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Measurement And Modeling Of Heat Transfer Mechanisms In Mulch Materials

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MEASUREMENT AND MODELING OF HEAT TRANSFER MECHANISMS IN MULCH MATERIALS

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ABSTRACT. *Crop residues or mulches affect soil temperature influencing plant growth and related processes in the soil. A hot/cold plate combination was used to quantify heat transfer through several common dry test mulch materials (rubber chips, pine straw, wheat straw) and identify and quantify heat transfer mechanisms with the goal of modeling apparent thermal conductivity of the mulch. Mulch material bulk densities ranged from near 0 kg/m^3 to 33 kg/m^3 , mulch thickness ranged from 61 mm to 140 mm and test temperatures ranged from 20°C to 45°C. To determine the effect of thermal radiation on heat transfer, measurements were taken with the test material between both a set of low emissivity aluminum (Al) plates and a set of high emissivity black painted plates. To quantify free convection, measurements were made in a thermally unstable configuration with the hot plate on the bottom and the cold plate on top and in a thermally stable configuration with the cold plate on the bottom and the hot plate on top. In thermally unstable situations (i.e., bottom plate hot, top plate cool), free convection and conduction mechanisms best explained the heat flux. In thermally stable conditions, radiation and conduction best explained heat flux. The percentage of heat due to thermal radiation decreased as mulch thickness and density increased in both the thermal stable and unstable conditions. The percentage of heat transfer due to free convection (unstable case) and due to conduction (stable case) generally increased as mulch thickness and density increased. For a given mulch material, the thermally unstable condition results in an increased apparent thermal conductivity (k) value. The difference between the k values for stable and unstable cases tended to diminish with pine straw or wheat straw mulches compared to air. Increasing the mulch thickness (plate spacing) resulted in the most difference with low mulch densities or no mulch. Differences are probably not statistically meaningful at the high mulch densities. For pine straw the average k was 0.11 W m^{-1} K^{-1} and for wheat straw 0.08 W m^{-1} K^{-1}. Models were created to develop the radiation, conduction and convection parameters for the mulches tested, with r^2 values for the estimated parameter fit ranging from 0.75 to 0.99. These models could be used to estimate the apparent k of dry mulches in the field.*
Keywords. *Mulch, Heat transfer, Conduction, Convection, Thermal radiation.*

Mulches are an integral part of cultural practices in growing agricultural and horticultural crops. The increasing popularity of no-tillage farming, for instance, results in more soils being covered by a layer of organic residue or mulch. Mulches have impact on various aspects of the underlying soil. A mulch-covered soil is less susceptible to erosion and has a different moisture regime than a bare soil. Tolk et al. (1999) reported a 17% increase in maize grain yield resulting from mulch application. This increase was attributed to a decrease in evaporation from the soil, so that more water was available for use by the plant.

Mulching can also have large impacts on soil temperature (Bristow et al., 1986; (Bussiere and Cellier, 1994). For a variety of crops, mulches are used deliberately to change soil temperature (and moisture) regimes. Different mulch types modify soil temperatures in different ways. Tindall et al. (1991) found that straw mulches have the potential to improve tomato yields in high temperature environments, such as that found in the state of Georgia. Soil temperatures also are critical in biological and chemical processes that control nutrient cycling.

To predict (simulate) the effect of mulches on soil temperatures and other variables, simulation models have been developed (Van Bavel and Hillel, 1975; Chung and Horton, 1987; Bristow, 1988; Sui et al., 1992; Bussiere and Cellier, 1994; Bristow and Horton, 1996). Lascano and Baumhardt (1996) modified an energy and water balance model (ENWATBAL) to simulate a mulch layer. They used the same mulch resistance for both water vapor and heat transfer. Hares and Novak (1992) created a two-dimensional, physically based numerical model to simulate surface energy balance and soil temperature under strip tillage conditions. Predictions agreed reasonably well with field measurements.

