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APPARENT THERMAL CONDUCTIVITY OF MULCH MATERIALS EXPOSED TO FORCED CONVECTION

S. J. van Donk, E. W. Tollner

ABSTRACT. *Soil temperature controls plant growth and many related processes in the soil. A mulch or crop residue covering the soil may alter soil temperatures significantly. Available simulation models often lack experimental data for the mulch thermal conductivity and its dependence on air velocity. The apparent thermal conductivity (k) of wheat straw, pine straw, tire chips, dry sandy soil, and the thermal resistance of Bermudagrass sods were measured using a guarded hot plate at air velocities between 0 and 5 m/s. For all mulch materials, k ranged between 0.1 and 0.6 W m^{-1} °C^{-1}, and increased with increasing air velocity, except for the more compact materials such as soil and, to a lesser extent, small tire chips. We found a minimum in k around 1 m/s for the thicker (> 0.1 m) layers of wheat straw and pine straw, which was tentatively attributed to interactions between the straw and the convection (free versus forced mechanism at the 1 m/s velocity). A model was created for predicting apparent thermal conductivity through mulches in thermally unstable environments. Using estimated mulch opacity parameters and fitting convection parameters, r^2 values ranging from 0.72 to 0.99 were obtained. The model may be used in field situations where the soil under a mulch is warmer than the air above the mulch, which is a typical nighttime condition. The model should be tested using independently measured data.*

Keywords. *Guarded hot plate, Mulch, Heat transfer, Thermal conductivity, Air velocity.*

Soil temperature controls many biological, chemical, and physical processes, and a management practice such as mulching can have large impacts on soil temperatures (Bussiere and Cellier, 1994; Bristow and Campbell, 1986). Soil temperature management offers the potential to (more successfully) grow crops that require a temperature regime different from the unmanaged environment. Tindall et al. (1991) found that straw mulches have the potential to improve tomato yields in high temperature environments, such as that of the state of Georgia, USA. Soil temperature management can aid in controlling diseases, such as aflatoxin development in peanuts (Hill et al., 1983). Soil temperatures also are critical in biological and chemical processes that control nutrient cycling. 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. Mulches can be classified as natural or synthetic. Examples of synthetic mulches are plastic film, cloth, fiberglass matting, and chips from waste automobile tires. Some examples of natural mulch materials are cover crops, bark, compost, gravel, pine needles, wood chips, and layers of organic residue that are typical for no-tillage systems.

Typically, during nights and winters, an organic residue-type mulch covering a soil reduces soil heat loss to a colder atmosphere. Because of this thermal insulation and because generally mulch albedo (short wave reflectance) is higher than that of the soil, surface mulches reduce soil temperature amplitude, so that temperature extremes are less extreme in mulch covered soil as compared to those in a bare soil. Mulches affect the radiation balance and also affect heat and vapor transfer by conduction, convection, and evaporation. 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 solar radiation at the start of spring is low. Often, higher soil temperatures are required to get crop growth and development started. Mulch can be a negative factor in this process by keeping the soil wet and cold for longer periods than would be the case for bare soil, thus shortening the length of the growing season (Horton et al., 1996). Bristow (1988) studied bare soil, vertical mulch, and horizontal mulch. Soil temperatures for a dry soil were significantly different. The bare soil surface was warmest, the soil surface under the horizontal mulch was coolest, and the soil surface temperature under the vertical mulch was in between.

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; Sui et al., 1992; Bussiere and Cellier, 1994; Bristow and Horton, 1996). 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 give the mulch apparent thermal conductivity they used (table 1). Most of the

Article has been reviewed and approved for publication by the Soil & Water Division of ASAE.

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Table 1. Apparent thermal conductivity (k) for different mulch materials θ_m is mulch water content (kg/kg)

Publication	Mulch	k (W m^{-1} °C^{-1})
Bristow and Horton, 1996	Coconut fiber matting	0.125
Bussiere and Cellier, 1994	Sugar cane residues (dead leaves)	$0.1 + 0.03\times\theta_m$
Chung and Horton, 1987	Crop residue (corn) mulch	0.126
Riha et al., 1980	Forest litter	$0.1 + 0.03\times\theta_m$
Shen and Tanner, 1990	Flail-chopped corn residue	0.0625
Van Wijk et al., 1959	Air-dry corn-stalk mulch	0.17

authors do not describe how they obtained the mulch apparent conductivity.

Van Bavel and Hillel (1975) conducted a simulation study of soil heat and moisture dynamics as affected by a mulch of dry soil aggregates. The concept of mulch thermal conductivity is being used in the model, but the article does not describe where the actual value of mulch thermal conductivity comes from. Sui et al. (1992) developed a numerical model for simulating the temperature and moisture regimes of soil under porous and film mulches. Both volumetric heat capacity and thermal conductivity of the porous mulch were evaluated according to de Vries (1963). However, the authors do not mention what shape factors (critical in the de Vries approach) and what constituent thermal conductivities were used.

Heilman et al. (1992) determined the water vapor conductance through a herbicide-killed winter wheat as a function of wind speed. Vapor conductance was calculated from measurements of evaporation (using the Bowen ratio technique) and vapor density below and above the residue. Their experimentally obtained conductance function was used by Lascano and Baumhardt (1996) as an additional resistance in the ENWATBAL simulation model, in order to simulate energy and water balances of a soil-residue-crop-atmosphere system. The same resistance was used for transfer of both heat and water vapor. Campbell et al. (1980) observed that penetration into a layer of fiber (coats, clothing) by wind reduces its effectiveness as a barrier to heat flow. They found that both heat and vapor conductance could be described as a linear function of wind speed. Bussiere and Cellier (1994) also recognized that convective heat transfer can be important in many types of organic residues. From their simulations, they concluded that further experimentation is required for a better understanding and an accurate modeling of convective heat transfer. For their sugar cane residue mulch, they assumed the same value for thermal conductivity as Riha et al. (1980) found for forest litter (table 1).

Van Wijk et al. (1959) measured the thermal conductivity of an air-dry corn-stalk mulch, but did not describe the method used for the measurement. Shen and Tanner (1990) did not know of any experiments on sensible heat transfer in crop residues, "although data are needed to model the energy balance of conservation tillage systems". They 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. The influence of forced convection was not studied. Horton et al. (1996) encourage greater interaction between modelers and experimenters, 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. They recommend further work on determining heat and mass transfer properties of crop residue.

A hot plate was built in order to quantify heat transfer through several mulch materials and to quantify the influence of forced convection on the apparent thermal conductivity of mulch materials. The results of this work should enable modelers to improve the predictive capabilities of their models.

