. In summary, crop residue acts to soil as clothing acts to skin. Compared to bare soil, crop residues can reduce extremes of heat and mass fluxes at the soil surface. Managing crop residues can result in more favorable agronomic soil conditions. This paper reviews research results of the quantity, quality, architecture, and surface distribution of crop residues on soil surface radiation and energy balances, soil water content, and soil temperature.

1. Introduction

Soil is like a skin for the earth, acting as an interface through which there exists a continuous transfer of energy and mass. Following this analog, a crop residue mulch is to soil what clothing is to people. People use clothing to reduce body heat loss to surrounding cold air. Likewise, during winter, crop residue covering a soil tends to reduce soil heat loss to a colder atmosphere. Both clothing and crop residue can act as thermal insulators. Because of their insulating properties and generally higher shortwave reflectance, surface mulches cause a reduction in soil temperature fluctuations so that the extremes are not as pronounced in mulch-covered soil as they are in bare soil.

The main impact of surface residues on soil environmental conditions is through effects on surface temperature and soil moisture and their complex interaction with surface energy balance. Crop residues affect the radiation balance; they also affect vapor transfer and loss of heat by conduction, convection, and evaporation (Horton et al., 1994; Steiner, 1994). The objectives of this paper are to briefly summarize the effects of surface crop residue on soil temperature and water content, to present the surface energy balance relationships, to describe how surface crop residues affect the components of the surface energy balance, to discuss some of the simulation models developed for residue covered surfaces, and to state research needs.

2. Crop Residue Effects on Soil Temperature and Soil Moisture

Several investigators have reported that the soil thermal regime under crop residue mulch is different from that of bare soil, with soil temperatures often being lower under mulched surfaces than in

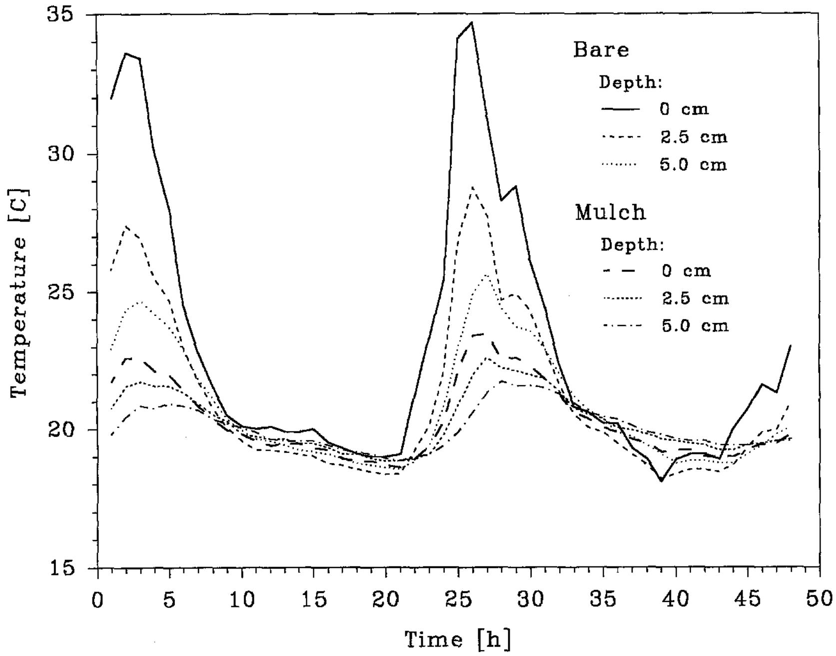

Fig. 1. Temperature observations at the soil surface, and the 2.5 and 5.0 cm depths for bare and soybean mulched conditions in central Iowa