Quantification of heat transfer within the mulch material is often a weakness. There is a lack of good experimental data to be used in such models (Shen and Tanner, 1990; Bussiere and Cellier, 1994). Only some of the authors actually report the mulch apparent thermal conductivity they used (van Donk, 1999). Thermal radiation, conduction, and free and forced convection are all expected to be contributing mechanisms in heat transfer through

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mulch materials. Experiments conducted by van Donk (1999) examined the influence of forced convection on the apparent conductivity of several mulches. Heat transfer by thermal radiation acts in parallel with heat transfer by conduction and convection. Thermal radiation from the sky is either directly transmitted through gaps in the mulch or it is absorbed and re-emitted by mulch elements. The same happens to thermal radiation emitted by the soil upward through the mulch.

Pelanne (1969) conducted experiments on the separation of heat transfer mechanisms in low-density glass fiber insulation. He used an apparatus with the test material between a hot and a cold plate. In order to study radiative heat transfer, he made measurements with the plates painted black (high emissivity) as well as gilded (low emissivity). He considered radiative heat transfer to be due to two separate components: radiative conductivity and radiative transmission. Radiative conduction was thought of as the process of heat transfer by fibers absorbing and reemitting thermal radiation. Radiative transmission is the direct transmission of radiation through the “holes” in the insulation.

In a field situation, when the soil surface is warmer than the air above the mulch, heat transfer upward may be increased through the mechanism of free convection. This type of convection is suppressed when the soil surface is cooler than the air above the mulch (Shen and Tanner, 1990). In the field, heat transfer upwards through the mulch typically can be expected during the night and transfer downwards during the day. Heat transfer may also be by conduction and possibly by radiation and forced convection. Free convection will be relatively more important when forced convection is negligible (low wind speed), and when conduction is small, as would be the case in a “fluffy” or straw-type mulch, with close to 100% volume being air (with a low thermal conductivity). Shen and Tanner (1990) conducted laboratory experiments with a flail-chopped corn residue, measuring heat flux through the material between two temperature controlled plates. To investigate the role of free convection, the plates were inverted. Free convection was found to be insignificant for their type of mulch.

The objective of the work presented in this article was to identify and quantify the contributions of thermal radiation and free convection to overall heat transfer through several mulch materials. Insight into these contributions will enable modelers to more realistically model mulch apparent thermal conductivity. If mechanisms other than conduction are significant, mulch apparent thermal conductivity can no longer be represented by a single constant. Instead, there should be a mulch apparent thermal conductivity submodel, simulating all relevant heat transfer mechanisms.

THEORY

Thermal radiation between plates of different temperature and equal emissivity is expressed as (Pelanne, 1969):

$$q''_r = \frac{\sigma\left(T_h^4 - T_c^4\right)}{R + 2\left(\frac{1}{\varepsilon - 1}\right)} \qquad (1)$$

where

q''_r = heat flux due to thermal radiation (W m^{-2})
σ = Stefan-Boltzmann constant = 5.67×10^{-8} W m^{-2} K^{-4}
T_h = temperature of hot plate (K)
T_c = temperature of cold plate (K)
R = opacity parameter
ε = emissivity of hot plate
= emissivity of cold plate

The opacity parameter, R, is equal to 1 when the space between the plates is empty. It increases with increasing density and/or thickness of the layer of material between the plates, reflecting a reduction in radiative heat transfer. Heat flux due to free convection can be expressed as:

$$q''_{cv} = h \; \Delta T \qquad (2)$$

$$h = \frac{Nu \; k_{cd}}{L} \qquad (3)$$

where

q''_{cv} = heat flux due to free convection (W m^{-2})
ΔT = temperature difference between hot and cold plate (°K)
h = convective heat transfer coefficient (W m^{-2} K^{-1})
k_{cd} = thermal conductivity of the mulch (W m^{-1} K^{-1})
Nu = Nusselt number
L = characteristic length (in this case distance between hot and cold plate, m)