Methods and Materials

The mulch materials selected were wheat straw, pine straw, two varieties of tire chips (chopped automobile tires), Bermudagrass sod, and dry soil. Apparent thermal conductivity of these materials was measured using a hot plate, consisting of a test, guard, and bottom plate (fig. 1). Van Donk (1999) describes this apparatus and its verification in detail.

Figure 2 shows the experimental setup. A propeller fan (0.84 m diameter) is drawing air through a 4.88 m long, 1.22 m wide, and 1.22 m high wind tunnel. The hot plate, covered with mulch material, has been placed at the end of the tunnel. The purpose of the wind tunnel is to have a guided, relatively uniform airstream over the mulch. Air velocity is measured about 0.45 m above the mulch using a

Figure 1–Guarded hot plate at the end of a wind tunnel.

Figure 2–Top view of setup for forced convection heat transfer experiments.

Figure 3–Measuring air velocity over a small tire chip mulch covering the hot plate.

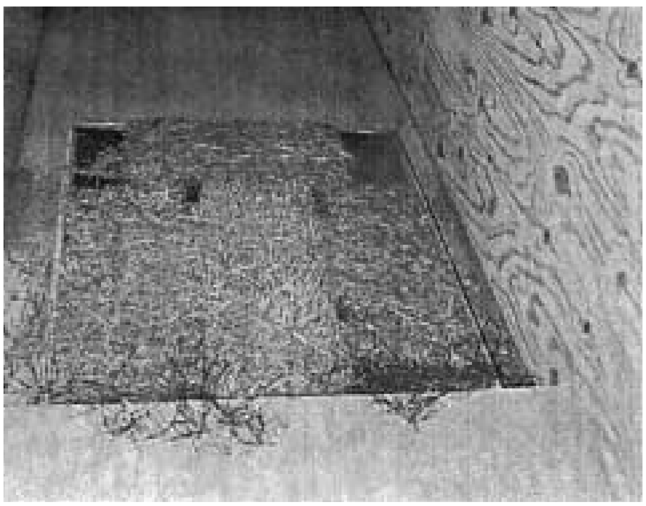

Figure 4–Measuring thermal resistance of Bermudagrass sods.

hot film anemometer (fig. 3), at four different positions corresponding to the four corners of the test plate. The average of these four measurements has been used in the presentation of the results. Figure 3 shows small tire chips covering the hot plate and figure 4 shows Bermudagrass sod on the hot plate.

The apparent thermal conductivity of the mulch is calculated from the temperature difference between top and bottom of the mulch, the power input into the test plate (steady state heat flux through the mulch), and the mulch thickness:

$$k = \frac{q''L}{\Delta T} \quad (1)$$

where

- k = apparent thermal conductivity of the mulch (W m^{-1} °C^{-1})
- q'' = steady state heat flux through the mulch (W m^{-2})
- L = thickness of the mulch layer (m)
- ΔT = temperature difference between top and bottom of the mulch (°C)

The temperature of the top of the material was measured using a Telatemp infrared thermometer. Temperature readings were consistent for the less coarse materials (soil, small tire chips) and somewhat less consistent for the coarser materials such as the straws and the large tire chips. The bottom (warm side) temperature of the material was measured using two thermocouples (Omega, self adhesive, copper/constantan) on the test plate. Before calculating k, q″ was corrected for differences in temperature among the test, guard, and bottom plates of the hot plate (van Donk, 1999).

Dimensions of the materials were measured and results are shown in table 2. The average and standard deviation for every material are for sample sizes of 20. Particle densities were determined using a gas pycnometer. Every density value in table 2 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. Both the small and the large tire chips were obtained from Waste Tire Management, Lawrenceville, Georgia.

Table 3 shows some base data for the forced convection experiments. Typically, for each mulch material, measurements were made for two different mulch layer thicknesses at air velocities varying from 0 to 5 m/s. Mulch thickness and mass were measured directly, and from these bulk density was calculated. Porosity was calculated from the bulk density in table 3 and the material (particle) density in table 2. The Bermudagrass sod consisted of a soil layer with standing dormant grass stubble. The stubble was on average 40 mm long and the layer thickness of the soil it was standing in averaged 18 mm.

The materials used in the experiments were dry and moisture effects on k were not expected. However, moisture content was still measured before and after experiments on a mulch, using ASAE Standard S358.1 for

Table 2. Dimensions and densities of mulch materials

	Length (mm)		Width (mm)		Depth (mm)		Particle Density
Material	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	(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
Small chips	27	12	8.2	2.9	3.9	1.8	1160
Large chips	54	23	34.1	14.2	10.3	4.5	1140
Soil							2660

Table 3. Parameters of mulch materials used in forced convection experiments

Material	Thickness (mm)	Amount (kg/m^2)	Bulk Density (kg/m^3)	Porosity (m^3/m^3)
Wheat straw	74	0.9	12	0.99
Wheat straw	163	2.3	14	0.99
Pine straw	63	1.6	25	0.98
Pine straw	112	2.1	18	0.99
Pine straw	124	3.7	30	0.98
Small chips	30	14.6	488	0.58
Small chips	43	21.0	488	0.58
Large chips	44	22.7	517	0.55
Large chips	79	40.8	517	0.55
Soil	23	40.0	1651	0.38
Soil	61	101	1651	0.38
Bermudagrass		13.6		

Table 4. Gravimetric moisture content (% wet basis) of mulch materials before and after experiments were run

Material	Before	After	Effect
Wheat straw	8.3	6.4	No
Pine straw	11.5	7.9	No
Small chips	0.9		No
Large chips	0.8		No
Soil	0.9	0.4	No
Bermudagrass, soil		0.9	Yes
Bermudagrass, stubble		5.9	Yes

drying 'forage products in their various forms' (24 h at 103°C). Moisture contents are shown in table 4. 'Before' in table 4 refers to soil moisture content just before starting the experiments. This measurement was not made for Bermudagrass, since taking samples would destroy the sod that was used for the heat transfer measurements. 'After' refers to soil moisture content just after the experiments. According to table 4 the materials dried somewhat after sitting on the hot plate for a few days.

The 'after' measurement was not made for small and large chips, because the 'before' moisture content was already so low that it would not affect heat transfer. 'Effect' refers to whether or not the decrease in moisture content caused a change in k. There was only a moisture effect for Bermudagrass. When the sods were drying out on the hot plate, the thermal resistance increased somewhat until they were so dry that no further increase in thermal resistance occurred. These final, stabilized values are reported in the results section.

