Microclimate Modification with Plastic Mulch

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Horticultural production must achieve the maximum quality of a harvested organ in addition to sufficient yield. By contrast, the goal of agronomic production generally is to maximize the amount of plant biomass per unit of land area by maximizing the amount of solar radiation absorbed by the entire crop. Therefore, agronomic crops typically are planted at high densities so that the plants will cover the soil surface as rapidly as possible. In contrast, many horticultural systems are designed to optimize yield per plant rather than per unit land area; they demand less dense plant spacings to achieve the desired quality and to facilitate cultivation, harvesting, and produce handling. Less dense plantings create “sparse” crops, where the canopy does not fully shade the underlying surface. Therefore, environmental interactions in most horticultural crops include those between the plant and the exposed soil as well as those between the plant and the atmosphere.

The economic value of most horticultural crops routinely justifies modifying the crop’s microclimate to accelerate growth, improve quality, and/or extend the growing season. Environmental modifications can be expensive, as in the cases of heated glasshouses and supplemental lighting, or they can be technologically simple and inexpensive, as in the case of home gardeners’ “hot caps” or “wall-o-water.” To achieve the most economically efficient and biologically effective microclimate, one must understand the physics of energy transfer between the crop and the environment. Although these physical principles have not changed during the past 25 years (Tanner, 1974), we have improved some of the techniques of monitoring the crop microclimate and have measured energy exchanges in a variety of horticultural systems. This paper will review previous research and present new data to demonstrate the influence of black plastic mulch on the plant microclimate, with an analysis based on the physical principles outlined by Tanner (1974).

PLASTIC MULCH

Plastics chemistry is advanced enough to provide growers with a film with optical properties that are ideal for a specific crop in a given location (e.g., Graham et al., 1995; Splittstoesser and Brown, 1991; Stevens et al., 1991), but horticulturists first must define the optimum above- and below-ground environ-

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ments for that crop. For example, clear plastic mulch promoted the establishment of bermudagrass (Cynodon dactylon L.) during the fall, but the same mulch was detrimental to summer establishment because mean soil temperatures frequently exceeded those that are tolerated by these seedlings (Sowers and Welterlen, 1988). In a subtropical climate, peppermints (Capsicum sp.) grew faster and set fruit earlier on white plastic mulch than on straw mulches (Vos and Sumarni, 1997), whereas in a hot, semiarid climate, black plastic resulted in scalding of the fruits and thus reduced yields (Roberts and Anderson, 1994). These reports and others show the importance of accounting for the above-ground as well as the below-ground influences of a mulch (Table 1). The list in Table 1 is far from exhaustive, but it illustrates the range of crops studied and the attention paid to particularly high-value crops like tomatoes (Lycopersicon esculentum Mill.) and peppers.

Black plastic is the overwhelming standard among growers worldwide (Schales, 1990), but specialized applications of other colored plastics have been documented. In hot climates, for example, season-long soil warming beneath a black plastic may be undesirable: white and aluminized reflective mulches are good alternatives. Typically, black and clear mulches raise soil temperatures above ambient, whereas white and aluminized plastics may either raise or lower soil temperature slightly. In early July in Kansas, daytime soil temperatures at 10 cm were ≈ 4 °C lower beneath white and aluminized reflective plastics than beneath black plastic, and 1 to 2 °C lower than in bare soil (Ham et al., 1993). In a color-changing system where black, photodegradable mulch is laid over white plastic, soil temperatures decline as the black mulch degrades and exposes more white plastic (Graham et al., 1995). This system warms soil rapidly in the spring and suppresses weeds during the entire season, while avoiding excessively high soil temperatures during the summer. Early yields of tomatoes were higher over red and black mulches, which induce higher soil temperatures, than over white and reflective plastics (Decoteau et al., 1989). The high early yields in tomatoes that have been regularly documented for black and clear plastic mulches (e.g., Bhella, 1988; Wien and Minotti, 1987, 1988; Wien et al., 1993) recently were attributed to preferential partitioning of carbon to fruits rather than to foliage (Teasdale and Abdul-Baki, 1997).

An above-ground spectral response exists in addition to the response to elevated soil temperatures, and may be physio-chemical (e.g., phytocrome regulation) or radiative (e.g., increasing or decreasing the heat load on the foliage). For example, in a pepper canopy, twice as much reflected photosynthetically active radiation (PAR) was measured above clear plastic mulch than above black plastic or bare soil (Cebula, 1995). Elsewhere, white plastic reflected six times more PAR than black and ≈50% more than a silver reflective mulch (Decoteau et al., 1989). Radiative effects were observed over a reflective, aluminum foil mulch that raised daily maximum air temperatures within a satsuma mandarin (Citrus unshui Kovich) canopy by up to 3 °C and lowered minimum nighttime temperatures by 0.3 to 1.3 °C (Richardson et al., 1993). Although both red and black plastics raised soil temperatures by the same amount, higher early yields and less foliage were observed in plants grown on the red plastic. Both red and black mulches reflected about the same amount of PAR, but red plastic increased the ratio of red to far-red (R:FR) in the reflected light (Decoteau et al., 1988, 1989). The R:FR ratio and the amount of blue light reflected toward the canopy apparently are critical. In turnips (Brassica rapa L.), blue and green mulches induced longer leaves and higher shoot : root ratios than white mulch. The R:FR ratio of light reflected from white plastic is lower than that of sunlight, which in turn is lower than that of blue or green plastics. Blue and green plastics differ in reflected blue light, which influenced the development of flavor compounds in the turnip roots (Antonius et al., 1996).

One shortcoming of the literature on mulch is that most papers describe empirical studies of the response of some crop to mulching (Table 1), but few include extensive measurements of relevant microclimate variables. This is disconcerting because, as mentioned by Tanner (1974), the plant’s transpiration rate and, in turn, its temperature, are tightly coupled with its microclimate. Micrometeorological data can contribute to the identification of the physiological mechanisms that drive a crop’s response to mulching. However, measurements of only a few hours or days are inadequate for interpreting physiological responses, which can reflect changes in the microclimate from weeks or even months earlier (Monteith and Elston, 1971). More detailed environmental measurements must be incorporated into field studies if we are to separate complex physiological processes into individual components that respond to discreet variables in the physical environment.