The mulch is a composite layer such as a straw-air layer, so k_{cd} is the integrated thermal conductivity of this composite material. Globe and Dropkin (1959) measured data for heat transfer between two horizontal plates, heated from below, and found this correlation:

$$Nu = 0.069 \; Ra^{1/3} \, Pr^{0.074} \qquad (4)$$

$$Ra = \frac{g \, \beta \left(T_h - T_c\right) L^3}{\alpha \, \upsilon} \qquad (5)$$

$$\beta = \frac{1}{\frac{\left(T_h + T_c\right)}{2}} \qquad (6)$$

$$Pr = \frac{\upsilon}{\alpha} \qquad (7)$$

where

Ra = Raleigh number
Pr = Prandtl number
g = gravitational constant = 9.81 m s^{-2}

β = volumetric thermal expansion coefficient (K^{-1})
α = thermal diffusivity of air ($m^2\ s^{-1}$)
ε = viscosity of air ($m^2\ s^{-1}$)

Equations 2 through 7 taken together results in this expression for convective heat flux:

$$q''_{cv} = 0.069\ k_{cd}\, g^{1/3}\, \alpha^{-0.407}\, \upsilon^{-0.259} (\Delta T)^{4/3}\, \beta^{1/3} \quad (8)$$

Heat flux due to conduction only is given by:

$$q''_{cd} = k_{cd} \frac{\Delta T}{L} \quad (9)$$

where
q''_{cd} = heat flux due to conduction (W m^{-2})

These mathematical expressions for the three heat transfer modes were used in the data analysis as explained below.

METHODS

The dry mulch materials selected were pine straw, wheat straw, sandy soil, and tire chips (chopped automobile tires). Dimensions of the materials were measured and results are shown in table 1. The average and standard deviation for every material are for sample sizes of 20. Densities were determined using a gas pycnometer. Every density value in table 1 is the average of three replicates. The soil was taken from the top (Ap) horizon of a field containing 76.8% sand and 3.6% clay at the USDA-ARS J. Phil Campbell Sr., Natural Resource Conservation Center in Watkinsville, Georgia. Wheat straw came from the same Center. Pine straw was purchased from local vendors. Tire chips were obtained from Waste Tire Management, Lawrenceville, Georgia. Porosity was calculated from the bulk density in table 2 and the material (particle) density in table 1. Mulch moisture content was measured before the heat transfer experiments were conducted, using ASAE Standard S358.1 for drying "forage products in their various forms" (24 h at 103°C). Average moisture contents were 6.4, 7.9, and 0.4% wet basis for wheat straw, pine straw, and soil, respectively.

Table 1. Straw dimensions and particle densities of mulch materials

Material	Straw Length (mm)		Straw Width (mm)		Depth (mm)		Particle Density
	Avg	SD	Avg	SD	Avg	SD	($kg\ m^{-3}$)
Wheat straw	128	65	4.0	1.7	1.1	1.0	950
Pine straw	164	54	1.3	0.2	0.8	0.1	1380
Tire chips	27	12	8.2	2.9	3.9	1.8	1160
Soil							2660

Table 2. Parameters of mulch materials used in hot and cold plate experiments

Material	Thickness (mm)	Amount ($kg\ m^{-2}$)	Bulk Density ($kg\ m^{-3}$)	Porosity ($m^3\ m^{-3}$)
Wheat straw	61	0.72	11.8	0.99
Wheat straw	61	1.04	17.0	0.98
Wheat straw	140	1.65	11.8	0.99
Wheat straw	140	2.38	17.0	0.98
Pine straw	61	1.37	22.4	0.98
Pine straw	61	2.03	33.3	0.98
Pine straw	140	3.13	22.4	0.98
Pine straw	140	4.65	33.3	0.98
Tire chips	61	29.8	488	0.58
Soil	61	101	1651	0.38