Heat flux was modeled two different ways, according to mulch type. For wheat and pine straw, conduction, radiation and convection may all be of importance, thus for these materials the model is:

$$q'' = q''_{cv} + q''_r \tag{2}$$

where
q''_{cv} = heat flux due to free convection (W m^{-2})
q''_r = heat flux due to thermal radiation (W m^{-2})

No conduction term was included in equation 2, since conduction is implicitly accounted for in the convection term (Globe and Dropkin, 1959). For soil and tire chips, heat flux by thermal radiation and free convection was considered negligible thus for these materials the model is:

$$q'' = q''_{cd} \tag{3}$$

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

$$q''_{cd} = k_{cd}\frac{\Delta T}{L} \tag{4}$$

where
k_{cd} = thermal conductivity of the mulch (W m^{-1} °C^{-1})
L = thickness of the mulch layer (m)

Since there was a possibility that forced air penetrates into a mulch layer, affecting heat flux, k_{cd} was not modeled as a single parameter, but as:

$$k_{cd} = Av + B \tag{5}$$

where
v = air velocity (m/s)

The parameter B indicates the thermal conductivity at v = 0 m/s. Heat flux through a mulch by means of thermal radiation was modeled as follows (Pelanne, 1969; van Donk, 1999):

$$q''_r = \frac{\sigma\left(T_h^4 - T_c^4\right)}{R + \frac{1}{\varepsilon_h} + \frac{1}{\varepsilon_c} - 2} \tag{6}$$

where
σ = Stefan-Boltzmann constant = 5.67 × 10^{-8} W m^{-2} K^{-4}
T_h = temperature of hot plate (K)
T_c = temperature at the top of the mulch (K)
R = opacity parameter (dimensionless)
ε_h = emissivity of hot plate
ε_c = emissivity at the top of the mulch

The opacity parameter R is equal to 1 when there is no material on the hot plate. It increases with increasing density and/or thickness of the layer of material on the hot plate, reflecting a reduction in radiative heat transfer. Van Donk (1999) developed an empirical model of R as a function of mulch thickness and density. This model was used to calculate R for wheat straw and pine straw in the present study. The emisssivity of the Aluminum hot plate was assumed to be 0.05 (van Donk, 1999) and the emissivity at the top of the mulch (looking at the wind tunnel ceiling) was taken as 0.90.

Van Donk (1999) calculated the convective heat flux for the case of heat transfer between two plates of different temperature as follows:

$$q''_{cv} = 0.069\ C\,k_{cd}\,g^{1/3}\,\alpha^{-0.407}\,\nu^{-0.259}\left(\Delta T\right)^{4/3}\beta^{1/3} \tag{7}$$

where
C = convection parameter (dimensionless)
k_{cd} = thermal conductivity of air (W m^{-1} °C^{-1})
g = gravitational constant = 9.81 m/s^2
α = thermal diffusivity of air (m^2/s)
ν = viscosity of air (m^2/s)
β = volumetric thermal expansion coefficient (K^{-1})

$$\beta = \frac{1}{\frac{T_h + T_c}{2}} \tag{8}$$

Equation 7 uses a correlation found by Globe and Dropkin (1959), who measured data for heat transfer between two horizontal plates, heated from below:

$$Nu = 0.069\ Ra^{1/3} Pr^{0.074} \quad (9)$$

$$Ra = \frac{g\ \beta \left(T_h - T_c\right) L^3}{\alpha\, \nu} \quad (10)$$

$$Pr = \frac{\nu}{\alpha} \quad (11)$$

where
Nu = Nusselt number
Ra = Raleigh number
Pr = Prandtl number

In the present study, the top of the mulch is not covered by a plate, but is in open connection to the air and free convection is expected to behave differently. Therefore, we did not use the convection parameter C estimated by Van Donk (1999), but instead estimated it using the data of this study. Another difference is that here the mulch was exposed to forced convection. Thus, an extra term, including air velocity, was introduced to account for this:

$$q''_{cv} = C\, k_{cd}\, 0.069\ g^{1/3} \times \alpha^{-0.407} \nu^{-0.259} \left(\Delta T\right)^{4/3} \beta^{1/3} \frac{1 - d\nu L}{L} \quad (12)$$

where
d = velocity parameter (s/m)

The parameters C and d were estimated for each bulk density/thickness combination for pine and wheat straw using nonlinear regression techniques.

Results

For the straw and tire chip materials (figs. 5 through 8) the apparent thermal conductivity of the material increases with increasing air velocity (v). This observation is explained by the fact that at higher air velocities air penetrates more into the material, thus increasing heat transfer within the material by means of forced convection. For a layer of soil, k essentially stays constant with increasing air velocity (fig. 9), because air cannot easily penetrate into the soil. For small chips (fig. 7), there is a modest increase of k with increasing v. For large chips (fig. 8) this increase is larger, attributed to more air space being in the material and thus more potential for air penetration. The measured soil thermal conductivities of about 0.38 W m^{-1} $°C^{-1}$ (fig. 9) compare very well with those found by other researchers for dry, sandy soils. Biscoe et al. (1977) reported 0.38, Fuchs and Hadas (1973) 0.36, and Kaye (1973) 0.35 W m^{-1} $°C^{-1}$.

Small tire chips (fig. 7) is the least conductive of the materials investigated. Dry soil (fig. 9) is the most conductive at lower air velocities. At the higher air velocities, wheat straw (fig. 5) is the most conductive. Both the wheat straw and pine straw mulch layers consist of predominantly air, with porosities close to 1 (table 3). If pure conduction were the only heat transfer mechanism, we would expect k of the straw mulches to be very close to k of still air (0.025 W m^{-1} $°C^{-1}$). However, figures 5 and 6 illustrate that k = 0.2 W m^{-1} $°C^{-1}$ or greater. This indicates that thermal radiation and/or free convection are important heat transfer mechanisms in these straw layers.