The remainder of this paper will focus on plastic mulch and its effects on the transfer of...
| Crop               | Plastic          | Reported biological effect                                                                 | Reported environmental effect                                      | Reference                           |
|--------------------|------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------------------------|-------------------------------------|
| Bermudagrass       | Clear            | 1) Improved germination and establishment (fall)                                              | Elevated soil temperature                                           | Sowers and Welterlen, 1988          |
|                    |                  | 2) Decreased germination and establishment (summer)                                          |                                                                     |                                     |
| Pepper             | Black            | Earlier flowering, higher early yield                                                       | Increased soil temperature, soil water conserved                    | VanDerwerken and Wilcox-Lee, 1988  |
| (Capsicum sp.)     | White and        | Scalding injury (reduced yield)                                                             | Elevated canopy temperature, Reflective properties deterred         | Roberts and Anderson, 1994         |
|                    | aluminized       | Delayed viral diseases virus vectors, esp. thrips                                          |                                                                     | Vos et al., 1995                   |
|                    | Clear            | 1) Decreased stand establishment                                                             | 1) Excessive soil temperature                                      | Caverio et al., 1996               |
|                    |                  | 2) Increased yield                                                                          | 2) Increased soil temperature                                       |                                     |
|                    | White and        | Faster plant growth, earlier fruit set, increased yield and fruit size concentrations, reflected light | Soil temperature, soil water conservation, soil nutrient           |                                     |
|                    | aluminized       |                                               |                                                                     |                                     |
|                    | Black            | Increased tree height and girth                                                             | Reduced weed competition                                           |                                     |
|                    |                  |                                               |                                                                     | Adams, 1997                        |
| Oak (Quercus sp.)  | Black            | No significant effect on growth or survival                                                 |                                                                     |                                     |
| Willow and Pine    | Black            | Increased yield                                                                             | Decreased weed competition                                          | Ricotta and Masiunas, 1991         |
| (Salix planifolia Pursh) |              |                                               |                                                                     |                                     |
|                    |                  |                                               |                                                                     | Davis, 1994                        |
|                    | Black            | Increased yield                                                                             |                                                                     |                                     |
| Basil (Ocimum basilicum L.) | Black | Increased soil temperature                                                             |                                                                     |                                     |
| Parsley (Petroselinum crispum (Mill.) Nym. ex A.W. Hill) | Black | Decreased yield                                                                          |                                                                     |                                     |
| Summer squash      | Aluminized       | Delayed onset of mosaic virus, leading to increased yield                                  | Reflective properties deterred aphids                               | Brown et al., 1993                 |
| Zucchini (Cucurbita pepo var. melopepo (L.) Alaf.) | Black | Increased plant size; increased yield                                                       |                                                                     |                                     |
|                    |                  |                                               |                                                                     | Bhella and Kwolek, 1984           |
| Muskmelon (Cucumis melo L.) | Black | Increased early yield                                                                       | Increased soil temperature                                           | Bonnano and Lamont, 1987           |
| Watermelon [Citrullus lanatus (Thumb.) Matsum. & Nakai] | Black | Earlier flowering; increased early and total marketable yield                              |                                                                     |                                     |
|                    |                  |                                               |                                                                     | Decoteau and Rhodes, 1990         |
| Corn               | Black            | Accelerated canopy establishment, increased yield                                           | Soil temperature                                                    | Van der Werf, 1993                 |
|                    | Black            | Increased grain yield                                                                       | Soil water conserved                                               | Fisher, 1995                       |
| Sweet potato       | Black            | Increased shoot biomass, leaf area; increased yield, marketable roots                      | Increased soil temperature and/or decreased soil compaction         | Hochmuth and Howell, 1983          |
| [Ipomoea batatas (L.) Lam.] | Black |                                               |                                                                     |                                     |
| Tomato             | Clear            | More flower clusters; increased yield; higher shoot N, P, K, Ca                            |                                                                     |                                     |
|                    | Black            | Higher yields; greater biomass                                                             | Higher soil nitrogen                                                |                                     |
|                    | Various          | Timing and magnitude of yield                                                               | Root zone temperature and spectrum of reflected light              |                                     |
|                    | Clear            | 1) Increased root length                                                                    | 1) Soil temperature                                                | Wien et al., 1993                  |
|                    |                  | 2) Increased branching, earlier flowering                                                  | 2) ---                                                             |                                     |
|                    | Various          | Increased yield of high quality fruit                                                       | Reflected light deterred disease vectors                            | Csizinsky et al., 1995             |
|                    | Black            | Increased root length, early shoot growth, early yield                                      | Soil temperature and nitrogen dynamics                              |                                     |
|                    | Black and        | Early flowering, increased total yield                                                      | Soil temperature, near-surface air temperature                      | Mashingaidze et al., 1996          |
|                    | clear White      | Increased yield                                                                            | Lower soil temperatures                                            | Hanna et al., 1997                 |
| Strawberry         | Black and clear  | Increased partitioning to fruits; increased early yields                                   | Elevated soil temperature                                           | Waggoner et al., 1960              |
| (Fragaria xananassa Duch.) | Black |                                               |                                                                     |                                     |
|                    | Black and clear  | Improved sugar:acid ratio in fruit; higher yield reflected into canopy                     | Increased soil temperature, quality of radiation                    | Gupta and Acharya, 1993             |
| Coffee             | 1) White         |                                               | 1) Slight increase or decrease in soil temperature; conserve soil water | Gurnah and Mutea, 1982             |
|                    |                  |                                               |                                                                     |                                     |
|                    | 2) Black and clear |                                               | 2) Increased soil temperature; conserve soil water                  |                                     |
| Satsuma mandarin orange | Black | Earlier bud break, increased canopy volume, fruit set, yield, quality                     | Increased air temperature within canopy                             | Richardson et al., 1993            |
energy (i.e., heat) within the crop microclimate. An energy transfer accounting system, the “surface energy balance,” will be reviewed, and data representing the energy balance of a mulched field will be presented. Each form of energy transfer in crops will be explained and typical measurement techniques mentioned. The subscripts “soil,” “mulch,” and “canopy” will denote energy transfer to or from the bare soil between strips of plastic mulch, to or from the plastic mulch, and to or from the crop, respectively.