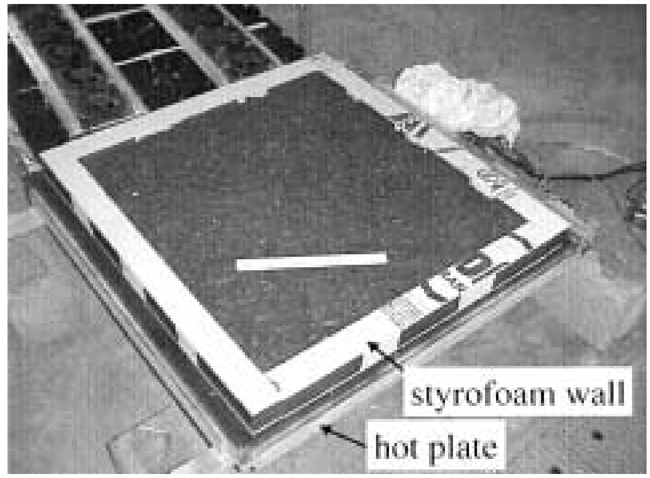

Figure 1–Tire chips placed on bottom plate and surrounded by a styrofoam wall.

Apparent thermal conductivity of these materials was measured using a hot and cold plate apparatus. Van Donk (1999) describes this apparatus and its verification in detail. A mulch is placed on the bottom plate and is surrounded by a 64-mm-thick styrofoam wall with a thermal conductivity of 0.027 W $m^{-1}\ K^{-1}$ (fig. 1). The function of the styrofoam wall is to (1) keep the mulch material in place, (2) support the second plate that is placed on top of the mulch, and (3) minimize lateral heat flow in the mulch. The styrofoam wall and the guard plate section minimized lateral heat flux through the mulch material overlying the test plate section. Next the second plate is placed on top of the mulch using an engine hoist, resulting in the mulch being sandwiched between the two plates (fig. 2).

Apparent thermal conductivity of a mulch material is determined as follows. The plates are set to and maintained at fixed temperatures. The temperature difference between the hot and the cold plate is maintained by supplying the appropriate amount of power to the hot plate. Measured power input to the test plate section (heat flux) are taken after steady state (power input and temperature profile in

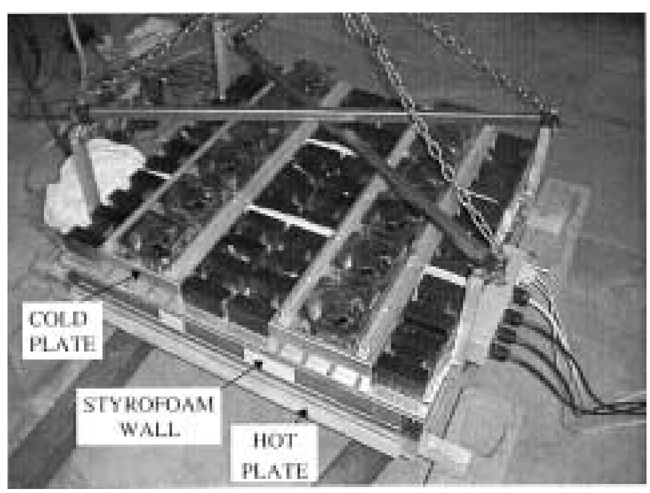

Figure 2–Mulch is sandwiched between hot and cold plate.

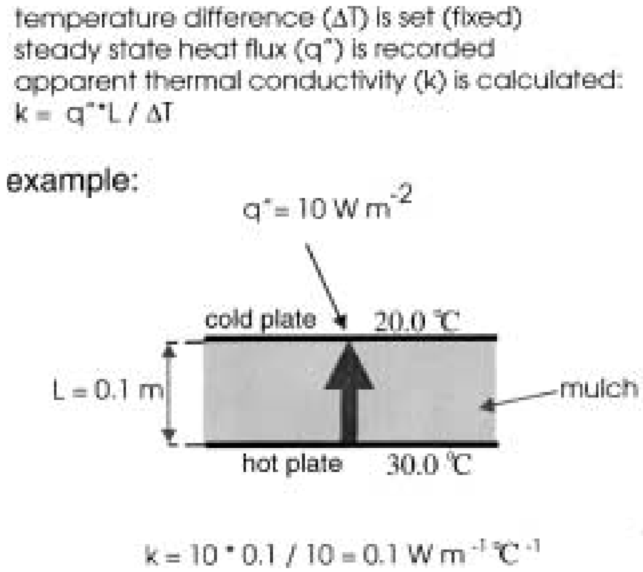

Figure 3–Sample calculation of apparent thermal conductivity of a mulch, using a hot and a cold plate.