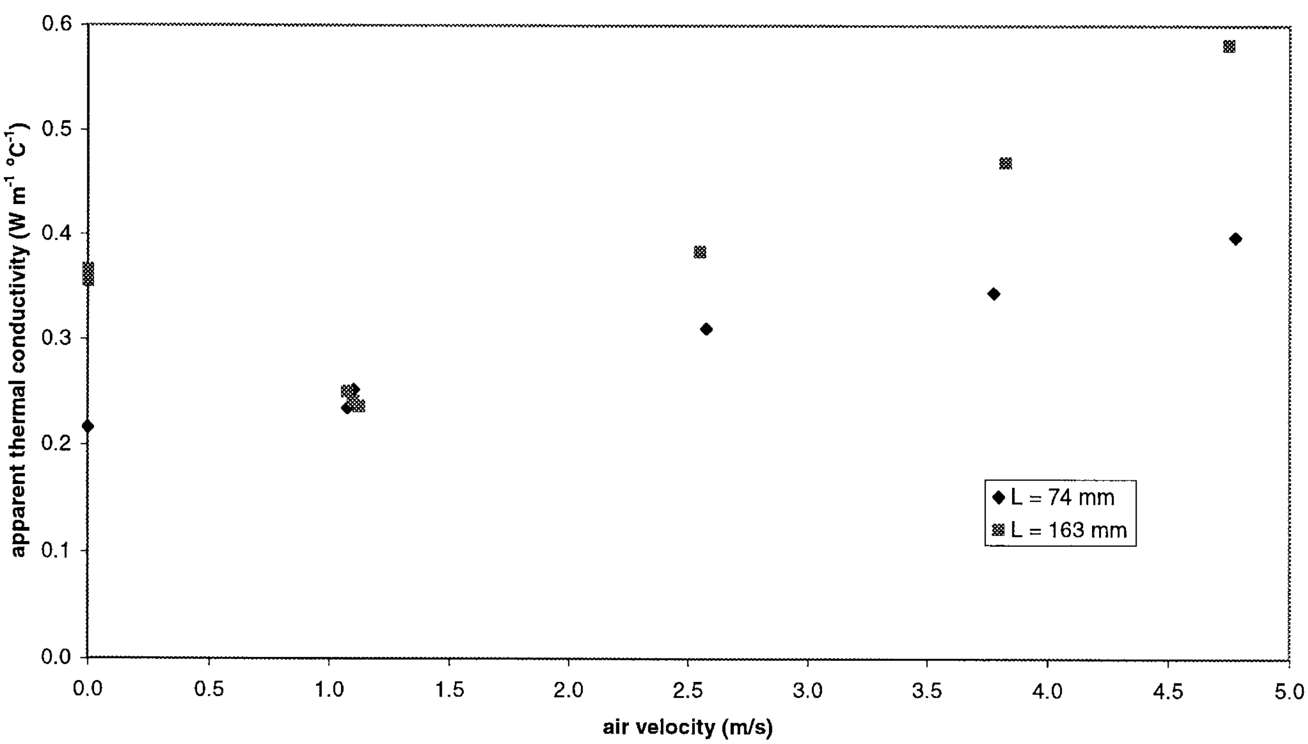

Figure 5–Apparent thermal conductivity of two layers of wheat straw as a function of air velocity.

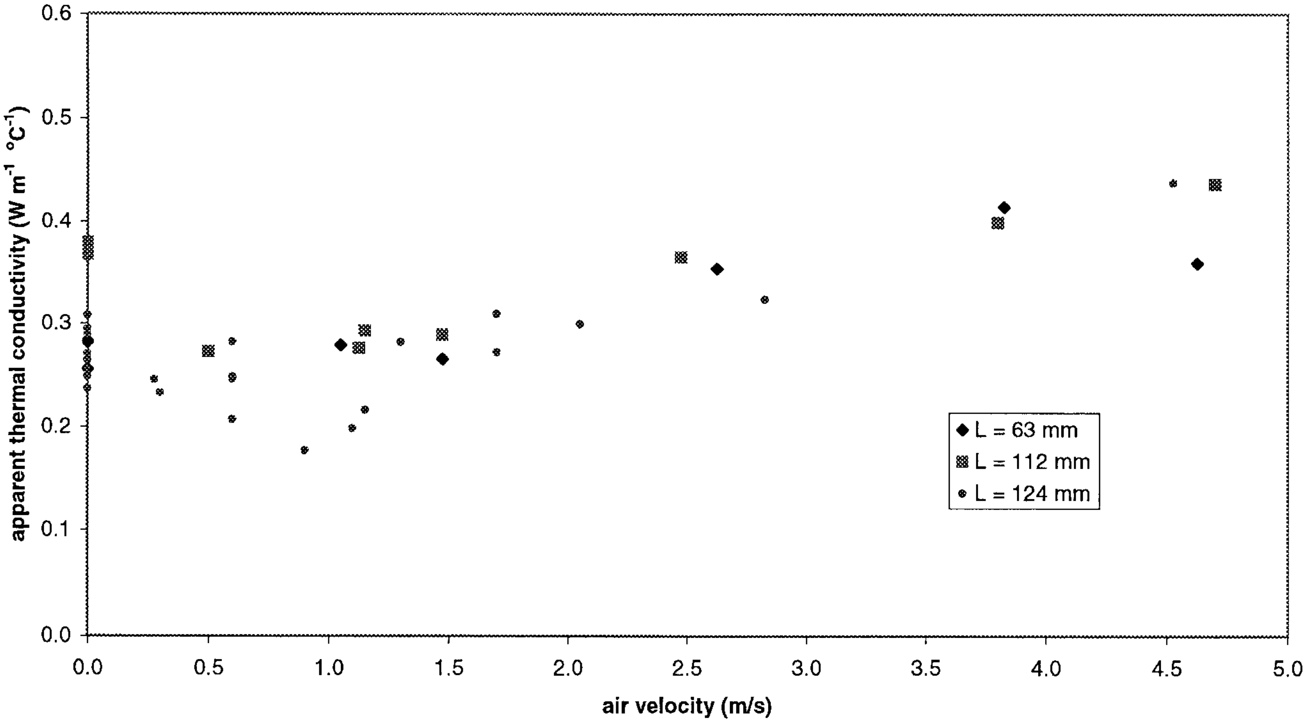

Figure 6–Apparent thermal conductivity of three layers of pine straw as a function of air velocity.

