Agricultural and Forest Meteorology, 37 (1986) 319—329
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

ESTIMATION OF SOIL HEAT FLUX FROM NET RADIATION DURING THE GROWTH OF ALFALFA

B.E. CLOTHIER*, K.L. CLAWSON**, P.J. PINTER, JR., M.S. MORAN, R.J. REGINATO and R.D. JACKSON

U.S. Department of Agriculture, Agricultural Research Service, U.S. Water Conservation Laboratory, 4331 East Broadway Road, Phoenix, AZ 85040 (U.S.A.)

(Received September 11, 1985; revision accepted February 11, 1986)

ABSTRACT

Clothier, B.E., Clawson, K.L., Pinter, P.J. Jr., Moran, M.S., Reginato, R.J. and Jackson, R.D., 1986. Estimation of soil heat flux from net radiation during the growth of alfalfa. Agric. For. Meteorol., 37: 319—329.

Soil heat flux studies have indicated that the instantaneous daytime flux can be estimated as a fraction of the net radiation, the ratio ranging from 0.1 to 0.5, depending on the amount of vegetation present and on the time of day. Soil heat flux and net radiation were measured for an alfalfa crop over two regrowth cycles during the fall growing season. For both sparse alfalfa stubble and full vegetative canopy, the surface soil water content did not significantly affect the fraction of net radiation consumed as soil heat flux. The ratio of soil heat flux to net radiation around midday was found to be a linearly decreasing function of crop height only for heights up to 450 mm. As crop growth continued beyond this height, the ratio remained nearly constant at 0.1. The ratio data were also found to be well-fitted by a linearly decreasing function of a spectral vegetation index (near-IR to Red ratio) over both regrowth cycles. These results indicate that both crop height and spectral vegetation indices can be used to estimate soil heat flux from net radiation measurements.

INTRODUCTION

Combining remotely sensed data with ground-based meteorological data offers the possibility of evaluating surface energy fluxes over relatively large areas (Reginato et al., 1985). In general, the sum of the surface fluxes of sensible (H) and latent heat (λE) is equal to the difference between the net radiation (R_n) and the surface soil heat flux (G). Net radiation and sensible heat flux can be evaluated from combined remote and ground-based measurements. Thus the evaporative loss of water from the area (λE) can be obtained by difference, if G is known or can be estimated. Since G cannot be measured remotely and the number of heat flux transducers required to adequately characterize a relatively large area with diverse vegetative cover would be prohibitive, its estimation is preferred.

Soil heat flux is generally considered small relative to the other surface fluxes and has, at times, been ignored in energy balance models (Hatfield et

* Permanent address: DSIR, Palmerston North, New Zealand.
New address: NOAA, ERL, 1750 Foote Drive, Idaho Falls, ID 83402, U.S.A.

0168-1923/86/$03.50

al., 1984). DeBruin and Holtslag (1982) presented a large body of hourly soil heat flux data and showed that for a short grass pasture the daytime ratio G/R_n was equal to 0.1, at least on average. Use of this simple relationship obviated the need for detailed measurement of G in their study of the surface energy fluxes. However, the standard error of the estimate was some 50% of the mean value of G. The bare soil data of Fuchs and Hadas (1978) showed G/R_n to be about 0.35 and independent of the surface soil water content. Idso et al. (1975), however, found that for bare soil this ratio changed considerably with soil water content, ranging from 0.5 for a dry soil down to 0.3 for a wet soil. Plots of G versus R_n for these two bare soil data sets showed a distinct hysteresis in the diurnal G, R_n relationship. Hysteresis implies that the ratio G/R_n is time-of-day dependent. These data, for both pasture and bare soil, however, suggest that instantaneous values of soil heat flux estimated from net radiation would at least be adequate for many remotely sensed surface energy-balance studies. Nevertheless, better estimation of G would improve techniques for estimating instantaneous evapotranspiration rates from one time-of-day measurement (Heilman et al., 1976; Hatfield et al., 1984; Reginato et al., 1985).

Our objective was to examine the diurnal pattern of surface soil heat flux and net radiation over an entire growth cycle of alfalfa, under both well-watered and water-deficient conditions. This would provide data to allow better estimation of soil heat flux from net radiation data, especially for remote sensing applications.