**ENERGY (HEAT) EXCHANGE IN THE CROP ENVIRONMENT**

**Net radiation**

Net radiation ($R_n$; Fig. 1), the largest daytime energy input, is the sum of all radiation (R) exchange at the surface of a plant ($R_{n,canopy}$), soil ($R_{n,soil}$), or mulch ($R_{n,mulch}$; Fig. 2). It is composed of solar shortwave ($R_{SW}$, 0.2 to 1.4 μm) and terrestrial longwave ($R_{LW}$, 2 to 50 μm) radiation. The peak wavelength for energy emitted by most terrestrial objects is ~9 μm. Photosynthetically active radiation comprises the 0.4–0.7 μm waveband; solar energy above 0.7 μm is referred to as “near-infrared” radiation. Longwave radiation often is called infrared or “thermal” radiation. Solar radiation may be a direct beam or may be diffuse due to scattering by clouds, atmospheric molecules, vegetation, a translucent rowcover, etc.; the total of direct and diffuse radiation is called global irradiance ($R_s$).

By convention, energy fluxes are assigned positive or negative values to denote their direction: energy transferred toward the crop (or soil, or mulch) is assigned a positive value, and energy moving away from the crop a negative value to define the direction of the vector [the energy flux (Fig. 2)]. Thus, daytime $R_n$, which is dominated by incoming $R_s$, is positive, but nighttime $R_n$, which is dominated by $R_{LW}$ leaving the crop or mulch surface, is negative.

Both solar and terrestrial radiation are absorbed, reflected, and transmitted in various proportions according to the optical properties of a surface: absorptance ($\alpha$), reflectance ($\rho$), and transmittance ($\tau$). Table 2 lists optical properties of several surfaces, including black plastic mulch and various crops. Optical properties generally are listed as an average value for a particular waveband (e.g., $\alpha_{SW}$ for 0.2–1.2 μm), weighted by the energy spectrum in the waveband. Soil, mulch, and other vegetation can reflect solar radiation toward a canopy, thereby increasing the total impinging on the plant surface (Fig. 2). For example, a reflective foil sheet covering the ground beneath an apple (Malus ×domestica Borkh.) tree increased the absorption of PAR by the canopy by 40% compared with bare soil and by 24% when the mulch covered half of the soil surface (Green et al., 1995).

All objects emit longwave radiation ($R_{LW}$) as a function of their temperature and emissivity ($\varepsilon$). Emissivity is the fraction of radiation emitted by a surface compared with that emitted by a “perfect” emitting body ($\varepsilon = 1.0$) at the same temperature, an ideal that does not exist in nature. The relationship is formalized by the Stefan-Boltzmann law:

\[ R_{LW} = \varepsilon \sigma T^4 \]  

where $\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W·m$^{-2}$·K$^{-4}$) and $T$ is the temperature of the surface (K). Using this formula we can calculate that a leaf at 20 °C ($\varepsilon = 0.96$) would emit $400$ W·m$^{-2}$ and black plastic mulch at 55 °C ($\varepsilon = 0.92$) would emit $600$ W·m$^{-2}$.

Over uniform surfaces, including closed canopies (Fig. 1), $R_n$ is measured with a net radiometer that accounts for both short- and longwave radiation. The instrument’s output is the difference between downward and upward fluxes of both $R_{SW}$ and $R_{LW}$. Idso (1974) thoroughly reviewed the use and calibration of net radiometers, the basic design of which has not changed since that time. Measuring $R_n$ of distinct patches on a nonuniform surface, or of a sparse canopy, is technically more challenging because the radiometer, with a hemispherical view, may “see” more than the desired surface. For example, $R_n$ of an isolated tree was measured by use of eight net radiometers.
Table 2. Optical properties of various surfaces.