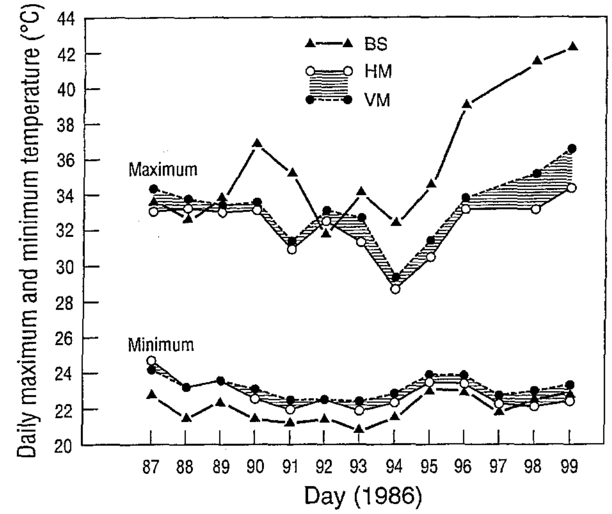

Fig. 2. Daily maximum and minimum soil temperatures at the 2.5-cm depth below bare (BS), horizontal mulch (HM) and vertical mulch (VM) surfaces (from Bristow, 1988)

bare (or plowed) soils (Englehorn, 1946; McCalla and Duley, 1946; Verma and Kohnke, 1951; Jacks et al., 1955; Lemon, 1956; Borst and Mederski, 1957; McCalla and Army, 1961; Unger, 1978; Gupta et al., 1983; Bristow, 1988; Unger, 1988). Figure 1 displays soil temperature observations from central Iowa that show effects of surface crop residue on diurnal soil temperatures. Daytime summer soil temperature was lower under mulch than for bare conditions, and temperature amplitudes were reduced for mulched soil as compared to bare soil.

Bristow (1988) studied bare soil (BS), vertical mulch (VM), and horizontal mulch (HM) treatments, and found that soil water dominated the energy exchange process at the soil surface, and that it was only when the soils began to dry that significant differences in soil temperatures became evident. After several dry days, the HM treatment soil was 10 °C cooler than the bare soil surface; the VM soil was 7 °C cooler (Fig. 2). Minimum soil surface temperatures responded in a manner opposite to that of the maximum temperatures. The differences in minimum temperatures between treatments were greatest under wet conditions and then decreased as the soils dried. The BS treatment yielded the lowest minimum surface temperature in all cases. These trends were reflected at shallow depths in the soil profile as is evidenced by the maximum and minimum temperatures that were recorded at 2.5 cm (Fig. 2).

Reduction of springtime surface soil temperatures under surface mulch can have either positive or negative consequences, depending on the climate. In temperate climates, soil usually is cold and wet and there are fairly low levels of solar radiation at the onset of spring, which together can slow crop growth and development (Unger and Stewart, 1976). Mulch can aggravate this situation by keeping the soil wet and cold for longer periods than would occur for bare soil, thereby shortening the length of the potential growing season. Management strategies that involve mulch banding to leave some bare soil exposed can increase soil warming in these situations. In tropical environments, the opposite usually occurs. The growing season is often preceded by a long dry period, and because solar radiation levels are high, near-surface soil temperatures can be very high (Bristow and Abrecht, 1989). The presence of mulch on the seed row can reduce soil temperature and improve processes such as germination and seedling establishment. Mulch banding also can be a useful management practice in tropical environments.

Larson (1964) was one of the first to discuss management possibilities in distinctly different zones within the crop row. He described a seedling environment zone (row zone) and a water management zone (interrow zone). Bond and Willis (1969) suggested that crop residues could be concentrated in the row or between rows for purposes of minimizing the evaporation of soil water. Black (1970) studied the effects of residue quantity and placement on the distribution of soil water and soil temprature in an experiment with dryland winter wheat (*Triticum aestivum* L.) in Montana. Three row spacings were used, and wheat straw mulch was applied immediately after planting in September. Residue placement consisted of a spatially uniform distribution (random) or strips of residue between or on the row. Soil temperature was measured at the 5-cm depth both in the row and between the row on an hourly basis. In early spring, differences in maximum soil temperatures as large as 10 °C were documented between residue treatments whereas differences in minimum soil temperatures rarely exceeded 1 °C. The results also showed that the between-row residue placement consistently resulted in higher in-row soil temperatures than did the in-row residue placement. In fact, the in-row mean maximum temperatures for the between-row residue placement were quite similar to those obtained for the bare soil control. This result demonstrates that residue placement can be an effective management tool.