MATERIALS AND METHODS

Soil heat flux was measured under an 8-month-old stand of alfalfa (*Medicago sativa* L.) grown on an Avondale loam soil (Anthropic Torrifluvent, fine loamy, mixed (calcareous), hyperthermic) at Phoenix, AZ during 1984. The cultivar "Lew" is a phytophthera-resistant variety which shows no winter dormancy. Several studies concerning the thermal properties of Avondale loam have been reported previously (Idso et al., 1975; Kimball and Jackson, 1975; Kimball et al., 1976a,b).

The experiment spanned the fall growth period beginning 28 September (day-of-year 272) following a harvest on 25 September, through another harvest on 15 November (Day 320), and ended on 7 December (Day 342). The measurements therefore covered a range of vegetative conditions, from almost-bare soil to the full cover of a 600-mm high stand of alfalfa (Fig. 1).

Soil heat flux was measured in two plots (designated 2B and 3B), using the so-called combination method (Tanner, 1963). This involved installing three, 60-mm diameter by 4.5-mm thick, heat flux plates (Micromet Instruments, Bothell, WA)* at 50-mm depth in adjoining plots identified as 2B and

* Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

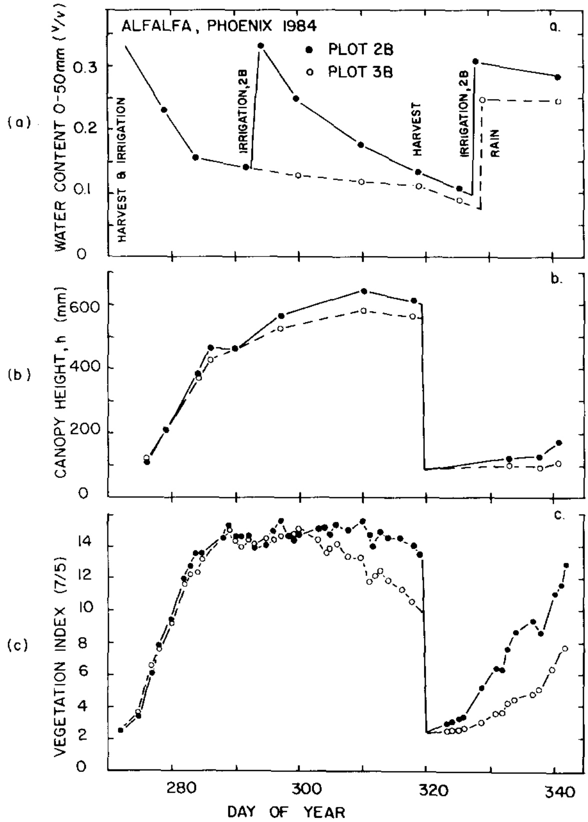


Fig. 1. (a) Volumetric water content θ in Plots 2B (●) and 3B (○); (b) alfalfa canopy heights; and (c) vegetation index values.

3B. The voltages from the plates were scanned at about 1.5-min intervals to obtain the average for each 30-min period. The soil heat flux density at 50-mm depth (G_{50}) in each plot was taken as the average of the three plates for each 30-min time period.

Calorimetry was used to calculate the flux due to heat storage changes in the 0—50-mm depth of soil. The total surface heat flux (G) was found as the sum of the flux at 50 mm and that due to storage in the zone above,

$$G = G_{50} + \int_0^{50} C(z)\,(\partial T/\partial t)\mathrm{d}z \tag{1}$$

where $C(z)$ is the volumetric heat capacity, T is temperature (°C), t time (s), and z depth (mm). The depth-wise constant volumetric soil heat capacity was found using (deVries, 1963),

$$C = C(z) = (1.03 + 4.19\theta) \times 10^6 \ (\mathrm{J\,m^{-3}\,{}^{\circ}C^{-1}}) \tag{2}$$