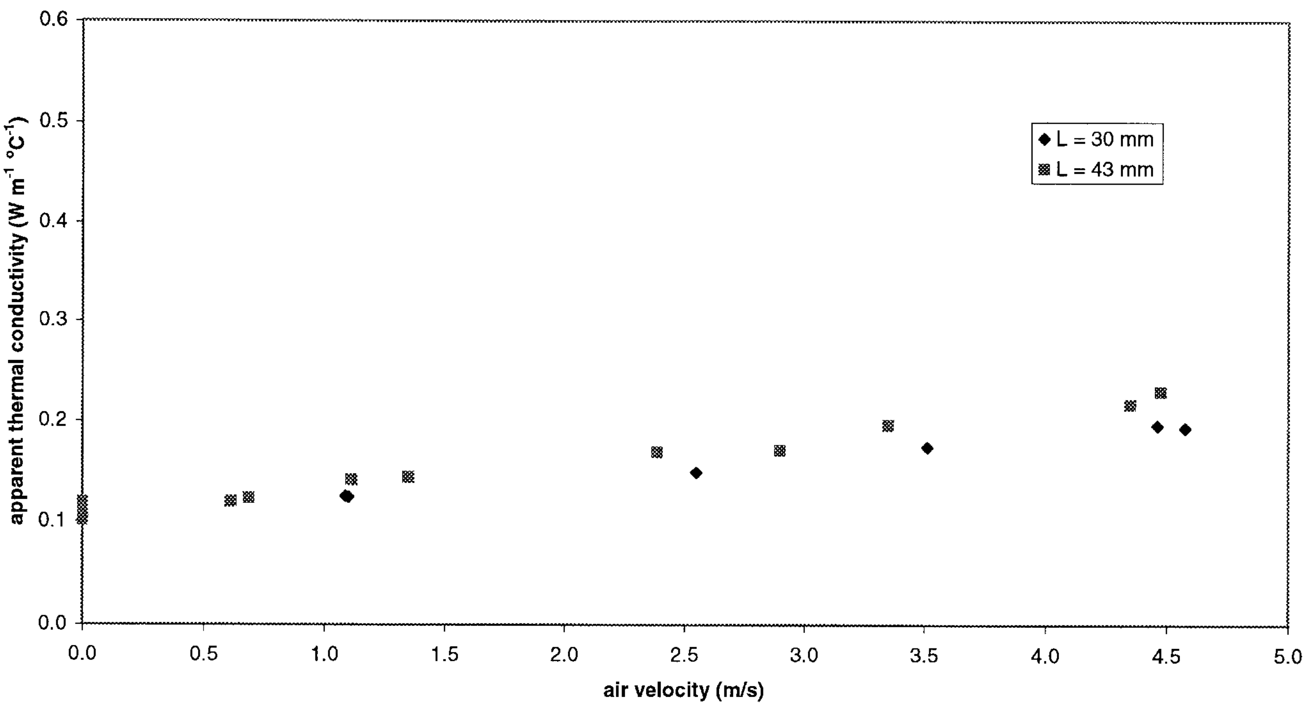

Figure 7–Apparent thermal conductivity of two layers of small tire chips as a function of air velocity.

The measured k values are greater than the values reported in the literature (table 1). Measured and reported values are difficult to compare, since most previous authors did not describe how k values were obtained. For most of the cited literature, determining k was not the main research objective. For Shen and Tanner (1990) however, determining k was the main objective and the method for determining k of a flail-chopped corn residue was described in detail. The reported k value of 0.0625 W m^{-1} $°C^{-1}$ is much lower than the k values determined in the present study. This difference may be (partially) explained by the fact that the mulch was denser (37.5 kg m^{-3}) in the former research. In denser material heat transfer by thermal radiation and convection will be reduced, thus accounting for a lower k value. This explanation is supported by the k values measured for pine straw (fig. 6). The smallest

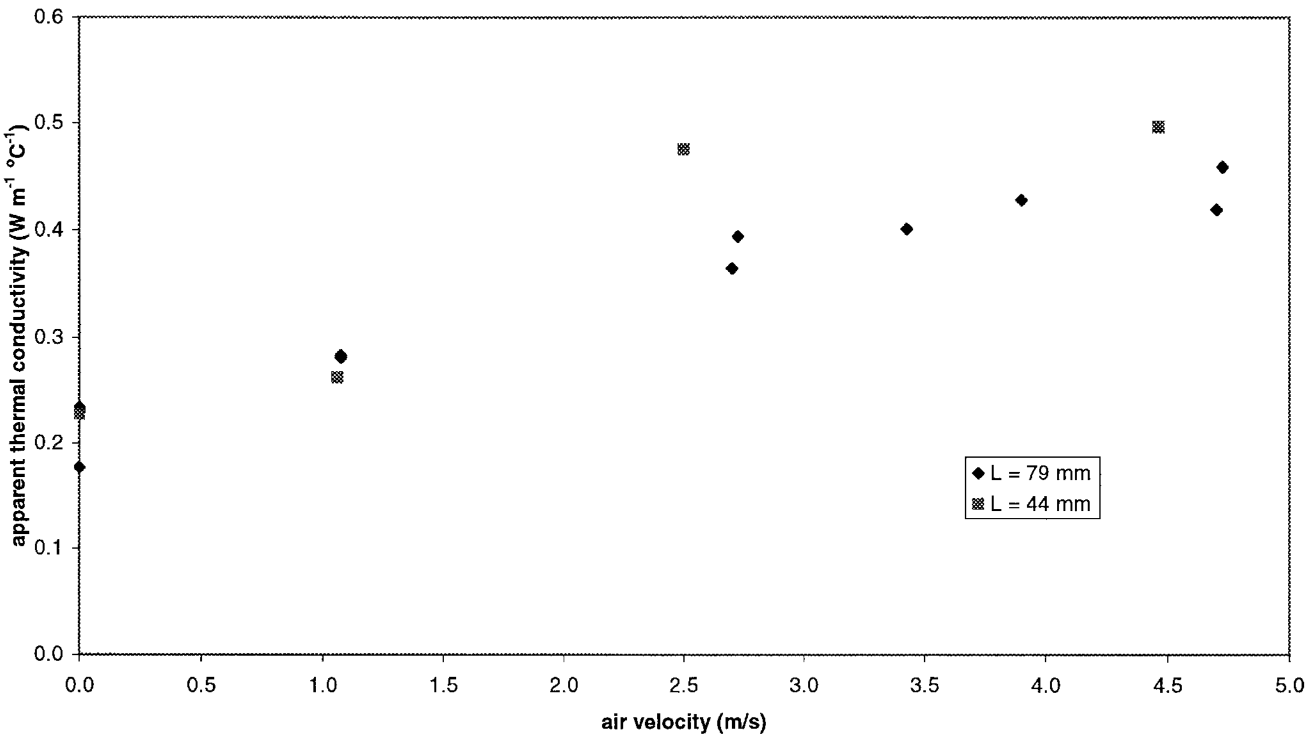

Figure 8–Apparent thermal conductivity of two layers of large tire chips as a function of air velocity.