Allmaras and Nelson (1971, 1973) conducted field experiments with corn (*Zea mays* L.) in Minnesota to describe patterns in root growth in response to horizontal nonuniformities of soil water and temperature produced by row-interrow variants of tillage and straw mulch. Straw mulch was applied between the row or in the row at a rate of 4500 kg/ha, and a bare soil treatment was included as a control. Allmaras and Nelson (1971) reported differences of less than 2 °C between in-row and interrow mean temperatures. These differences in soil temperature are noticeably smaller than the large temperature differences obtained by Black (1970). Despite the smaller temperature differences, the measurements of temperature with depth indicated that positional variability in soil temperature persisted to at least the 45-cm depth. The use of strip mulches in corn production has also been examined by Lal (1978) in a tropical environment.

In these studies the presence of a growing crop confounds the interpretation of the observed soil temperature patterns. Horton et al. (1984), Horton (1989), and Ham and Kluitenberg (1992) have shown that shading due to the plant canopy alone can lead to significant horizontal variation in soil temperature. Only a few experiments (Bristow and Abrecht, 1989; Hares and Novak, 1992b; Lindwall and Erbach, 1984) have been performed in which the effect of surface mulch is studied independent of plants.

Bristow and Abrecht (1989) reported the results of a strip mulch experiment conducted on loamy sand and clay loam soils without plants. Crop residue mulches were simulated with a fiber mat. Mats were oriented to give bare zones of widths 0 (completely covered), 5, and 15 cm, in addition to a bare control. Soil temperatures were measured at the 5-cm depth in the center of the bare strips. Rates of drying were greatest with bare soil surfaces and least with complete mulch cover. Under both wet and dry conditions, maximum temperature at the 5-cm depth increased significantly with increasing bare row width.

The results of Bristow and Abrecht (1989) and Abrecht and Bristow (1990) reinforce the understanding that soil temperature and soil water status cannot be treated separately. Placement of a strip mulch affects surface energy balance and thus soil water and soil temperature. In the semiarid tropics where residue strips may be used to reduce harmfully high soil temperatures, the beneficial effects of the residue on soil temperature and soil water work together. The residue reduces evaporation of soil water and reduces soil temperature. In the high latitudes, the effects of strip mulch on evaporation and temperature tend to work against each other. In the work of Black (1970) for instance, the between-row residue placement provided the greatest degree of inrow soil warming. The most favorable soil water conditions, however, were obtained with an in-row residue placement. The lower residue rate, whether randomly distributed or placed inrow, was the management technique that would probably result in the best hydrothermal environment for plant growth.

The effect of the dominant role played by water in influencing soil temperature is obvious as shown in Fig. 2 for data for Bristow (1988). When wet, soil temperatures in all treatments were similar. Once the bare surface started to dry (Day 89), there was a rapid increase in soil temperature in this treatment. However, it took only 6 mm of rain late in the afternoon on Day 91 to cause near surface temperatures in all treatments to converge. Drying in the bare soil then proceeded more rapidly and divergence in soil temperatures occurred on the second day after rain. It was not, however, until several days later that soil temperatures in the VM and HM treatments began to diverge. An interesting feature of these data is that the minimum temperatures converged with drying.

3. The Surface Energy Balance

The energy balance at the soil surface is described by

$$R_n + H + LE + G + Q \qquad (1)$$

where R_n is net radiation, H is sensible heat flux, LE is latent heat flux, G is soil heat flux, and Q is the flux of heat into storage. All terms can be expressed in units of W/m^2.

The net radiation at the surface can be partitioned in a number of different ways, depending on the surface and atmospheric conditions, resulting in an energy balance that can be quite different for bare and mulch-covered surfaces. This section describes energy balance for bare soil, and the next section describes how residue modifies the surface energy balance. Although we have introduced the storage term here for completeness, it is generally ignored when dealing with soil surfaces (either mulch covered or bare), because it is assumed to be small in comparison to the other terms.

Values of R_n can be measured directly using net radiometers (Rosenberg et al., 1983) or estimated as

$$R_n = (1-\alpha)S_g + L_i - L_0 \qquad (2)$$

where S_g is global shortwave irradiance (W/m^2), L_i is longwave sky irradiance (W/m^2), L_0 is longwave radiation emitted by the surface (W/m^2), and α is the surface albedo (fraction of S_g reflected by the surface).