with a bulk density of 1.4 Mg m^{-3} from Kimball and Jackson (1975). Here θ is the volumetric soil water content, being the gravimetric water content times the bulk density. Diurnally constant values of θ were linearly interpolated from weekly gravimetric measurements of the surface (0—50 mm) water content (see Fig. 1a). Temperature profiles in the soil at 0 mm (just under the surface), 10 mm, 20 mm and 50 mm were measured by thermocouples in plots 2B and 3B. Three separate profiles, but with each depth connected in parallel, were measured in both plots. For each half-hour period the average temperature ($\bar{T}_t$) of the 0—50 mm zone was found using the weights of 0.1, 0.2, 0.4, and 0.3 applied to the 0, 10, 20 and 50-mm depth temperatures. These weightings accounted for the relative thicknesses of the soil slabs in which thermocouples were centrally located. Therefore, the heat stored in the upper 50 mm of soil over the previous half-hour, S_{50}, was found as:

$$S_{50} = (28.5 + 116.4\theta)(\bar{T}_t - \bar{T}_{t-1})(\mathrm{W\,m^{-2}}) \quad (3)$$

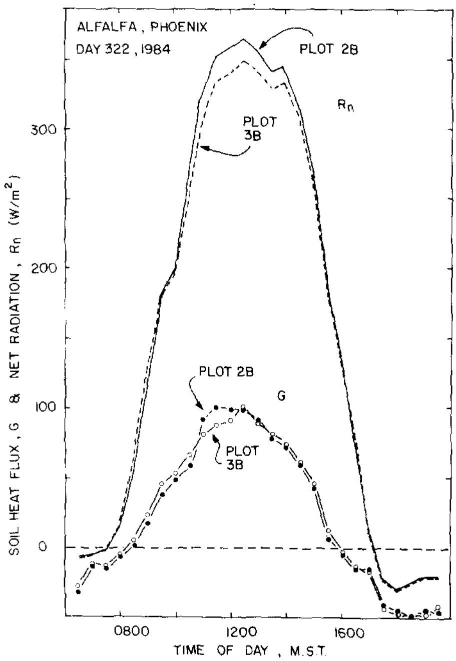
Equation 1 can now be written as:

$$G = G_{50} + S_{50} \quad (4)$$

The two plots were differentially irrigated to provide a range of soil surface water contents. Both plots were flood irrigated on 27 September (day 271), two days after the late summer harvest. Plot 2B received an additional flood irrigation on 19 October (day 293), mid-way through the fall growth period. Following the harvest on day 320, Plot 2B was again irrigated (day 325). Three days later, a 37-mm rain virtually eliminated the surface water content differences between the two plots. During each irrigation, about 100 mm of water was applied.

Surface water contents were measured by taking five soil cores from each plot at approximately weekly intervals. The cores were sectioned into 0—50 mm and 50—100 mm samples, weighed, then dried. A bulk density of 1.4 Mg m^{-3} was used to convert the gravimetric water contents to volumetric water contents. The data presented in Fig. 1 show the soil surface drying trends and irrigation events.

During the growth of the alfalfa, routine measurements of canopy height and spectral reflectance were made. Canopy heights were measured one or two times per week at 12 sites in each plot. Spectral reflectance was measured with a hand-held radiometer having two visible (0.5—0.6 μm, and 0.6—0.7 μm), and two near-infrared (0.7—0.8 μm, and 0.8—1.1 μm) channels. Measurements were made regardless of cloud conditions on most mornings during the experiment at a time that corresponded to a constant solar zenith angle of 57°. A vegetative index, the ratio of the reflectance in the near-IR band (0.8—1.1 μm) to that in the red band (0.6—0.7 μm) was calculated from the spectral data (Jackson et al., 1983; Pinter, 1983). This vegetation index (VI) is related to the amount of green phytomass present in the canopy. This may provide a parameter, capable of being remotely



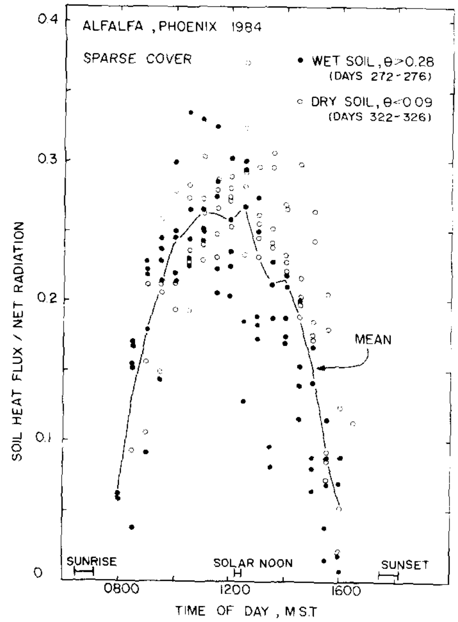


Fig. 2. Net radiation, R_n, and soil heat flux, G, in Plots 2B ($\theta = 0.149$) and 3B ($\theta = 0.095$) on day 322 (17 November 1984).