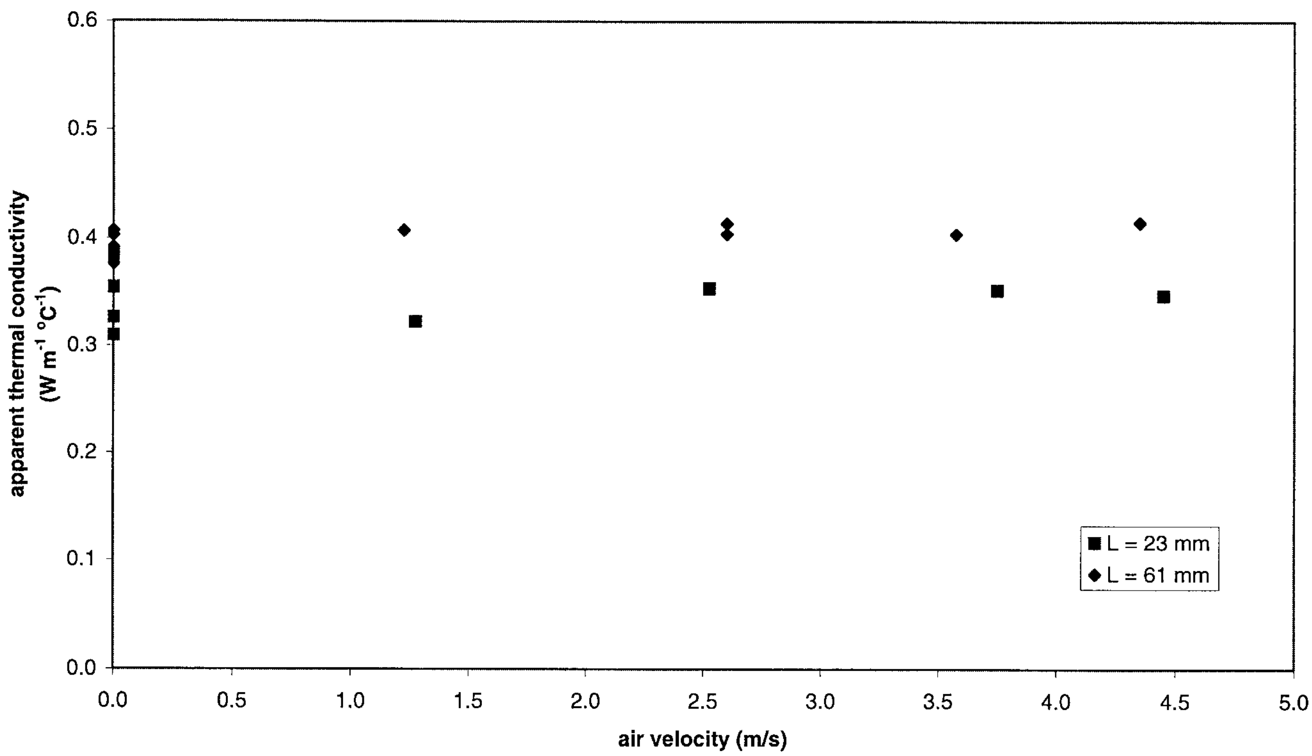

Figure 9–Apparent thermal conductivity of two layers of soil as a function of air velocity.

k values were found for the layer of pine straw with the greatest density (30 kg m^{-3} and 124 mm thick).

From figures 5, 8, and 9 the thermal conductivity seems to depend on layer thickness. However, this difference may be due to the inability to measure layer thickness accurately, especially for the coarser materials. Figure 10 illustrates that there is no difference in k between the layers (compare to fig. 9) if, in the calculations, thickness is varied ±2 mm for both layers.

For both wheat and pine straw some of the results were intriguing. There is a minimum k around 1 m/s for the thicker layers (figs. 5 and 6). At an air velocity of 0 m/s the

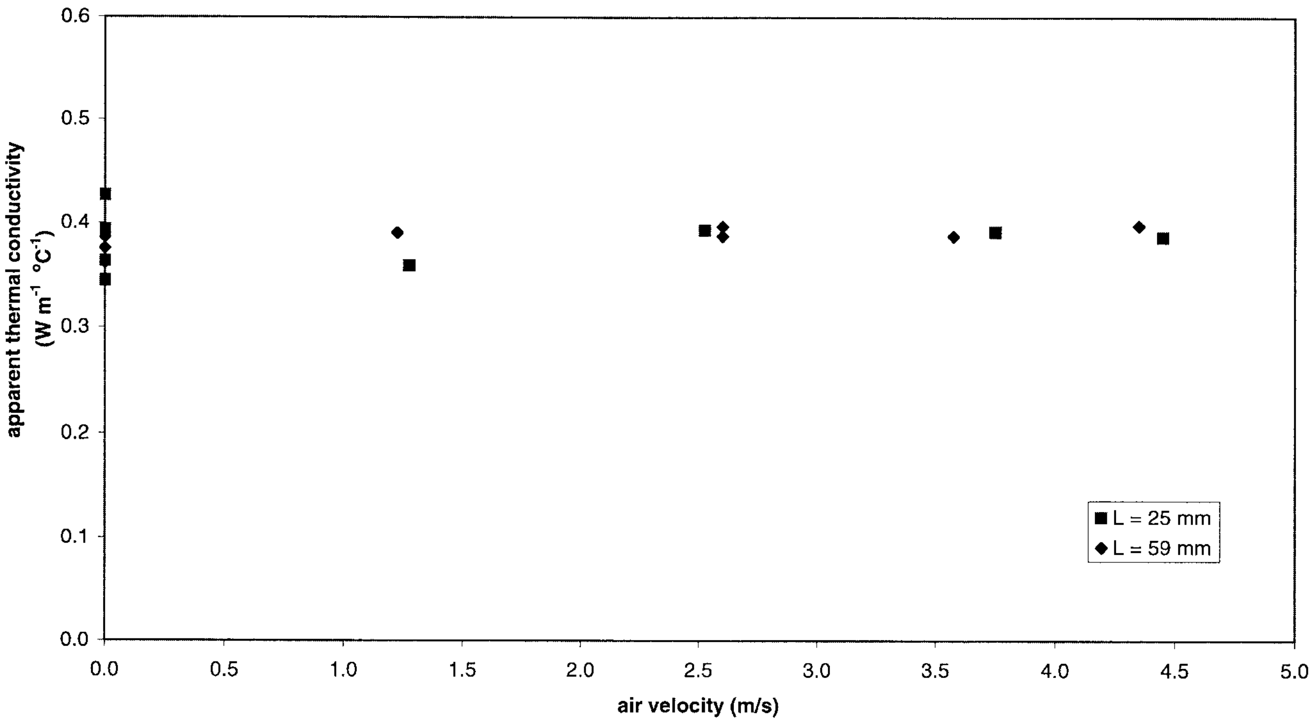

Figure 10–Influence of layer thickness measurement accuracy on the apparent thermal conductivity of soil.

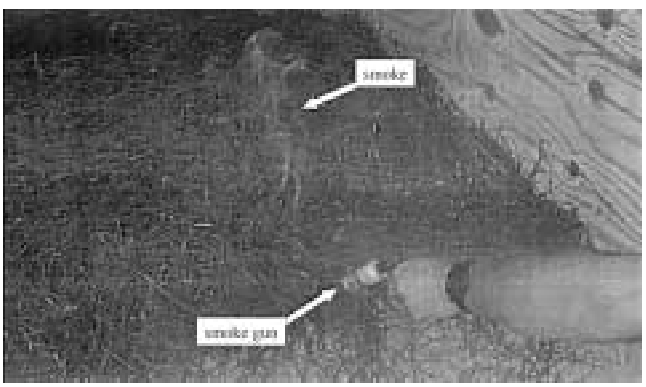

Figure 11–Visualizing airflow over a layer of pine straw using smoke at an air velocity of 0 m/s.