The longwave sky irradiance, L_i, can be estimated using the Stefan-Boltzman equation expressed as

$$L_i = \sigma\varepsilon_a T_{Ka}^4 \qquad (3)$$

where σ is the Stefan-Boltzman constant (5.67×10^{-8} W/m^2/K^4), ε_a is atmospheric emissivity, and T_{Ka} is air temperature (K). The atmospheric emissivity can be estimated using air temperature (Campbell, 1977) or atmospheric vapor density (Campbell, 1977; van Bavel and Hillel, 1976).

The longwave radiation emitted by the surface, L_0, can be estimated as

$$L_0 = \sigma\varepsilon_s T_{Ks}^4 \qquad (4)$$

where ε_s is surface emissivity and T_{Ks} is surface temperature (K).

The latent and sensible heat fluxes at the surface can be calculated using the following equations:

$$LE = L(\rho_{vs} - \rho_{va})/r_{va} \qquad (5)$$

$$L = 2.49463 \times 10^9 - 2.247 \times 10^6\, T_s \qquad (6)$$

$$H = \rho C_p(T_s - T_a)/r_{Ha} \qquad (7)$$

Here E is the evaporative flux (m/s), L is the latent heat of vaporization (J/kg) calculated using the surface temperature T_s (°C), ρ_{vs} is vapor density (kg/m^3) at the surface, ρ_{va} is atmospheric vapor density (kg/m^3), r_{Va} and r_{Ha} are the aerodynamic boundary layer resistances (s/m) to vapor and heat transfer, and ρc_p is air volumetric heat capacity (J/m^3/°C).

The aerodynamic boundary layer resistances are functions of wind speed and surface structure and can be calculated in various ways. van Bavel and Hillel (1976) calculated them as

$$r_{Va} = r_{Ha} = S_t[\ln(2.0/z_0)]^2/(0.16\,u) \qquad (8)$$

where S_t is a stability correction factor, z_0 is the roughness length (m) and u is wind speed (m/s) at a height of 2 m.

The vapor density at the surface, ρ_{vs}, can be calculated from the Kelvin equation as

$$\rho_{vs} = \rho^*_{vs} \exp[(M_w \Psi)/(R T_{Ks})] \tag{9}$$

where ρ^*_{vs} is the saturated vapor density (kg/m^3), M_w is the molecular weight of water (kg/mole), Ψ is the matric potential (J/kg) at the surface, R is the universal gas constant (8.314 J/mole/K), and T_{Ks} is surface temperature (K).

The soil heat flux density, G, at the soil surface can be described using Fouriers law of heat conduction

$$G = -\lambda \frac{\partial T}{\partial z} \tag{10}$$

where λ is soil thermal conductivity (W/m/°C) and $\partial T/\partial z$ is the vertical soil temperature gradient (°C/m). The soil thermal conductivity can be measured (Jackson and Taylor, 1986; Bristow et al., 1994) or estimated from bulk density, texture, and water content (De Vries, 1963; Campbell, 1985).

4. Impact of Surface Crop Residue on the Soil Energy Balance

4.1 Energy Balance Components

The two parameters α and ε_s are dependent on surface conditions. Both vary with water content, and both are affected by surface cover. Sharratt and Campbell (1994) studied three different surface residue treatments: black straw, white straw, and natural barley straw. The albedo values for the black, white, and natural straws were 0.50, 0.30, and 0.20, respectively. The shortwave reflectivity of a light-colored residue may be considerably larger than that of a dark-colored soil surface, thereby reducing the amount of solar radiation that reaches the soil surface. In this case, there will be less energy available at the soil surface for evaporating water or for heating the soil. Figure 3, from Hares and Novak (1992b), shows observed R_n for bare and crop residue covered surfaces. Daytime R_n values were larger for the bare surface than the mulched surface. Figure 4 from Bristow (1988), shows daily values of R_n for bare and mulched surfaces. Rain occurred on days 86 and 91. The rain-moistened surfaces show greater R_n for bare than for mulched, and this appeared to be an albedo effect. Bare soil dries more quickly than mulched soil leading to higher surface T. Therefore mulched soil had greater R_n than dry bare soil due to a surface temperature effect.