| Surface          | Shortwave optical properties | Longwave optical properties | Reference                  |
|------------------|-----------------------------|-----------------------------|---------------------------|
|                  | $\alpha_{SW}$ | $\rho_{SW}$ | $\tau_{SW}$ | $\varepsilon = \alpha_{LW}$ | $\rho_{LW}$ | $\tau_{LW}$ |          |
| Plastic mulch    |              |              |              |                                  |              |              |          |
| Black            | 0.96         | 0.03         | 0.01         | 0.920.87$^*$ | 0.67$^*$ |              | Ham et al., 1993 |
| White            | 0.51         | 0.48         | 0.01         | 0.89$^*$     | 0.51$^*$ |              |              |
| Aluminized       | 0.60         | 0.39         | 0.01         | 0.28$^*$     | 0.09$^*$ |              |              |
| Clear            | 0.05         | 0.11         | 0.84         | 0.05         | 0.13     | 0.82         | Avissar et al., 1986$^*$ |
| Bare Soil        |              |              |              |              |          |              |          |
| Silt loam:       |              |              |              |              |          |              |          |
| dry              | 0.73         | 0.27         | ---          | 0.93         | 0.07     | ---          | Ham and Senock, 1992 |
| wet              | 0.85         | 0.15         | ---          | 0.96         | 0.04     | ---          |              |
| Sandy loam:      |              |              |              |              |          |              |          |
| dry              | 0.67         | 0.53         | ---          | 0.88         | 0.12     | ---          | Graser and Vanel, 1982$^*$; Ham et al., 1993$^*$ |
| wet              | 0.82         | 0.18         | ---          |              |          |              |              |
| Clay loam:       |              |              |              |              |          |              |          |
| dry              | 0.70         | 0.30         | ---          |              |          |              | Idso et al., 1975 |
| wet              | 0.86         | 0.14         | ---          |              |          |              |              |
| Sand:            |              |              |              |              |          |              |          |
| dry              | 0.65         | 0.35         | ---          | 0.91         | 0.09     | ---          | Campbell and Norman, 1998$^*$; Graser and Vanel, 1982$^*$ |
| wet              |              |              |              | 0.94         | 0.06     | ---          | Buettner and Kern, 1965$^*$ |
| Silty clay:      |              |              |              |              |          |              |          |
| dry              | 0.77         | 0.23         | ---          | 0.92         | 0.08     | ---          | Graser and Vanel, 1982$^*$; Chen et al., 1989$^*$ |
| wet              | 0.85         | 0.15         | ---          | 0.93         | 0.07     | ---          |              |
| Crops            |              |              |              |              |          |              |          |
| Apple (leaf)     |              |              |              | 0.95         | 0.01–0.05 | 0.0–0.04   | Gates, 1980 |
| Barley (canopy)  |              |              |              | 0.23         | 0.98     |              | Fritschen, 1967$^*$; Heilman et al., 1981$^*$ |
| (Hordeum vulgare L.) |          |              |              |              |          |              |              |
| Corn (leaf)      |              |              |              | 0.29         | 0.94     |              | Davies and Buttimor, 1969$^*$; Idso et al., 1969$^*$ |
| (canopy)         |              |              |              | 0.17         | 0.98     |              | Brown and Covey, 1966; Jacobs and Van Pul, 1990$^*$ |
| Cotton (leaf)    |              |              |              | 0.52         | 0.22     | 0.26         | Gates, 1980$^*$; Idso et al., 1969$^*$ |
| (canopy)         |              |              |              | 0.21         |          |              | Montieth and Unsworth, 1990 |
| Cottonwood (leaf) |              |              |              | 0.51         | 0.22     | 0.27         | Gates, 1980 |
| (Populus deltoides) |          |              |              |              |          |              |              |
| Geranium (leaf)  |              |              |              | 0.55         | 0.22     | 0.23         | Gates, 1980$^*$; Idso et al., 1969$^*$ |
| (Pelargonium ×hortorum L.H. Bail.) | | | | | | | |
| Orange (canopy)  |              |              |              | 0.16         | 0.94     |              | Montieth and Unsworth, 1990$^*$; Idso et al., 1969$^*$ |
| [Citrus sinensis (L.) Osbeck] | | | | | | | |
| Peach (leaf)     |              |              |              | 0.59         | 0.25     | 0.16         | Gates, 1980 |
| [Prunus persica (L.) Batsch.] | | | | | | | |
| Pepper (leaf)    |              |              |              | 0.53         | 0.21     | 0.26         | Gates, 1980$^*$; Idso et al., 1969$^*$ |
| (Capsicum annuum L.) | | | | | | | |
| (canopy)         |              |              |              | 0.22         |          |              | Davies and Buttimor, 1969 |
| Snap bean (leaf) |              |              |              | 0.82         | 0.10     | 0.08         | Moss and Loomis, 1952$^*$; Fuchs and Tanner, 1966$^*$ |
| (Phaseolus vulgaris L.) | | | | | | | |
| (canopy)         |              |              |              | 0.24         |          |              | Montieth and Unsworth, 1990 |
| Sunflower (leaf) |              |              |              | 0.54         | 0.24     | 0.22         | Gates, 1980 |
| (Helianthus annuus L.) | | | | | | | |
| Sugar cane (canopy) |              |              |              | 0.15         | 0.99     |              | Montieth and Unsworth, 1990$^*$; Idso et al., 1969$^*$ |
| (Saccharum officinarum L.) | | | | | | | |
| Tobacco (leaf)   |              |              |              | 0.29         | 0.97     |              | Davies and Buttimor, 1969$^*$; Idso et al., 1969$^*$; Davies and Buttimor, 1969$^*$; Fuchs and Tanner, 1966$^*$ |
| (Nicotiana tabacum L.) | | | | | | | |
| (canopy)         |              |              |              | 0.24         | 0.97     |              | Montieth, 1959$^*$; Idso et al., 1966$^*$ |
| Turfgrass (canopy) |              |              |              | 0.25         | 0.97     |              | Montieth, 1959$^*$; Idso et al., 1966$^*$ |
| (mixed sp.)      |              |              |              |              |          |              |              |
| Tomato (leaf)    |              |              |              | 0.28         | 0.98     |              | Davies and Buttimor, 1969$^*$; Idso et al., 1969$^*$ |
| (canopy)         |              |              |              | 0.22         | 0.98     |              | Montieth, 1959$^*$; Nkemdirim, 1973 |
| Wheat (canopy)   |              |              |              | 0.22         | 0.98     |              | Huband and Montieth, 1986$^*$ |
| (Triticum aestivum L.) | | | | | | | |
| Other surfaces   |              |              |              |              |          |              |          |
| Water (large body) | 0.02–0.06   | 0.99         | 0.01         | ---          |          |              | Gates, 1980$^*$; Buettner and Kern, 1965$^*$ |
| Snow (old)       | 0.25         | 0.75         | 0.95         | 0.05         | 0.94     | ---          | Tanner, 1974 |
| Aluminum foil (bright) | 0.20         | 0.80         | 0.95         | ---          |          |              | Tanner, 1974$^*$; Campbell & Norman, 1998$^*$ |

$^*$Value for plastic on soil.
$^*$Longwave properties only.
$^*$Shortwave properties only.
$^*$Mean of bean, tobacco, swiss chard, and spinach.
mounted on a rotating, circular frame (Green, 1993; McNaughton et al., 1992). In addition to unique instrument configurations, mathematical adjustments must be made for the geometry of an irregular system and for the optical properties of any extraneous surfaces detected by the net radiometer. Such corrections become more complex with the patchiness of the surface and often require additional temperature measurements to calculate the longwave components of dissimilar surfaces. In the absence of direct measurements, \( R_{\text{c}} \) can be calculated from equations that account for \( R_{\text{s}} \), the optical properties of the surface, and the temperatures of the surface and its surroundings. Davies and Idso (1979) offer a comprehensive treatment on calculating the components of a surface radiation balance from standard meteorological data.

**Soil heat flux**

Heat transfer in soil (Fig. 1) occurs by conduction (G): the movement of energy by molecular vibrations in a solid or between a solid and a motionless fluid. Heat moves upward to the surface (positive flux) or downward into the soil profile (negative flux) from warmer to cooler layers of soil according to Fourier’s Law:

\[
G = -D_{\text{h}} \frac{(T_{z} - T_{1})}{(z_{2} - z_{1})} \tag{2}
\]

where \( D_{\text{h}} \) is the thermal “diffusivity” of soil—its ability to transmit heat \((\text{W} \cdot \text{m}^{-1} \cdot \text{°C}^{-1})\), and \((T_{z} - T_{1})/(z_{2} - z_{1})\) is the change in temperature \((T)\) with depth in the soil \((z)\). Conduction between an opaque plastic mulch and the underlying soil surface (Fig. 2) determines the effect of the mulch on soil temperature (Ham and Kluitenberg, 1994). Colored plastics (except aluminized, reflective mulches) absorb nearly all solar radiation, raising their surface temperature (Table 2). If the mulch has been installed tightly and is in direct contact with the soil, the thin layer of air between plastic and soil is minimized and heat is transferred readily by conduction, leading to a rise in soil temperature. Alternatively, if a plastic mulch is laid loosely, leaving an “air gap” between plastic and soil, then heat first must be conducted from the plastic to the still air layer before diffusing through the air gap and being transferred to the soil. Because air has a much lower thermal diffusivity than soil, heat transfer from the mulch in this scenario is slowed and most of the energy at the hot plastic surface is transferred by convection to the atmosphere.