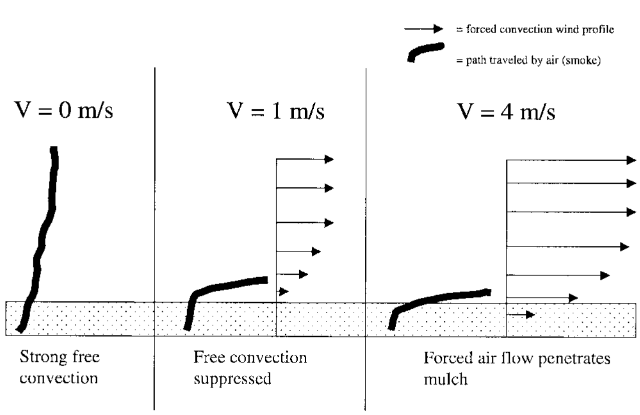

Figure 12–Interaction of free and forced convection in and above a layer of pine straw heated by a hot plate.

steady state heat flux was larger than around 1 m/s, causing k to be larger at 0 m/s. The data series for a layer thickness of 124 mm (fig. 6) was obtained a few weeks after the other data series. This data series includes more measurements in the region where the minimum in k was observed (between 0 and 2 m/s) and it confirms the previous findings. To further investigate this phenomenon, experiments were carried out to visualize the air movement in the boundary layer over the mulch, using a source of smoke. A smoke gun (E. Vernon Hill, Inc., San Francisco, California) was used to insert smoke into a layer of pine straw (fig. 11). The (qualitative) results of these experiments are illustrated in figure 12. At an air velocity of 0 m/s the smoke rises almost vertically above the pine straw in a well developed free convection current. At 1 m/s, this free convection current seems to be suppressed by the horizontal forced convection current, decreasing heat transfer by means of free convection. The forced air does not seem to penetrate into the pine straw, so forced convection does not yet contribute to increase heat transfer. The overall result is that heat transfer, and with it apparent thermal conductivity, is smaller at 1 m/s than at 0 m/s. At 4 m/s the forced air seems to penetrate into the straw, thus enhancing heat transfer and apparent thermal conductivity.

For the Bermudagrass sods, k cannot be calculated since it consists of two distinctly different layers: a soil and a stubble layer. Thus the results are given as thermal resistance in figure 13. Thermal resistance decreases with increasing v, which is consistent with the results for the other materials. The following regression equation represents the data:

$$R_m = -0.0203 \times \nu + 0.3823 \qquad (13)$$

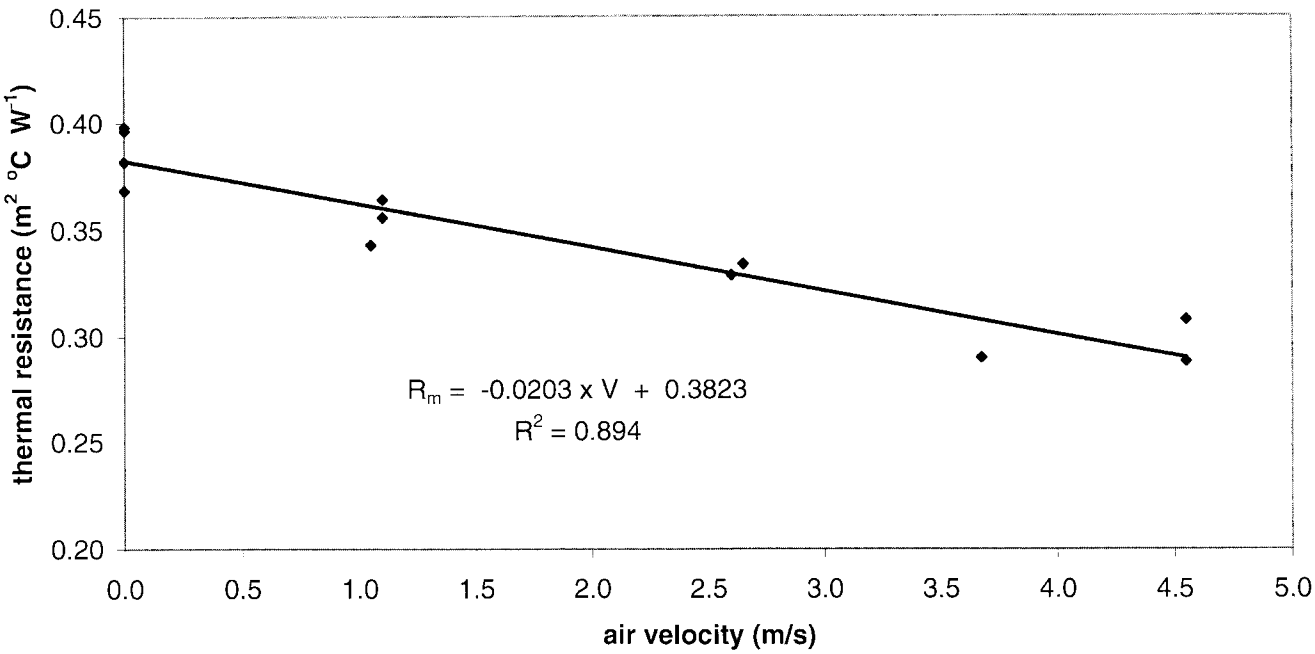

Figure 13–Thermal resistance of Bermudagrass sod as a function of air velocity.

where

R_m = thermal resistance of dormant Bermudagrass sod (m^2 °C W^{-1})

v = air velocity (m/s)

This equation was used in the simulation of temperatures of a soil covered by dormant Bermudagrass sod (van Donk, 1999).

Most apparent thermal conductivity (k) values obtained here are greater than the corresponding ones obtained by van Donk (1999) in his experiments, which were conducted with mulch materials placed between a hot plate and a cold plate. There are a number of possible reasons for these differences. For the straw materials there may be at least two reasons. One is that the infrared thermometer, that was used in the forced convection experiments, 'looks' into the straw layer, recording a warmer temperature. A second reason is that buoyant convection is suppressed with the cold plate on top, acting as a lid. In the forced convection experiments there is no 'lid', giving a buoyant convection current more opportunity to fully develop, increasing heat transfer and k.

For soil these two reasons do not apply, since the infrared thermometer can not look into the soil and there is no buoyant convection in the soil. The higher k values (0.38 vs. 0.22 W m^{-1} $°C^{-1}$ between the two plates) for soil may be explained by a contact resistance: there may be a narrow air gap between the top of the soil and the overlying cold plate. Although this is a narrow gap, this may be important since the gap is filled with still air having a thermal conductivity of only 0.026 W m^{-1} $°C^{-1}$. Using only the hot plate and measuring the top soil temperature with an infrared thermometer may be the better method for measuring k of soil.