Fig. 3. Daylight values of G/R_n measured over two 5-day periods following cutting of the alfalfa in Plot 2B.

evaluated, against which the ratio of soil heat flux to net radiation can be regressed. Since the canopy height and the VI are both related in some way to phytomass, it is not surprising to find that a simple parabolic regression of the two parameters had a correlation coefficient (R) of 0.91 ($n = 24$).

RESULTS

Similarity of plots

Since it was intended to compare the heat flux between Plots 2B and 3B under different conditions, it was necessary to confirm their similarity under the same conditions. Following harvest on Day 320, both plots were at similar water contents and vegetative cover. On Day 322, the vegetation index was <3 and the alfalfa was <110 mm tall, having just been harvested. The surface soil water contents for Plots 2B and 3B were 0.149 and 0.095, respectively. The difference in their heat capacities was $<15\%$. The soil heat flux and the net radiation measured during day 322 are shown in Fig. 2. The agreement is excellent, thereby justifying the comparative use of the two plots.

Instantaneous heat flux

The diurnal trace of the soil surface temperature, T_0, exhibits a maximum at about 1400—1500 h M.S.T. on most days. This is a lag of about 2 h after solar noon and after the time of maximum (cloud-free) R_n. At, or just after, the time of maximum T_0, $\partial T/\partial z|_{z=0}$ will be zero, and therefore the soil heat flux will be zero. This can be seen in Fig. 2 where $G = 0$ at about 1530 h. Note that net radiation is still significant, about half the maximum R_n, at this time. Thus, if energy balance calculations are to be made around the time of the maximum soil surface temperature, negligible error will result from ignoring the soil heat flux. Coincidentally, this may be the most likely time of the greatest expression of plant-water stress symptoms, and could be advantageous in the remote assessment of crop water status. Energy balance calculations for earlier times in the day, however, should take account of the soil heat flux.

For analytical purposes, the diurnal T_0 trace can be considered a cosine wave of angular frequency ω. If this assumption is valid, then the maximum in G will precede the time of maximum T_0 by $\pi/(4\omega)$, or 3 h (Carslaw and Jaegar, 1959). In this example if the T_0 maximum is around 1430 h then G should peak at about 1130 h. Therefore the diurnal trace of G will be about 1 h (or $\pi/[12\omega]$) out of phase with respect to R_n. This phase shift can be seen in Fig. 2, especially for Plot 2B. Consequently when, as is commonly done, diurnal values of G are plotted against R_n (Fuchs and Hadas, 1972; Idso et al., 1975; deBruin and Holtslag, 1982), a hysteresis loop is found. This is expected as the morning rise in G precedes that of R_n. In the afternoon, G declines more rapidly than R_n.

Therefore on a cloud-free day, a rapid morning rise in the G/R_n ratio can be expected on the basis of the phase lead of G ahead of R_n. This ratio should then follow a gradual decline through noon, with a more rapid drop-off to zero in mid- to late-afternoon when T_0 reaches its maximum. In Figs. 3 and 4, the G/R_n ratios measured during daylight hours are plotted for 20 days which cover a range of environmental conditions. The diurnal pattern of G/R_n follows the trend outlined in the aforegoing analysis. However, cloudiness on some days led to substantial variation about the relatively smooth trace of cloud-free days.