the mulch are constant in time) has been reached. At steady state, the power that is provided by the hot plate equals the energy rate that is absorbed by the cold plate. Then the apparent thermal conductivity of the mulch is calculated from the temperature difference between hot and cold plates, the steady state heat flux through the mulch and distance between the hot and cold plate (see fig. 3):

$$k = \frac{q''L}{\Delta T} \qquad (10)$$

where

k = apparent thermal conductivity of the mulch (W m^{-1} K^{-1})

q'' = steady state heat flux through the mulch overlying the test section, computed by dividing the wattage by the test plate area (W m^{-2})

Two thermocouples (Omega, self adhesive, copper/constantan) were placed on the smaller, central test plate and four on the guard plate surrounding the test plate, giving a total of six on the hot plate (= test + guard plate). Five thermocouples were placed on the cold plate. Before calculating k as outlined above, q'' was corrected for differences in temperature among the test, guard, and bottom plates of the hot plate (van Donk, 1999).

To determine the effect of thermal radiation on heat transfer, measurements were taken with mulch between both a set of unpainted aluminum (Al) plates and a set of black painted Al plates. Krylon ultra flat black spray paint was used to obtain black plate surfaces. The emissivity of the black plates was assumed to be 0.95 and the emissivity of the Al plates was taken as 0.05, based on values found in the literature (table 3).

Table 3. Emissivities for aluminum and black surfaces at room temperature

Surface	Emissivity	Reference
Aluminum, polished	0.05	Omega, 1991
Aluminum, polished	0.04	Kreith and Bohn, 1997
Aluminum, polished	0.04	Thomas, 1992
Aluminum, polished	0.039	Sucec, 1985
Aluminum, rough surface	0.07	Omega, 1991
Flat black spray paint	0.95	Pelanne, 1969
Dull black paper	0.94	Omega, 1991
Coal soot	0.95	Sucec, 1985
Black lacquer paint	0.96	Kreith and Bohn, 1997

To quantify free convection, measurements were made in a thermally unstable configuration with the hot plate on the bottom and the cold plate on top as in figure 2, and in a thermally stable configuration with the cold plate on the bottom and the hot plate on top. The hypothesis is that in the stable configuration there is no free convection and in the unstable situation there may be free convection, depending on the type of material between the plates. If free convection is significant, the heat flux will be larger in the unstable situation compared to the stable situation.

Measurements on wheat and pine straw were taken at two different bulk densities, two different mulch layer thicknesses (table 2), and two different temperature settings. In one setting, the cold plate was at 20°C and the hot plate was at 35°C, and in a second setting, the cold plate was at 20°C, and the hot plate at 45°C. Cold plate temperatures below 20°C were not considered in order to avoid condensation, since dewpoint temperatures in the laboratory were up to 18°C. Condensation would affect heat transfer in an undesirable manner. Including the settings for thermal radiation and free convection, this resulted in 32 measurements for each straw material.

For both soil and tire chips only one bulk density was used, since these materials are virtually incompressible (table 2). Also, only one layer thickness was used for soil and tire chips, resulting in eight measurements for each of these two materials. Measurements were also taken with only air between the hot and cold plates. The same combinations were taken as for the wheat and pine straw, except for the variation in bulk density, resulting in 16 measurements for air. For all mulch materials (and air), every measurement was replicated two times.