To estimate heat flux at the soil surface \((G_{s})\), a “combination method” has been established as a standard technique (Kimball and Jackson, 1979). This method is a practical application of Fourier’s Law that involves measuring conduction at some depth in the soil \((G_{s})\), commonly 5 to 10 cm, with heat flux plates (Fuchs, 1986), estimating the volumetric heat capacity \((pc)\) of the soil between the surface and the flux plates \((\Delta z = 5 \text{ or } 10 \text{ cm})\), and measuring the rate of change in temperature \((T_{1} - T_{2})/t_{1} - t_{2})\) in that layer of soil:

\[
G_{s} = G_{1} + pc_{p} \frac{(T_{1} - T_{2})}{(t_{1} - t_{2})} \Delta t \tag{3}
\]

Historically, estimating \(pc_{p}\) is the least reliable part of the combination method because it requires gravimetric sampling of the water content in the layer between the surface and the heat flux plates. Practical constraints limit the frequency of gravimetric sampling (e.g., daily to weekly). Recently, the development of a sensor to measure \(pc_{p}\) directly, near the soil surface and in small volumes of soil (Campbell et al., 1991; Tarara and Ham, 1997) has improved the reliability of the combination method by providing frequent \((e.g., \text{hourly})\) measurements above the flux plate. Mayocchi and Bristow (1995) reviewed the measurement of \(G\) and discussed the impact of errors in measurement of \(pc_{p}\) and potential errors connected with the depth of the evaporation front in the soil.

**Latent heat flux**

Evaporation affects energy transfer because of the latent heat of vaporization \((\lambda)\): the amount of energy that is absorbed by water in changing from a liquid to a gas \((\lambda = 2450 \text{ J} \cdot \text{g}^{-1})\). The same amount of energy is released when water condenses. Thus, condensation warms, but the evaporation cools a surface. We use \(LE\) to denote “latent” \((\text{generally evaporative})\) heat flux. Evaporation transfers energy from the surface to the water vapor, which then diffuses or is carried into the atmosphere. Latent heat flux cools a leaf surface so that the temperature of a well-watered, transpiring canopy will be similar to, or lower than, that of the surrounding air. Canopy temperatures are related to transpiration rates. A parallel situation occurs at a wet soil surface: evaporation reduces the difference in temperature between the surface and the air.

In 1802, Dalton recognized a functional relationship among wind speed, atmospheric humidity, and temperature at the evaporating surface, although exact equations were not defined until much later (Brutsaert, 1982). For the past several decades, Ohm’s Law \((V = IR)\) has been applied to evaporation as a conceptual tool (Jones, 1992). Ohm’s flow of current \((I)\) is analogous to \(LE\), Ohm’s voltage potential \((V)\) represents the difference in humidity between the evaporating surface and the air, and Ohm’s electrical resistance \((R)\) becomes a conceptual analogue to the factors that limit \(LE\). As with conduction, an equation states the relationship concisely:

\[
LE = -\lambda \sum_{n} \left( f_{i} / L_{i} \right) \tag{4}
\]

where \(f_{i}\) is measured sap flow \((\text{g} \cdot \text{s}^{-1})\) per plant and \(L_{i}\) is leaf area per plant \((\text{m}^{2})\).

Sap flows of transplanted tomatoes (Fig. 3) show the potential for differences in \(LE_{\text{canopy}}\) between mulched and bare soil plants, and the magnitude of transpiration in a sparse crop: maximum flows approached 250 to 300 \(\text{g} \cdot \text{h}^{-1} \cdot \text{m}^{-2}\) of leaf area \((\approx 225 \text{ W} \cdot \text{m}^{-2} \cdot \text{LAI}_{\text{canopy}}\) based on LAI). The plants shaded about half of the plastic \((\text{LAI} = 1\text{–2})\) and had already set fruit on the lowest trusses. Transplant density was <1 plant per m² of land area. By contrast, irrigated corn in a high-density stand \((= 7.5 \text{ plants per m}^{2} \text{ of land area})\) at the same location was transpired in LAI = 5 \((\text{closed canopy})\; J.M.\; Ham, \text{unpublished data})\). Roughly speaking, 1 ha of sparse tomato plants may use the same amount of water as 1 ha of dense corn plants, but the corn distributes \(LE_{\text{canopy}}\) across more leaf area.

The horticultural goal of maximizing \(R_{S}\) per plant also means increasing \(R_{S}\) per plant, consequently inducing higher \(LE_{\text{canopy}}\) to dissipate that energy. Dense crops distribute the energy in \(R_{S}\) and \(R_{C}\) \((\text{W} \cdot \text{m}^{-2}\) of surface area) among a larger number of individual plants, thus reducing the total amount of energy that...
a single plant must dissipate. Furthermore, dense canopies create a cool, humid microclimate because latent heat and water vapor are not rapidly transported away from the interior of the crop. Air movement inside a closed canopy is much less than that in a sparse crop (Arkin and Perrier, 1974; Perrier et al., 1970, 1972) even as late as harvest if the canopy never covers the surface of the field. This scenario is true of most upright crops grown on plastic mulch, as well as spaced plantings like orchards and vineyards. For example, in one vineyard, changes in trellising from narrow, compact hedgerows to a wider, less dense canopy resulted in higher \( R_{n,\text{canopy}} \) and \( L_{E,\text{canopy}} \), and lower \( L_{E,\text{soil}} \) (Heilman et al., 1996). The size of coffee (\textit{Coffea arabica} L.) trees grown in hedgerows markedly influenced energy transfer from the plantation. At low LAI, the relative distribution of \( L_{E,\text{soil}} \) between soil and canopy resembled that of a sparse row crop, but at high LAI, \( L_{E,\text{canopy}} \) dominated and \( L_{E,\text{soil}} \) was negligible, as one would expect above the closed canopy of a field crop (Gutiérrez and Meinzer, 1994).