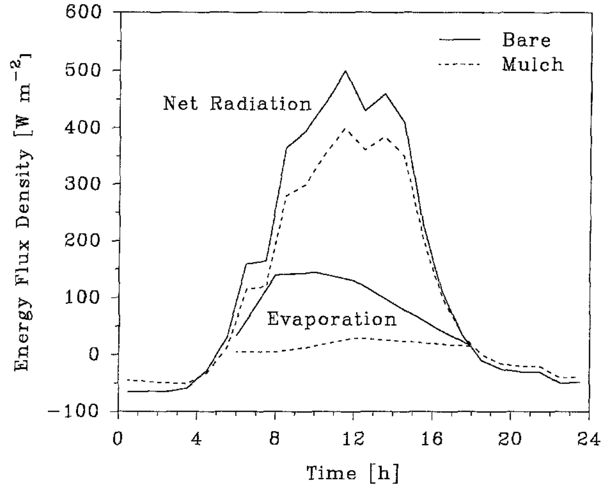

Fig. 3. Observed net radiation and evaporation for bare and crop residue covered soil (from Hares and Novak, 1992b)

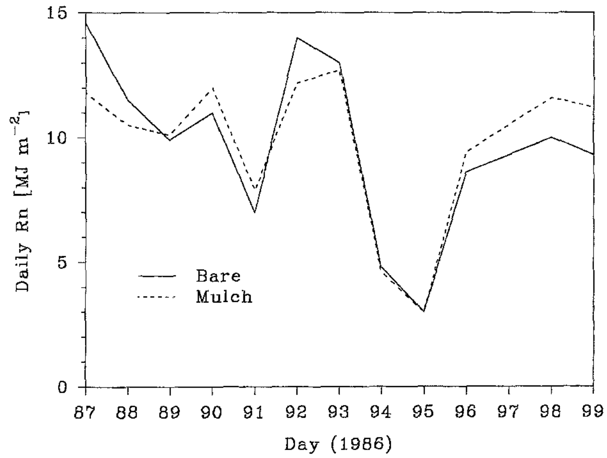

Fig. 4. Daily net radiation for bare and mulched soil surfaces (from Bristow, 1988)

The amount of mulch affects the transmission of radiation through the mulch. As mulch quantity increases, the percent of radiation that can be transmitted through it decreases (Tanner and Shen, 1990; Shen and Tanner, 1990). Quantity also is often associated with percent cover. As mulch mass increases, the percent of soil surface covered by the mulch increases, with obvious consequences on the amount of incident radiation that can reach the soil surface. Shen and Tanner (1990) have measured transmittance as a function

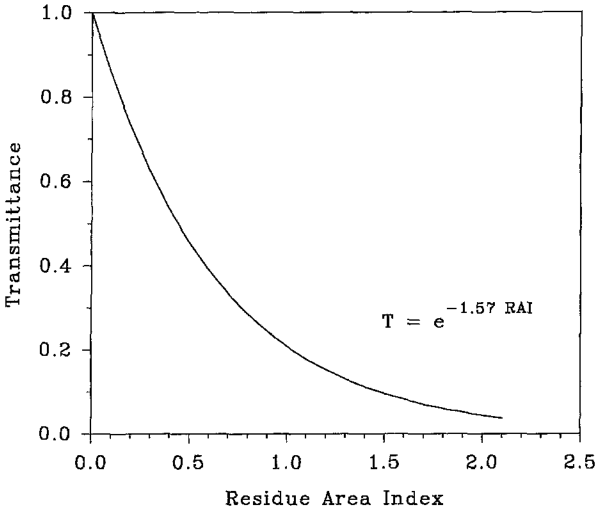

Fig. 5. The extinction of thermal radiation transmitted directly through flail-chopped corn residue (from Shen and Tanner, 1990)