The thermally stable and unstable cases were modeled separately. In the stable case, free convection is expected to be absent, so the convective heat flux was set equal to zero in the model leading to:

$$q'' = k_{cd}\frac{\Delta T}{L} + \frac{\sigma\left(T_h^4 - T_c^4\right)}{R + 2\left(\frac{1}{\varepsilon - 1}\right)} \qquad (11)$$

The thermal conductivity k_{cd} and opacity parameter R were estimated using the nonlinear model in equation 11 with the NCSS nonlinear regression package of Hintz (1999). This regression package computes all derivatives numerically and requires user-assigned starting values for each estimated parameter. Coefficients for air and for each thickness and density combination of both pine straw and wheat straw were analyzed using equation 11. The opacity R has large standard errors due to the relative insensitivity of the model to this term particularly at large values.

For the thermally unstable case the model included both the convection and radiation term. This leads to:

$$q'' = 0.069\ C\ k_{cd}\, g^{1/3}\, \alpha^{-0.407}\, \upsilon^{-0.259} (\Delta T)^{4/3}\, \beta^{1/3} + \frac{\sigma\left(T_h^4 - T_c^4\right)}{R + 2\left(\frac{1}{\varepsilon - 1}\right)} \tag{12}$$

No conduction term was included in equation 12, since conduction is implicitly accounted for in the convection term (Globe and Dropkin, 1959). Including a conduction term in equation 12 lead to numerical difficulties, thus we omitted it. The convection term in equation 12 was multiplied by a convection parameter C to account for decreasing convection when a mulch material is placed between the two plates. The convection parameter C for air and for each mulch thickness and density combination was estimated using non-linear regression techniques using the opacity parameter R that was estimated previously for the thermally stable case.

A conduction only model was used for soil and tire chips:

$$q'' = k_{cd} \frac{\Delta T}{L} \tag{13}$$

since inversion of hot and cold plates was not expected to produce much change in heat transfer in soil and tire chips (the high density of these materials inhibits convection inside the material). For the same reason, heat transfer by thermal radiation was not expected to be important for soil and tire chips either. Convection coefficients not significantly different from zero ($p < 5\%$) and very large opacity coefficients observed in preliminary analyses led to this reasoning.

RESULTS

Estimated parameters for both the thermally stable and unstable model are shown in table 4 with correlation coefficients ranging from 0.77 to 0.99. Standard error for the opacity parameter R increases rapidly with increasing mulch bulk density and thickness, indicating more inaccurate estimates as heat transfer by thermal radiation becomes smaller. This figure indicates the goodness of parameter fit. The estimated opacity parameter R for air was 1.04, which is close to the theoretically expected value of 1. Estimated thermal conductivity k_{cd} was 0.033 W m^{-1} K^{-1} compared to the theoretical value of 0.026 W m^{-1} K^{-1} for still air. The estimated C parameter was 1.41 times the

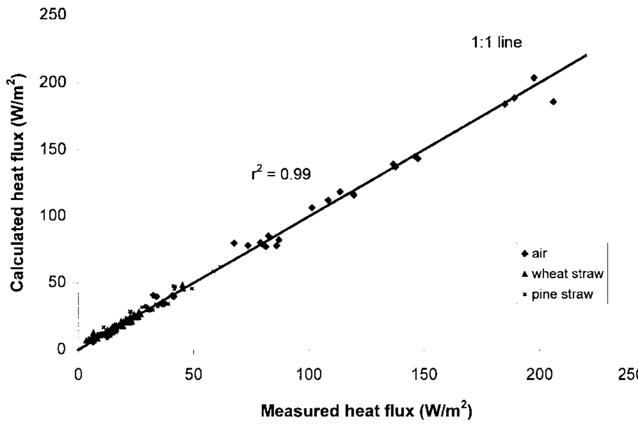

Figure 4–Calculated versus measured heat flux for pine straw, wheat straw, and air.

published value. The latter was determined with several liquids (Globe and Dropkin, 1959), thus this deviation is not surprising. For pine straw and wheat straw R increases with increasing mulch bulk density and with increasing mulch layer thickness, reflecting decreasing heat transfer by thermal radiation. Effective heat transfer decreased as density and mulch thickness increased. Calculated versus measured heat flow rate are shown in figure 4 for air, pine straw, and wheat straw.