Sparse vegetative cover

Immediately following the harvest on day 269 and the subsequent irrigation on day 271, Plot 2B had a very wet soil surface ($\theta \geqslant 0.28$) but also a sparse vegetative cover. Following the harvest on day 320, water was withheld from plot 3B so that it had a very dry soil surface ($\theta \leqslant 0.09$) but also a sparse vegetative cover. The G/R_n ratios for these two periods are given in Fig. 3. Generally the wet and dry soil G/R_n ratios are the same, although a t-test revealed a significantly ($P \leqslant 0.001$) higher G/R_n for the dry soil at just

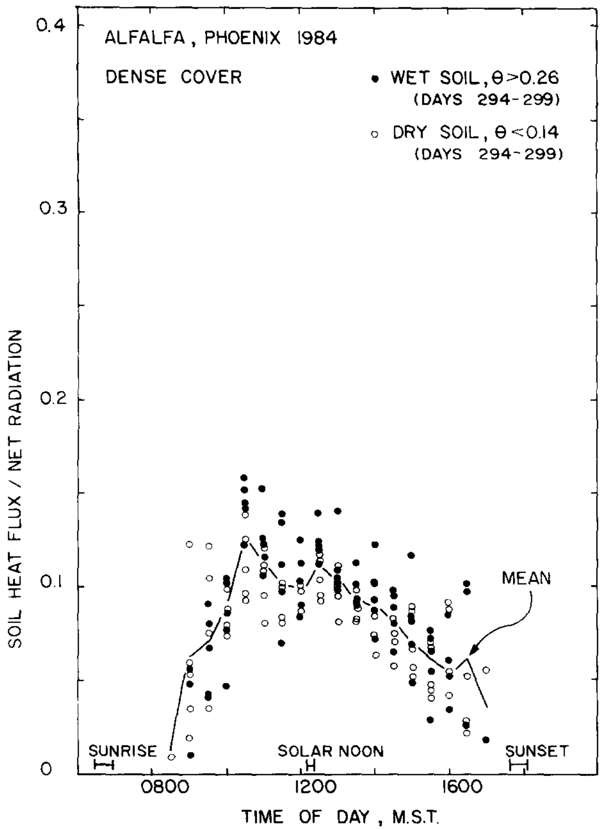


Fig. 4. Daylight values of G/R_n measured over two 5-day periods in Plots 2B (●) and 3B (○) with full-cover alfalfa.

the two times of 1430 and 1500 h. This minor difference is not surprising since this G/R_n comparison is between different days in different periods. However, the overall similarity of the wet and dry G/R_n ratios differs from the findings of Idso et al. (1975) on this same soil. They found for completely-bare Avondale loam, that G/R_n ranged from 0.3 for wet soil ($0.22 \leqslant \theta \leqslant 0.26$) up to 0.5 for dry soil ($0.04 \leqslant \theta \leqslant 0.16$). The absence of such a trend in the present data can probably be attributed to the presence of vegetation, albeit sparse. Despite mowing at harvest, there remained an alfalfa stubble about 100 mm in height, as well as some litter on the soil surface from leaf senescence and abscission during harvest. Even this small degree of cover was apparently sufficient to lower the midday G/R_n values of 0.5 found by Idso et al. (1975) to <0.3 as found here in Fig. 3. Furthermore, the meager vegetation cover was apparently sufficient to over-ride any surface soil wetness effect. Little difference in the soil surface temperatures (10—50 mm) was measured between the plots following the irrigation of one and harvest of both around Day 320. The lack of dependence of G/R_n upon

θ is practically important in that surface water content need not be considered as a variable when estimating G for crops. This result does not extend to completely bare soil, and might not be applicable during warm summer months.

Dense canopy

By about day 295, regrowth of the alfalfa had established a dense, full-cover, 500-mm tall canopy. On day 293, Plot 2B was irrigated (Fig. 1), so there was a substantial difference in soil surface water contents between the two plots. Over days 294—299, θ in Plot 2B declined from 0.33 to 0.26, whereas for the same period Plot 3B dried from $\theta = 0.14$ to 0.13. The half-hourly G/R_n ratios for these days are shown for both plots in Fig. 4. The diurnal trend in the ratio again exhibits asymmetry, with a rapid rise in the morning and a gradual decline through noon to zero in late afternoon. Now however, the peak G/R_n is reduced from around 0.3 to about 0.1 because of the presence of the more-substantial alfalfa canopy. Again, as was the case for sparse vegetative cover, there was no effect due to the substantial difference in the surface water contents.