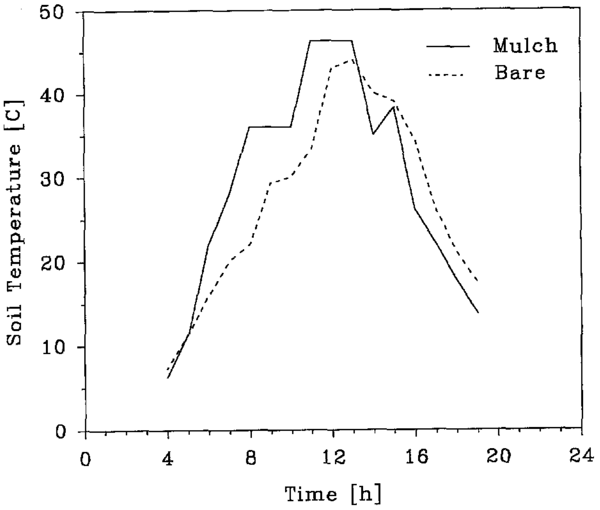

Fig. 6. Bare soil surface and mulch surface temperatures (from Hares and Novak, 1992b)

of mulch cover. Figure 5 shows clearly that crop residue is not nontransparent but that depending upon quantity some radiation transmits through mulch.

A wet soil beneath a crop residue mulch would receive much less energy at the soil-residue interface than a moist bare soil surface because the insulating residue would reduce the energy input (Figs. 3 and 4). Radiation would be reflected and high mulch surface temperature would emit large fluxes of longwave radiation. Sensible heating of the air would be greater thus lower fluxes into soil beneath a mulch would be expected. Figure 6, from Hares and Novak (1992b), shows soil and mulch surface temperature values. Large daytime mulch temperature values cause larger sensible heat fluxes from the mulch than from the bare surfaces. Bussiere and Cellier (1994) present energy partitioning data for moist, bare and mulched soil conditions. Net radiation was 20% lower for the mulched surface compared to the bare surface. Maximum soil heat fluxes were almost 200 and 75 W/m^2, maximum sensible heat fluxes were about 100 and 400 W/m^2 and maximum latent heat fluxes were about 500 and 350 W/m^2 for the bare and mulched soil, respectively.

For most mulch-covered surfaces, the soil will still be the major source of water for *LE*, and an additional resistance term is needed in Eq. (5) to account for the resistance of the mulch layer to vapor flux. This additional resistance term r_{vm} can be estimated as (Hillel et al., 1975)

$$r_{vm} = w/(D_a f \tau) \qquad (11)$$

where w is thickness of the mulch layer, D_a is vapor diffusivity in air (m^2/s), f is mulch porosity, and τ is a tortuosity factor. Eq. (11) does not consider advective transport of gas within the mulch layer, which, if present, will act to decrease r_{vm}. The latent heat flux for mulch covered surfaces can be expressed as

$$LE = L(\rho_{vs} - \rho_{va})/(r_{va} + r_{vm}) \qquad (12)$$

Additionally, crop residue mulches affect the surface vapor density by influencing the water potential and temperature at the soil surface. If soil is wetter and cooler under a crop residue mulch than for the bare condition, then the vapor densities may or may not be similar. Vapor density increases as water potentials increase (become less negative), but it can decrease as temperature decreases.

Bare soil and soil beneath a crop residue cover would have differing conductive fluxes. In general, the wetter the soil, the higher the thermal conductivity and the dryer the soil the higher the temperature gradient. The soil heat flux component under a surface mulch can, nonetheless, be treated in the same way as for bare soils. A more complete description of such a model is provided in Bristow and Horton (1995).

When considering the effects of surface crop residues on the soil surface energy balance, one must consider both the quantity and architecture (orientation of the vegetative elements) of the crop residue. Effect of mulch orientation on the energy balance components was studied in some detail by Bristow (1988). His treatments consisted of bare soil (BS), vertically-oriented surface mulch (VM), and horizontally-oriented surface mulch (HM). He reported that more incoming radiation was reflected by the VM treatment than by the HM treatment in the early morning and late afternoon, and that these differences were more noticeable under dry than under wet conditions. Secondly, the VM treatment lost more soil heat at night than the HM treatment when the soil was wet, but that the reverse occurred under dry conditions. Thirdly, the VM treatment showed a greater increase in daytime soil heat flux density with drying than the HM treatment. All these observations are associated with the way radiation is intercepted and transmitted by the different surfaces, with one obvious feature being the greater penetration of incoming solar radiation around midday in the vertically- than in the horizontally-oriented mulch.