Table 5 shows apparent thermal conductivities (k), calculated using parameters from table 4, and percentage estimated contribution of heat transfer mechanisms to overall heat transfer for each of the thermally stable and unstable models. The k values appeared to decrease somewhat with density within both the stable and unstable conditions. The k values in the unstable case tended to increase as thickness increased. The calculated percent contributions suggests that the contribution of thermal radiation tends to decrease with increasing mulch bulk density and mulch layer thickness as one would expect in each of the stable and unstable cases. With the stable case, the percentage of heat transported by conduction tended to increase somewhat with increased density. Similarly, in the unstable case increased mulch density and thickness resulted in slight increases in heat transport percentage by convection.

The heat flux increase due to thermal instability can be estimated by comparing k of the stable model with the k calculated using the unstable model as shown in table 5, right column. When either mulch material was placed

Table 4. Parameters, estimated using nonlinear regression, and standard errors (in brackets) for the thermally stable and unstable models for pine straw, wheat straw, and air

Mulch Characteristics			Thermally Stable Model (eq. 11)			Unstable Model (eq.12)	
Material	Layer Thickness (mm)	Bulk Density (kg m^{-3})	k_{cd} (W m^{-1} K^{-1})	Opacity Parameter R	r^2	Convection Parameter C	r^2
Air		0	0.033 (0.0032)	1.04 (0.01)	0.99	1.41 (0.047)	0.98
Pine straw	61	22.4	0.075 (0.0028)	8.8 (2.2)	0.97	0.77 (0.023)	0.97
Pine straw	61	33.3	0.069 (0.0070)	70 (117)	0.93	0.55 (0.014)	0.96
Pine straw	140	22.4	0.102 (0.0094)	60 (51)	0.93	0.55 (0.036)	0.85
Pine straw	140	33.3	0.073 (0.0287)	133 (667)	0.77	0.32 (0.022)	0.84
Wheat straw	61	11.8	0.053 (0.0029)	11 (1.3)	0.97	0.58 (0.017)	0.97
Wheat straw	61	17.0	0.052 (0.0028)	40 (16)	0.96	0.41 (0.011)	0.95
Wheat straw	140	11.8	0.064 (0.0067)	25 (6.9)	0.91	0.32 (0.023)	0.89
Wheat straw	140	17.0	0.057 (0.0240)	135 (598)	0.75	0.20 (0.009)	0.92

Table 5. Apparent thermal conductivity (k), calculated using parameters from table 4, and estimated percentage contribution of heat transfer mechanisms to overall heat transfer in pine straw, wheat straw, and air in a high emissivity environment

Mulch Characteristics			Thermally Stable Model			Unstable Model			Difference
Material	Layer Thickness (mm)	Bulk Density (kg m^{-3})	k (Wm^{-1} K^{-1})	Conduction (%)	Radiat. (%)	k (Wm^{-1} K^{-1})	Free Convection (%)	Radiat. (%)	Δk (Wm^{-1} K^{-1})
Air	61	0	0.367	9	91	0.510	34	66	0.143
Air	140	0	0.799	4	96	1.160	34	66	0.361
Pine straw	61	22.4	0.118	64	36	0.141	69	31	0.023
Pine straw	61	33.3	0.074	92	8	0.076	92	8	0.002
Pine straw	140	22.4	0.117	88	12	0.176	91	9	0.059
Pine straw	140	33.3	0.081	92	8	0.101	93	7	0.02
Wheat straw	61	11.8	0.088	60	40	0.109	68	32	0.021
Wheat straw	61	17.0	0.060	84	16	0.062	85	15	0.002
Wheat straw	140	11.8	0.099	65	35	0.127	72	28	0.028
Wheat straw	140	17.0	0.064	90	10	0.065	90	10	0.001

between the hot and cold plates, the difference in the k values diminished. Increasing the mulch thickness increased the difference between the stable and unstable cases. Increasing the density tended to reduce the difference between the stable and unstable cases. The differences between the stable and unstable cases are probably not statistically significant. The greatest percentage of thermal radiation is observed when there is only a layer of air between the hot and cold plate. In the stable case, thermal radiation accounts for more than 90% of overall heat transfer. Table 5 shows that for a 61 mm, 22.4 kg m^{-3} layer of pine straw, 36% of the heat transfer was by thermal radiation. The relative importance of thermal radiation decreases as mulch density and thickness increases in both the stable and unstable models.