Estimated parameters in the convection term of equation 12 are shown in table 5. Only measurements with v > 1 m/s were used for this estimation, given the peculiar behavior of heat flux and apparent thermal conductivity at v < 1 m/s (figs. 5 and 6). Correlation coefficients range between 0.72 and 0.99. The velocity parameter d is negative for all materials, reflecting increasing heat flux as air velocity increases.

Estimated parameters of equation 5 are shown in table 6. Correlation coefficients range between 0.92 and 0.98. For soil, the A parameter is very small, indicating that forced convection has no real effect on heat flux and apparent thermal conductivity as can be seen in figure 9. The B parameter is 0.37 W m^{-1} $°C^{-1}$ for soil, which matches the previously calculated value of 0.38 W m^{-1} $°C^{-1}$. Heat flux through small tire chips increases slightly (A = 0.021) with increasing air velocity (fig. 7). Apparent thermal conductivity of small chips is 0.11 W m^{-1} $°C^{-1}$ at v = 0 m/s. Heat flux through large tire chips increases more (A = 0.055) with increasing v, compared to small chips (fig. 8). This may be attributed to the coarser nature of the material, giving the forced air more opportunity to penetrate it, thus increasing heat flux. Calculated versus measured heat flux for all mulch materials is shown in

Table 5. Estimated parameters and standard errors (in brackets) in the convection term of the model given in equation 9

Material	Material Thickness L (mm)	Bulk Density (kg/m^3)	Convection Parameter C	Velocity Parameter d (s/m)	r^2
Wheat straw	74	12	0.09 (0.0050)	–2.77 (0.38)	0.98
Wheat straw	163	14	0.06 (0.0049)	–4.56 (0.55)	0.99
Pine straw	63	25	0.13 (0.0224)	–1.83 (1.18)	0.72
Pine straw	112	18	0.11 (0.0043)	–1.60 (0.17)	0.99
Pine straw	124	30	0.07 (0.0128)	–3.56 (1.25)	0.77

Table 6. Estimated parameters and standard errors (in brackets) of the model given in equation 5

Material	A (W m^{-2} $°C^{-1}$ s)	B (W m^{-1} $°C^{-1}$)	r^2
Small chips	0.021 (0.0013)	0.11 (0.0036)	0.97
Large chips	0.055 (0.0067)	0.23 (0.0183)	0.92
Soil	0.004 (0.0024)	0.37 (0.0066)	0.98

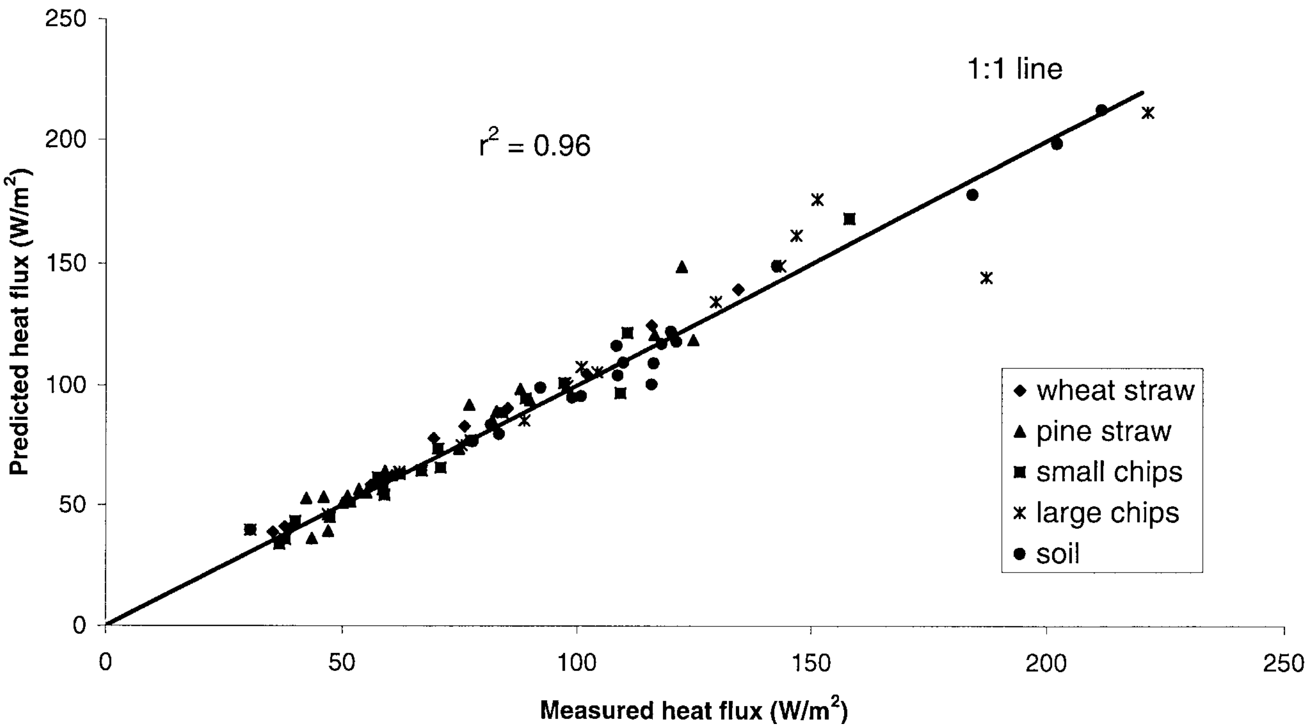

Figure 14–Predicted versus measured heat flux for five mulch materials.

figure 14. There is still a need for the model to be tested using independently measured data.

CONCLUSIONS

The apparent thermal conductivity (k) of wheat straw, pine straw, tire chips, dry sandy soil, and the thermal resistance of Bermudagrass sods were measured using a guarded hot plate, at air velocities between 0 and 5 m/s. For all mulch materials, k ranged between 0.1 and 0.6 W m^{-1} °C^{-1}. Thermal conductivity increased with increasing air velocity, except for the more compact materials, such as soil and, to a lesser extent, small tire chips. For dry, sandy soil, k was around 0.38 W m^{-1} °C^{-1} independent of air velocity. A minimum in k was observed around 1 m/s for the thicker (> 0.1 m) layers of wheat straw and pine straw, which was tentatively attributed to interactions between the straw and the convection (free versus forced mechanism at the 1 m/s velocity).

A model was created for heat transfer through mulches in thermally unstable environments. This model may be used in field situations where the soil under a mulch is warmer than the air above the mulch, which is a typical nighttime condition. It is likely to perform better than a similar model developed van Donk (1999) for the case of heat transfer through mulches between two plates of different temperature, since the current study better approximated a field situation. The model should be tested using independently measured data.

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