In some studies, useful R_n data have been obtained. The measurements of R_n should be continued, but additional information concerning the components *LE*, *G*, and *H*, which make up R_n, are probably more instructive than knowledge of R_n alone. Net radiation alone does not indicate whether most of the energy is dissipated as sensible heat, soil heat or latent heat. If R_n is primarily dissipated as latent heat, near-surface soil temperatures would probably remain close to air temperature and the chance of experiencing extreme soil temperatures would be minimal. However, if most of the energy is used to heat the soil, then extreme soil temperatures that can be detrimental to processes such as seedling establishment may occur.

In at least one study (Enz et al., 1988) measurements of R_n and G were combined with lysimeter measurements of LE for bare and wheat stubble-covered surfaces. Evaporation was always greater from the bare surface until it was dry (moisture content 8%) as the stubble surface still had soil moisture available for evaporation. While no correlation was found between daily evaporation and net radiation, daily evaporation was correlated with both the time since last precipitation and the wind speed.

Despite the importance of turbulent transport in partitioning available energy at surface-atmosphere interfaces, most research concerning mulch effects on surface energy balance has focussed on transfer processes in the soil and mulch layers. Aase and Siddoway (1980), however, measured wind profiles above a bare surface and two surfaces with wheat stubble at different heights to obtain values of the zero plane displacement, *d*, and z_0. Subsequent estimates of *H* increased substantially with increasing stubble height. Aase and Siddoway (1980) concluded that the enhancement of sensible heat transfer was due to increased turbulence generated by the standing stubble. No information is available concerning the scale and frequency of turbulent eddies created by stubble or mulch-covered surfaces yet these turbulence characteristics would enhance the understanding of turbulent transfer processes above such surfaces (Raupach, 1989).

Discussion of crop residue effects on surface and subsurface processes has focused primarily on situations in which coverage of the surface is spatially uniform. Although uniform coverage of the soil surface is common, many conservation tillage row-crop systems result in incomplete surface residue coverage or in crop residues that are oriented in more-or-less distinct strips, separated by strips of bare soil.

In the case of mulch covered soil, the "surface" is more diffuse in nature and this needs to be taken into account when computing the various components of the surface energy balance. For example, when computing R_n for a mulched surface, the albedo must represent the mulched surface as a whole, and not just the soil surface. Also, both the soil and mulch contribute to L_0 and H, and this needs to be taken into account. Using a weighted average surface temperature $\bar{T}$, where $\bar{T}$ can be calculated as

$$\bar{T} = cT_m + (1 - c)T_s \tag{13}$$

is one way to calculate L_0 and H for mulch covered soils. Here c is the fractional cover (0–1) provided by the mulch, which is assumed to be uniformly distributed in space, T_m is a mulch temperature (°C), and T_s is the soil surface temperature (°C).

The distinctive feature of the soil surface energy balance in the presence of crop residue strips is the positional variation in the energy balance in a direction perpendicular to the residue strips and/or crop row. Strips cause two-dimensional heat and water transfer to occur in the soil-mulch-atmosphere system. The basic energy balance of the soil beneath the mulched strip will be altered due to changes in net radiation, but differential rates of drying between the bare and mulched surfaces are responsible for most of the positional variability. In general, the bare strips dry more rapidly than the mulched strips after rainfall or irrigation. Decreases in soil water evaporation lead to increased soil heating, and bare-soil temperatures become higher than those for the soil beneath the mulched strips. The degree of positional variability in surface energy balance is, therefore, dependent on the time since an irrigation or rainfall.

Surfaces with strips of bare soil interspersed with mulch-covered strips also present conditions conducive to local advection. Each of the parallel strips exhibit abrupt changes in aerodynamic roughness and possibly surface temperature and moisture content that will influence near-surface vertical profiles of wind speed, air temperature, and humidity. Previous field research on advection, even in micrometeorology, has, however, generally addressed advection processes at much larger scales than are found for mulch strips (Rider et al., 1963; Rao et al., 1974). Novak et al. (1994) did compare the energy balance of a bare soil with that of small bare circular openings within an area having a thick mulch layer. Evaporation in the mulch opening was 15–20% higher than in the bare area, an effect attributed to the advection of warmer, drier air from the top of the mulch layer.