Correlations with measured canopy parameters

For energy balance calculations made late in the afternoon, it may well be acceptable to ignore the contribution of the soil heat flux term. Characteristically $G = 0$ at about the time of maximum soil surface temperature which typically occurs in mid- to late-afternoon. However, if an energy balance is to be determined earlier in the day, G may be a significant fraction of the budget. Soil heat flux is not routinely measured and appears incapable of being directly remotely-sensed. In such instances estimation of G is sought by considering its correlation with other terms in the energy balance and/or surface characteristics. In the following two sections, the mean of seven half-hour G/R_n ratios (1100—1400 h) will be correlated first with the canopy height, and then with the vegetation index. Forty-one days of complete observations from the two plots gave a total of 82 midday G/R_n values for consideration. The seven midday values of G/R_n exhibited only moderate variation. The average C.V. was just 15.7%, reflecting conditions.

Crop height

Average crop heights, h, were computed from 12 measurements in each plot on 26 days during the study period. Interpolation between days (Fig. 1) gave values of h for each plot on every day of the study. The average coefficient of variation in crop height from the 12 measurements for the 26 days was 15.5%. Figure 5 shows the plot of the midday G/R_n against alfalfa height. The trend in the data was simply considered to represent a linear decline in G/R_n until $h = 450$ mm. At $h \geqslant 450$, $G/R_n = 0.10 \pm 0.01$. A

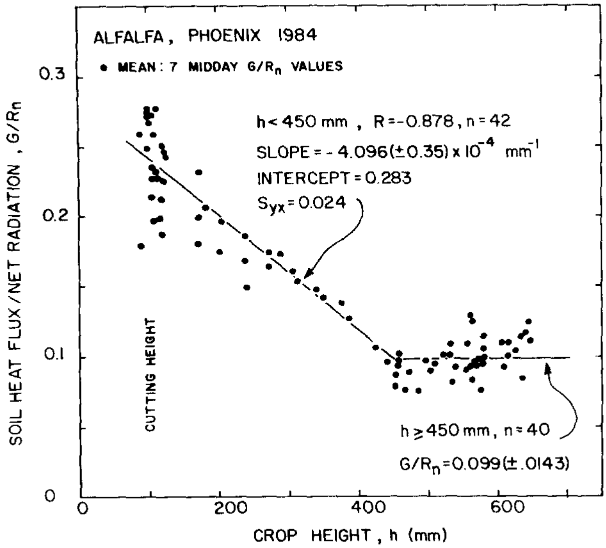


Fig. 5. The average of seven midday G/R_n values (1100—1400 h) regressed against alfalfa crop height, h.

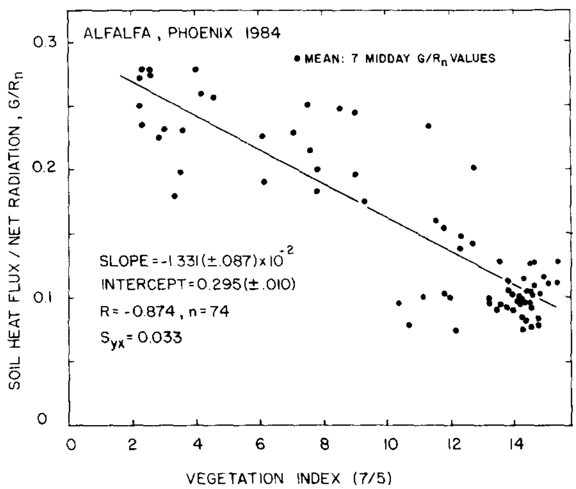


Fig. 6. The average of seven midday G/R_n values (1100—1400 h) against a vegetation index (near-IR/Red).

linear regression of the 42 data points in the decline stage indicated a standard error of the estimate ($S_{y \cdot x}$) of 11.8% of the mean value of G/R_n. The accuracy of this simple relationship would be sufficient for energy balance calculations in many cases.

Vegetation index

For some remote sensing applications even such primary information as crop height may not be readily available, especially if the energy budget of a large region is required in real-time. A vegetation index may be useful as a surrogate of crop biomass and allow estimation of the G/R_n ratio. The relationship found between G and an already-defined vegetation index is shown in Fig. 6 over the two regrowth cycles of the present study. The two cycles had quite different soil surface water contents and air temperature regimes. A greater scatter is evident than for the crop height relationship (Fig. 5), although the standard error of the estimate is still an acceptable 21.6% of the mean G/R_n. Since the average G/R_n was about 0.15, the average available energy term $(R_n - G)$ can be estimated to within about 4%.