Because plastic mulch is virtually impermeable to water and water vapor (Stevens et al., 1991; Waggoner et al., 1960), no evaporation occurs. Thus, there is essentially no \( L_{E,\text{mulch}} \) (Fig. 2). Evaporation of dew or irrigation water from the surface of the plastic is a short-lived, intermittent process that has a trivial effect on the energy balance of the mulch surface over the course of a day. For the purposes of this discussion, such evaporation will be ignored. From bare soil, \( L_{E,\text{soil}} \) occurs in relation to the water content of the surface and near-surface layers.

**Sensible heat flux**

Convection (H) is the transfer of energy to or from a surface by a moving fluid; because it is heat that we can feel, H denotes “sensible” heat flux. In a crop system, the fluid is air (Fig. 1). Like conduction, convection is driven by a difference in temperature. In a mulch-sparse crop system (Fig. 2), convection is governed by mulch-air, soil-air, and canopy-air differences in temperature:

\[
H = -g_s \rho c_p (T_s - T_a)
\]  

where \( T_s \) is surface temperature; \( T_a \) is air temperature; \( \rho c_p \) is the heat capacity of air; and \( g_s \) is a sensible heat “transfer coefficient”—the constant of proportionality between the energy flux (H) and its driving force (\( T_s - T_a \)). Often, \( g_s \) is conceptualized as a “conductance” to heat transfer that accounts for the aerodynamic characteristics of the surface and moving fluid. It varies with wind speed and the roughness of the surface, and mathematically is simply the inverse of the resistance concept introduced by Eq. [4]. In the literature, one is as likely to encounter equations of H in a “resistance” form as in a “conductance” form, the choice depending largely on the measurement techniques used and the conceptual preference of the author.
Convection generally denotes the vertical transfer of energy; when $H$ is transferred horizontally between patchy surfaces, it is called advection. Advection was identified in a number of early studies of sparse agronomic crops (e.g., Chin Choy and Kanematsu, 1974; Hanks et al., 1971). In a sparse cotton crop, advection from the dry soil surface (i.e., negative $H_{\text{soil}}$) increased LE$_{\text{canopy}}$ (Ham et al., 1990, 1991). In a vineyard in west Texas, advection from dry soil induced 17% to 36% of the evaporation from the vines (Heilman et al., 1994). These examples should be noted because the temperature differences between bare soil and a sparse canopy typically are less than those between a sparse canopy and many plastic mulches (Ham et al., 1993).

Sensible heat flux from plastic mulches and bare soil surfaces can be calculated from Eq. 6 if one records spatially representative measurements of $T_s$, $T_a$, and $g_s$. Estimates of $g_s$ can be obtained by applying the concept of a surface energy balance to “conductance sensors” (McInnes et al., 1994, 1996; Tarara and Ham, 1999). Similar techniques have been used to estimate $g_s$ for individual leaves (e.g., Brenner and Jarvis, 1995). Spatially representative measurements of soil surface and mulch temperatures are easier to obtain (Ham and Senock, 1992; Tarara and Ham, 1999) than are measurements of canopy temperature, especially in sparse crops where surface temperatures are highly variable. Infrared thermometry is well established for uniform vegetation (e.g., Fuchs and Tanner, 1966), but over seedlings the instrument will “see” both plant and underlying soil or mulch surface. It is possible to use infrared techniques in sparse canopies if corrections are made for the extent to which the canopy covers the soil and for the background radiation from the soil and/or sky that is detected by the instrument (Heilman et al., 1981; Lhomme et al., 1994; Stewart et al., 1994). These corrections are not trivial and are complicated further by the presence of a mulch.

**Surface energy balance**

The accounting system for energy transfer in a crop, the total “energy balance,” can be expressed conveniently in an equation:

$$R_n + G + H + LE + S + P = 0$$

where $S$ is energy stored within the volume of the crop. The energy consumed by photosynthesis ($P$), while critical to life, consumes <1% of the energy in solar radiation and typically is ignored in energy balance calculations (Nobel, 1974). Energy turnover by metabolic processes likewise is neglected (Larcher, 1980). When a crop’s canopy is “closed”—fully covering the underlying soil—Eq. 7 is simplified by treating the crop as a uniform, two-dimensional surface rather than a three-dimensional volume. This eliminates $S$, yielding the “surface energy balance” relation

$$R_n + G + H + LE = 0$$

diagrammed in Fig. 1. Each term is expressed as a “flux density,” or the rate of energy transfer per unit of surface area (W·m$^{-2}$).

### Fig. 5. Soil temperatures from Days of Year 217–223, 1995, at (A) 2.5 cm, (B) 10 cm, and (C) 20 cm beneath a transplanted tomato crop on raised beds covered with black plastic mulch or left bare. The crop shaded at least half of the bed surface. Data were collected near Manhattan, Kans. Temperatures were measured along the center of the beds with thermocouples housed in hypodermic needles ($n = 6$ per depth).

By the law of Conservation of Energy, the surface energy balance must close; i.e., the sum of all energy transfer to and from the crop is zero. Equation 8 also is valid for determining the energy balance of a soil or mulch surface. Many researchers have found it attractive to measure or model $R_n$, $G$, and $H$, then solve a surface energy balance for LE (e.g., Brunel, 1989; Kustas, 1990).

In contrast, for a sparse crop on plastic mulch, we must determine three relationships:

$$R_n + G + H + LE = 0$$

$$R_n + G + H + LE = 0$$

$$R_n + G + H + LE = 0$$

A 24-h energy balance for black plastic mulch (Eq. 10) and for the bare soil between rows (Eq. 9) is shown in Fig. 4. When we separate the energy balances of a sparse crop, conduct at the soil surface ($G_s$) is not included in the energy exchange of the canopy (Eq. 11).