Few energy balance measurements are available for strip mulches. Measurements of the soil surface energy balance as a function of position have never been conducted to the best of our knowledge. Data collection has instead focused directly on variables influenced by the surface energy balance, such as soil temperature and water content, but even these direct measurements are of limited availability.

4.2 Modeling Effects of Crop Residue on Soil Surface Energy Balance

Although several attempts have been made to relate soil temperature to mulch attributes, such as amount of mulch (Englehorn, 1946; Gupta et al., 1981) and fractionl cover of mulch, it is difficult to obtain universal relationships. This approach, which is based on empiricisms, would need an enormous amount of field work in order to accommodate the complex way in which the lower atmosphere, mulch, and soil interact. The recent move towards development of simulation models that attempt to incorporate the basic energy exchange processes occurring in the soil-mulch-atmosphere system is encouraged. Examples of such models are Horton and Chung (1991), Ross et al. (1985), Bristow et al. (1986), Chung and Horton (1987), Hares and Novak (1992a), Sui et al. (1992), Bussiere and Cellier (1994). Greater interaction between 'modelers' and 'experimenters' should also be encouraged, so that laboratory and field experiments are used to guide model development, while at the same time model output is used to guide the experimental process.

Models designed to treat the two-dimensional partial surface mulch problem have been developed. Chung and Horton (1987) developed an energy balance model of the strip mulch that uses two-dimensional coupled heat and liquid water flow in the soil. Hares and Novak (1992a) developed a numerical model that includes shortwave and longwave radiation effects of the mulch strips on the bare strips, but their model does not treat unsaturated water flow. Hares and Novak (1992b) presented an approach for describing energy transfer through a mulched surface. Analytical approaches for studying heat conduction in a two-dimensional field have been proposed by Kluitenberg and Horton (1990) and Novak (1993).

Hares and Novak (1992b) compared predicted and observed evaporation and soil temperature for bare, straw-mulched, and partially mulched surfaces in Vancouver, BC. Soil temperature and evaporation rates in bare and uniformly-covered straw-mulched plots were predicted reasonably well, except for the bare plot when evaporation was soil limited. For the strip-tillage plots, the model underestimated (energy-limited) evaporation rates and soil temperatures in 0.1-m-wide bare strips separated by 0.3-m-wide mulch strips. One reason for this disagreement could be that the model did not consider micro-scale advection of warmer and drier air from the mulch strips to the bare strips. Measurements showed that springtime soil temperatures in bare strips were nearly equal to those in an adjacent bare plot.

5. Conclusions

Research results indicate that crop residue mulch can have a large impact on soil temperature and soil water content. Several observations of mulch effects on temperature and water content are reported in the literature. The soil temperature and water content are linked with surface energy partitioning. Only a few studies have measured mulch effects on surface radiation balance, and even fewer studies of mulch effects on surface energy partitioning have been reported. We encourage further research on surface energy partitioning.

Research results suggest that the presence of soil water near the soil surface governs the soil surface energy balance and resultant soil temperatures. Under wet conditions, most of the incoming energy is used in evaporating water so that the latent heat term, LE, dominates regardless of the type of bare or mulched surface involved. In these cases, near-surface soil temperatures under bare and mulched surfaces are similar, and not very different from air temperature. It is only when drying takes place that differences in the way energy is partitioned begins to manifest as differences in soil temperature. When exposed to drying conditions, the LE term will decrease most rapidly in bare soils with a resultant rapid increase in soil temperature. It is only later in the drying cycle when soils under surface mulch begin to dry, that the effect of mulch geometry on the surface energy balance shows up as differences in soil temperatures.

Crop residue mulches have been used to manage soil temperature and soil water content. Both random residue distribution and mulch strips have been used. Further work is needed in order to fully understand the physical system. Radiation, aerodynamic, and heat and mass transfer properties of crop residue should be more frequently and fully determined. The dual-probe heat pulse technique can be used to document spatial and temporal dynamics in soils and mulches (Bristow et al., 1994). Simulation models of the soil-mulch-atmosphere system will be useful for management purposes only when accurate physical properties are available as model inputs. Advancements in actual observations of surface energy partitioning as well as the modeling of surface energy partitioning need to occur together in order to further our understanding and improve our management capability.

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