CONCLUDING REMARKS

For an alfalfa stand, the water content of the soil surface did not significantly affect the fraction of net radiation consumed as soil heat flux. A sparse 100-mm stubble remaining after mowing was sufficient to substantially lower the G/R_n ratio below that previously found for this soil when bare (Idso et al., 1975).

Two vegetation measures, the crop height and a spectral vegetation index, proved useful in specifying the G/R_n ratio. From a value of 0.3 for stubble the G/R_n ratio decreased from about 0.3 to about 0.1 with increasing crop height up to 450 mm where it remained nearly constant at 0.1. The G/R_n ratio decreased from about 0.3 to 0.1 with increasing (near-IR/Red) vegetation index. These results indicate that the soil heat flux can be estimated from net radiation measurements with reasonable accuracy. Adequate account of G is thus possible when remotely sensing the surface energy balance over relatively large areas.

REFERENCES

Carslaw, H.S. and Jaegar, J.C., 1959. Conduction of Heat in Solids. Oxford Scientific Publications (2nd edn.), 510 pp.

DeBruin, H.A.R. and Holtslag, A.A.M., 1982. A simple parametrization of the surface fluxes of sensible and latent heat during daytime compared with the Penman—Monteith concept. J. Appl. Meteorol., 21: 1610—1621.

DeVries, D.A., 1963. Thermal properties of soil. In: W.R. van Wijk (Editor), Physics of the Plant Environment. North-Holland, Amsterdam, pp. 210—235.

Fuchs, M. and Hadas, A., 1972. The heat flux density in a non-homogeneous bare loessial soil. Boundary-Layer Meteorol., 3: 191—200.

Hatfield, J.L., Reginato, R.J., and Idso, S.B., 1984. Evaluation of canopy temperature-evapotranspiration models over various crops. Agric. For. Meteorol., 32: 41—53.

Heilman, J.L., Kanemasu, E.T., Rosenberg, N.J. and Blad, B.L., 1976. Thermal scanner measurement of canopy temperatures to estimate evapotranspiration. Remote Sensing Environ., 5: 137—145.

Idso, S.B., Aase, J.K. and Jackson, R.D., 1975. Net radiation-soil heat flux relations as influenced by soil water variations. Boundary-Layer Meteorol., 9: 113—122.

Jackson, R.D., Slater, P.N. and Pinter, P.J., Jr., 1983. Discrimination of growth and water stress in wheat by various vegetation indices through clear and turbid atmospheres. Remote Sensing Environ., 13: 187—208.

Kimball, B.A. and Jackson, R.D., 1975. Soil heat flux determination: A null alignment method. Agric. Meteorol., 15: 1—9.

Kimball, B.A., Jackson, R.D., Reginato, R.J., Nakayama, F.S. and Idso, S.B. 1976a. Comparison of field-measured and calculated soil heat fluxes. Soil Sci. Soc. Am. J., 40: 18—25.

Kimball, B.A., Jackson, R.D., Nakayama, F.S., Idso, S.B. and Reginato, R.J., 1976b. Soil heat flux determination: temperature gradient method with computed thermal conductivities. Soil Sci. Soc. Am. J., 40: 25—28.

Pinter, P.J., Jr., 1983. Monitoring the effect of water stress on the growth of alfalfa via remotely sensed observations of canopy reflectance and temperature. Extended Abstract, 16th Conf. Agric. and Forest Meteorol., April 26—28, 1983. Ft. Collins, CO. Am. Meteorol. Soc. Boston, MA, pp. 91—94.

Reginato, R.J., Jackson, R.D. and Pinter, P.J., Jr., 1985. Evapotranspiration calculated from remote multispectral and ground station meteorological data. Remote Sensing Environ., 18: 75—89.

Tanner, C.B., 1963. Basic instrumentation and measurements for plant environment and micrometeorology. Soils Bull. 6, Univ. of Wisconsin, Madison, WI.