An energy balance cannot be measured directly. Rather, well-developed methods exist for measuring or estimating most of the variables in Eqs. 8–11. Solving these equations often is not the experimental goal per se, but instead is a means of estimating, rather than measuring directly, crop water use via LE$_{\text{canopy}}$ (Tanner, 1960). Consequently, researchers have focused on either measuring LE$_{\text{canopy}}$ itself or measuring $R_n$, $G$, and $H$ to solve Eq. 9 for LE$_{\text{soil}}$ and Eq. 11 for LE$_{\text{canopy}}$ to estimate crop water use. Historically, sparse crops have received less attention in research because their irregular aerodynamic and optical properties present significant technical and theoretical difficulties to measuring the components of the energy balance. Field-scale techniques that are appropriate for solving Eq. 8 over a closed canopy do not provide the detail necessary to separate the energy balance of sparse vegetation from that of the bare soil or a plastic mulch (Eqs. 9–11; Fig. 2).

**MICROCLIMATE MODIFICATION BY PLASTIC MULCH: APPLICATIONS**

The surface energy balance of plastic mulch and its influence on the above- and below-
ground crop environment are determined by both the optical properties of the plastic (Ham et al., 1993; Waggoner et al., 1960) and the degree of contact between the plastic and the underlying soil (Ham and Kluitenberg, 1994; Liakatas et al., 1986). The link between mulch-soil contact and mulch optical properties is illustrated by seemingly conflicting reports on soil temperature. These observations merit attention because growers have been advised to use clear plastic to “solarize” soil and opaque plastics to control weeds. Higher soil temperatures have been recorded beneath black plastic mulch, which transmits only 1% of RS, than beneath clear plastic, which transmits up to 84% of RS (Ham et al., 1993). Stretching the plastic film tightly across the soil apparently results in more effective soil heating by conduction than by direct transmission of solar radiation (Ham and Kluitenberg, 1994). Conversely, laying mulch loosely across the soil creates an insulating layer of air between plastic and soil, causing higher daytime soil temperatures under clear than under black plastic (Liakatas et al., 1986). In many reports where the extent of soil-plastic contact was not stated explicitly, clear plastic induced more extreme diurnal fluctuations in soil temperature than did black plastic (e.g., Bonanno and Lamont, 1987; Cebula, 1995; Waggoner et al., 1960). However, less extreme fluctuations were observed under clear than under black plastic when both were tightly stretched across raised beds (Ham et al., 1993). Generally, one can expect the highest midday soil temperatures under mulches with high shortwave absorptance (i.e., black) or high shortwave transmittance (i.e., clear).

During July in North Carolina, Wu et al. (1996) found that soil temperatures beneath clear plastic were 5 to 15 °C higher at 10 cm and 4 to 12 °C higher at 20 cm than beneath bare soil. Elevated temperatures were observed up to 30 cm. In Kansas, under a tomato crop that shaded about half of a mulched bed, soil temperatures were consistently 3 to 5 °C higher beneath black plastic than beneath bare soil, to depths of at least 20 cm (Fig. 5). Elevated soil temperatures were observed as late as harvest (Days of Year (DOY) 240–260), at which time the plants shaded most of the mulch. At the same site, in the absence of a crop, midday soil temperatures at 2.5 cm were up to 8 °C higher beneath black plastic mulch than under bare soil (Fig. 6B). These raised beds (13 cm high, 72 cm wide) had good mulch-soil contact.

Black plastic mulch and bare soil can have similar \( R_n \) (Fig. 7). At first glance, one might expect \( R_{n,\text{mulch}} \) to exceed \( R_{n,\text{soil}} \) because the black plastic absorbed 96% of RS while the bare soil absorbed only 67%. However, the mulch surface was generally warmer than the bare soil surface (Fig. 6A), thereby emitting more longwave radiation (\( \varepsilon_{\text{mulch}} = 0.87; \varepsilon_{\text{soil}} = 0.88 \)). Net radiation differed by \( \approx 70 \text{ W·m}^{-2} \) near midday when the soil surface was dry (Fig. 7A). When the bare soil surface was wet (Fig. 7B) its shortwave absorptance (\( \alpha_{\text{sw}} \)) increased (Table 2), which we would expect because a wet soil is darker than a dry
one. Also, evaporation (\(LE_{\text{soil}}\)) cooled the surface. Higher \(\alpha_{SW}\) (more \(R_S\) absorbed) coupled with a lower surface temperature than under dry conditions (less outgoing LW) resulted in \(R_{n,\text{soil}} \approx R_{n,\text{mulch}}\) around midday. Both \(R_{n,\text{soil}}\) and \(R_{n,\text{mulch}}\) track the diurnal pattern of \(R_S\). At night, \(R_S\) typically is slightly negative; global irradiance is zero and the longwave radiation emitted by each warm surface (negative flux) exceeds that absorbed from the cooler surroundings (positive flux).

Because of its large \(\alpha_{SW}\) (Table 2), the surface temperature of black plastic mulch can be relatively high during the day (Fig. 6A), leading directly to a large amount of emitted \(R_{LW}\) (e.g., 475 W·m\(^{-2}\) at 40 °C and 575 W·m\(^{-2}\) at 55 °C) that contributes to the incoming \(R_{n}\) of \(R_{n,\text{canopy}}\) (Fig. 2). If we assume that a white plastic surface is \(\approx 15\) °C cooler than a black one (Ham et al., 1993), emitted longwave would be somewhat lower (400 W·m\(^{-2}\) at 25 °C and 485 W·m\(^{-2}\) at 40 °C) from the white mulch. Black mulch reflects only a small amount of \(R_S\) into the canopy, \(< 25\) W·m\(^{-2}\) around noon on a sunny day (e.g., 3% of 800 W·m\(^{-2}\)). By contrast, white plastic reflects 48% of \(R_S\) toward the canopy (e.g., 385 W·m\(^{-2}\) of an incident 800 W·m\(^{-2}\)). Therefore, total radiation directed toward the canopy is higher above a white (785–870 W·m\(^{-2}\)) than above a black plastic (500–600 W·m\(^{-2}\)). Assuming equal \(T_a\) above both mulches and a 15 °C difference in surface temperature, \(H_{\text{mulch}}\) would be higher from the black (370–500 W·m\(^{-2}\)) than the white surface (60–200 W·m\(^{-2}\)). Thus, in this scenario, although the sum of radiation leaving a white plastic is higher than that leaving a black plastic, the total energy directed at the canopy via radiation and convection would be quite similar (=850 to 1100 W·m\(^{-2}\)) for these two plastics with very different optical properties.