The estimated parameters were used to develop a predictive, empirical model for k_{cd}, R, and C as a function of mulch bulk density and mulch layer thickness with the following results:

$$k_{cd} = 0.00131\ \rho_m + 0.039 \qquad r^2 = 0.55 \tag{14}$$

$$R = 28.73\ L\ \rho_m + 1 \qquad r^2 = 0.70 \tag{15}$$

$$C = -0.45\ \ln(\rho_m + 1) + 0.0180\ \rho_m\ e^L + 1.411$$
$$r^2 = 0.82 \tag{16}$$

where

ρ_m = mulch bulk density (kg m^{-3})

Estimated thermal conductivities for the conduction only model for soil and tire chips are shown in table 6. Correlation coefficients range from 0.80 to 0.96. Table 6 shows that the estimated thermal conductivities are greater in the unstable configuration for both soil and tire chips. Although it was not expected that convection was important in such dense materials, it may play a role because of the existence of a narrow air gap between the top of the mulch and the overlying plate. Free convection and also thermal radiation may be effective heat transfer mechanisms in this gap, causing the observed differences for soil and tire chips (table 6). Calculated versus measured heat flow rate for these materials are shown in figure 5.

Table 6. Estimated (eq. 13) parameters and standard errors (in brackets) for the thermally stable and unstable configuration for dry soil and automobile tire chips

	Thermally Stable Configuration		Unstable Configuration	
Mulch Material	k_{cd} (W $m^{-1}K^{-1}$)	r^2	k_{cd} (W $m^{-1}K^{-1}$)	r^2
Soil	0.199 (0.0092)	0.80	0.226 (0.0053)	0.95
Tire Chips	0.079 (0.0015)	0.96	0.084 (0.0019)	0.96

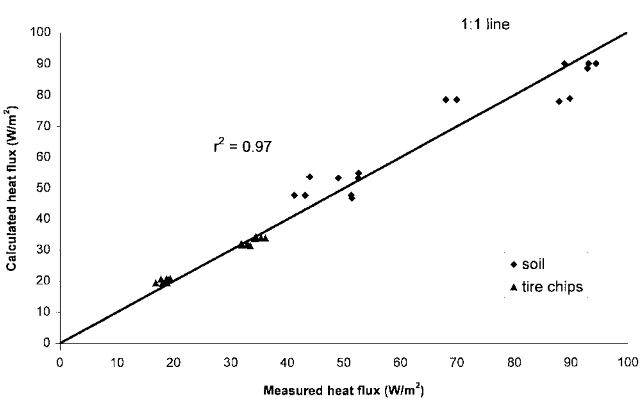

Figure 5–Calculated versus measured heat flux for soil and tire chips.

Conclusions

Thermal radiation, convection and conduction may all contribute to heat transfer in mulches such as pine straw and wheat straw. In thermally unstable situations, free convection is important and increases with decreasing mulch density. The thinner the mulch layer and the more void space in the mulch, the more important thermal radiation becomes. In a thermally stable situation, conduction and radiation mechanisms explain the heat transfer. For a given mulch material, the thermally unstable condition results in an increased apparent thermal conductivity (k) value. The increase is inversely proportional to mulch density and thickness. For pine straw average k was 0.11 W m^{-1} K^{-1} and for wheat straw 0.08 W m^{-1} K^{-1}. A model was created to develop the radiation, conduction and convection parameters for the mulches tested. Appropriate components could be used to estimate field apparent conductivity of dry mulches in the stable and unstable cases. Both models need further testing.

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