Plastic mulches influence the above-ground environment via radiation, transpiration, convection, and photobiology. Additionally, planting holes cut through plastic mulches potentially direct CO\(_2\) toward the canopy of seedlings, the so-called “chimney effect.” As much as 2× ambient concentrations have been measured above holes cut for transplants (Soltani et al., 1995).

Convection is the major mechanism of energy transfer from plastic mulch and from dry, bare soil. A midday temperature profile from the surface to 2 m illustrates the driving force for \(H\) (Eq. [6]; Fig. 8). The black plastic was \(\approx 20\) °C warmer than the air 2.5 cm above it; dry, bare soil between mulched beds was \(\approx 7\) °C warmer than the overlying air. At one site, mean daily air temperatures above white and clear plastics were within 1 °C of those above bare soil while air temperatures above black plastic were \(\approx 5\) °C higher (Wien et al., 1993). Therefore, black plastic mulch can obviously contribute a significant amount of sensible heat to the aerial environment of a sparse crop. Daytime \(H_{\text{mulch}}\) for black plastic ranged from \(< 10\%\) to \(90\%\) of \(R_{n,\text{mulch}}\) over the course of a day, but did not change with the wetness of the soil surface between beds (Fig. 9A). Midday \(H_{\text{mulch}}\) was \(\approx 60\%\) of \(R_{n,\text{mulch}}\) whereas...
H_soil did not exceed 40% of R_n,soil from a visibly dry soil surface or 10% of R_n,soil from a visibly wet surface. Midday LE_soil dissipated 25% of R_n,soil when the surface was dry and upwards of 60% of R_n,soil when the surface was wet (Fig. 9B). From a wet soil surface, H_soil generally is small and may be either positive or negative depending on surface and air temperatures. If T_s > T_a (i.e., H_soil > 0) the soil surface absorbs energy from the air and if T_s < T_a (i.e., H_soil < 0) heat is transported from the soil surface to the overlying layer of air.

Any differences in G_0 between mulch-covered and bare soil occurred during early morning and late afternoon (data not shown) when solar radiation, hence energy absorbed by the surface, was changing rapidly. Black plastic absorbed more solar radiation (α_mulch = 0.96; α_soil = 0.67), thereby creating a larger difference in temperature between the plastic and underlying soil than between the bare surface and its adjacent soil layer. During the day, G_0 dissipated between 25% and 50% of R_n (Fig. 9C). Data collected in Kansas indicated that simulated G_0 was comparable beneath clear and black plastic mulches (Ham and Kluitenberg, 1994). Neither plastic induced large fluxes, even during midsummer, because once energy was transferred from the plastic to the soil surface the extent of conduction depended on the thermal properties of the soil. A white-on-black plastic (white side up), which reflects 88% of R_n, caused the lowest simulated G_0. In midsummer, surface temperature were as much as 17°C lower on white than on black plastic mulches (Ham et al., 1991).

The geometry of a mulch-soil system also influences G_0. Raised beds lead to a larger conducting surface that is isolated on two sides from the rest of the soil. Under a clear mulch, high soil temperatures (>35°C) occurred more often in raised beds than in level soil (Caver et al., 1996). An average temperature increase of 2 to 4°C has been reported for raised beds (Chellami et al., 1997). The width of mulched strips can be manipulated to minimize a well documented “edge effect,” where the increase in soil temperatures beneath a mulch declines from the center to the edge of the plastic (Maher and Katan, 1981). Beds >60 cm wide apparently minimize the edge effect. However, in one solarization study, a gradient of decreasing soil temperature from the middle to the edge of a 2.5-m-wide mulched strip was correlated with a corresponding gradient in nematode control and in plant height (Grinstein et al., 1995).

In sparse crops, management practices that are intended to reduce soil evaporation, including plastic mulch, may increase LE_canopy by substantially increasing H_soil and H_mulch directed toward the canopy (Fig. 2). One would expect higher rates of transpiration from seedlings grown on black plastic mulch than from those grown on bare soil because of the potentially large values of H_mulch. In sparse cotton (Ham et al., 1991), wet soil in effect reduced LE_canopy by cooling the soil surface, thereby reducing the magnitude or changing the direction of H_soil and simultaneously reducing the amount of R_n reflected into the canopy by increasing α_canopy (Table 2). A dry soil surface sharply reduced LE_canopy but increased LE_canopy because of advection. Because of LE_canopy, transpiring vegetation generally is cooler than the surrounding air; therefore, H_canopy during the day usually is positive as the air warms the plant surface. The opposite (negative H_canopy) often occurs at night if the canopy temperature rises above that of the air because LE_canopy is negligible at night.

CONCLUSION

Growing most crops on plastic mulch results in partial canopy cover; consequently, the energy balances of both the mulch and the bare soil between rows affect the exchange of energy (i.e., heat) between the plant and its environment. Optical properties of the mulch and the extent of mulch-soil contact determine the effect of the plastic on both the above- and below-ground environment. Below-ground effects are manifested primarily in soil temperatures and the rate of conduction between the mulch and the underlying soil surface. The extent of soil warming depends partly on the degree of contact between plastic and soil. Plastics with high shortwave absorptance or high shortwave transmittance can be expected to raise soil temperatures most dramatically. Above-ground effects are primarily due to the optical properties of the mulch and the fact that plastic prevents evaporation (i.e., L_E_mulch = 0). Convection is the major mode of dissipating energy from the mulch surface. The magnitude of H_mulch depends largely on R_n and is not measurably influenced by the water content at the bare soil surface between rows of mulch. Black plastic mulch, the industry standard, can transfer by convection a large amount of heat to seedlings or transplants, potentially inducing high rates of transpiration. However, given well-mixed air, high LE_canopy from a wet surface may mitigate some of the effects of large quantities of sensible heat (H_mulch+ H_soil) directed toward seedlings. Management of the inter-row, bare soil surface should be considered in relation to the soil’s influence on the crop energy balance. One’s choice of plastic should be guided by the desired above- and below-ground effects, which are determined by the optical properties of the plastic, by mulch-soil contact, and by the geometry of mulched beds. The most effective combinations can be chosen by augmenting one’s understanding of crop biology with an understanding of the physics of a surface energy balance.

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