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Influence of plant cover on the share of the soil heat flux in the heat balance of the active surface

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A b s t r a c t. Soil heat flux is one of the heat balance components of active surface. Average value of this flux for a long period is equal zero, but for a short period it can be very high. It can be positive, when heat is flowing from the soil to the surface, or negative in the opposite case. The impact of solar radiation (net radiation) and leaf area index (LAI) on the value of soil heat flux were analyzed in the paper. The equations for the calculation of soil heat flux density as a function of net radiation were found for bare soil, grass and lupine field.

K e y w o r d s: heat balance, soil heat flux, leaf area index

INTRODUCTION

The surface, through which the exchange between energy and matter takes place, is called an active surface. Hence, both the surface of the bare soil and that of a field with well-developed plant cover can be qualified as an active surface. A surface of this kind absorbs short-wave sun radiation and emits long-wave radiation whose intensity depends on the temperature of the surface (Kędziora, 1995). The exchange of vapour between the soil and atmosphere, as well as the exchange of energy during the evaporation process connected with it, also takes place through an active surface.

One of the ways of the micrometeorological description of our environment is the presentation of the heat balance structure of the active surface. It is assumed that the fluxes coming to the surface have positive values and the outgoing have negative values. In literature it is usually described as an equation (Boyen *et al*., 1976; Kędziora, 1995; Monteith, 1977; Oke, 1978; Paszyński, 1972):

$$Rn+LE+S+G=0 \tag{1}$$

where: Rn is net radiation, LE is latent heat flux density, S is sensible heat flux density, and G is soil heat flux density. All the values are expressed in W m^{-2}.

It can be assumed that during a longer period of time, net radiation (Rn) is the only incoming component of the heat balance and it defines the amount of energy which can be used for other processes taking place on an active surface. In the Eq. (1), the fluxes of sensible (S) and latent (LE) heat are turbulent energy fluxes. Throughout longer periods of time, these fluxes are responsible for the flux of energy flowing from an active surface to the atmosphere and are connected with heating of the atmosphere (S) and evapotranspiration (LE) (Olejnik and Kędziora, 1991). However, during shorter periods of time (measured in hours), both of these fluxes can flow from the atmosphere in the direction of the active surface. In such a case, the active surface can be heated by the atmosphere (S) or dew will appear on its surface due to condensation of vapour from the atmosphere (LE), which is connected with energy emission (heat of water evaporation) on the active surface.

Another component of the heat balance of the active surface (Eq. (1)) is the heat which is exchanged with soil (G). This flux is created due to the differences in temperature between the surface of the soil and its deeper layers. If the surface of the soil, as a result of short-wave radiation absorption, has a higher temperature than its deeper layers, then the flux of soil heat is directed from the active surface inwards the soil (in that case G is negative in Eq. (1)). Whereas, if the temperature of the deeper layers of the soil is higher than the temperature on its surface, flux G is directed

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towards the active surface (in that case *G* is positive in Eq. (1)) (Olejnik *et al*., 2001; Taylor, 1972).

After a relevantly long period of time (a year or more), the value of the soil heat flux approaches zero or constitutes only a small fraction of the radiation balance (Kędziora, 1995; Lee *et al*., 2004; Olejnik and Todd *et al*., 2000). The soil heat flux is also modified by the thermal and wind conditions of the atmosphere (Soler *et al*., 2002).

On the other hand, when the equation of the heat balance refers to periods which are shorter (a month, a day, or an hour), the share of soil heat in the heat balance of the surface can be substantial. This applies mostly to active surfaces with very poor plant cover (*eg* waste land) or to surfaces with no plant cover at all (stubble or ploughed fields). On such surfaces, particularly after long periods without precipitation, when the soil is over dry, temporary values of the soil heat flux can reach even 50% of the value of the net radiation *Rn*, and, in particular cases, they may even exceed that value (Kędziora, 1995). In some cases, the accuracy of estimation of the *G* flux can have a vital influence on the quality of estimation of other, turbulent components of the heat balance (*S* and *LE*) (Allen *et al*., 1998). It is particularly important when methods based on the principle of conservation law of energy (*eg* Bowen method) (Olejnik and Eulenstein, 1997) are used for the estimation of fluxes *S* and *LE*.

Correct estimation of the soil heat flux is also essential for model works, such as the estimation of the seasonal evapotranspiration from the surfaces of fields under crops (Olejnik *et al*., 2001).

This article contains the results of measurements of the soil heat flux and the net radiation for three different active surfaces. Moreover, the article presents the analysis of *G/Rn* ratios for respective surfaces in an attempt to estimate what percentage of the net radiation is constituted by the soil heat flux. What is more, it presents an attempt at derivation of the simple linear dependencies which allow estimation of the value of the soil heat flux (*G*) as a function of the value of the net radiation (*Rn*) for three different types of active surface.

METHODS

The measurements were curried out at the experimental station in Poznań, in the days from 19 to 25th of September. Three different active surfaces were prepared in advance (circles of 5 m radius). They were grass, lupine field and bare soil. The location of the examined surfaces was chosen in such a way as to exclude the influence of one on another, as well as to exclude possible influence of other objects (buildings, trees, *etc*.) on the conducted measurements of the soil heat flux and net radiation.

The actual measurements were preceded by pilot measurement series in order to calibrate the sensors used for measuring the radiation balance (pyranopyrgeometer, saldometer and pyrradiometer – produced by Kipp, Zonen and Thies) and the heat flux exchanged with the ground (12 thermocouple soil heat plates - produced by Sojo and Kuksa-Flux) (Bilicki, 2001; Fuchs and Tanner, 1968; Urbaniak, 2001).

An instrument for measuring the net radiation was placed 0.5 m above each of the surfaces and four plates for measuring soil heat flux were placed 0.02-0.03 m deep under the ground surface.

All the sensors were linked to a 32-channel data-logger produced by Kest-Electronics as well as to a portable computer. The data acquisition system was programmed in such a way that it collected data from all the sensors at one-second intervals and then it assessed average hour values of the net radiation and soil heat flux, for each of the respective surfaces.

Additionally, during measuring *G* and *Rn* fluxes also the leaf area index (LAI) was measured twice, at the beginning and at the end of the measurement session. For that purpose the LAI-2000 sensor, produced by the LICOR Company, was used. Also the measurement of albedo for all three examined surfaces was curried out, using a pyranopyrgeometer.

RESULTS AND DISCUSSION

The graphs presenting the courses of net radiation flux (*Rn*) as well as soil heat flux (*G*) were prepared on the basis of collected data for all the active surfaces analysed, including the whole measurement period. As an example, Fig. 1 presents the daily course of the above-mentioned values for the first two days of measurement. This simple graphic analysis showed that there were substantial differences in the values of the analyzed flux of energy for two different active surfaces. For example, the surfaces covered with plants showed lower daily amplitudes of soil heat flux (*G*) than the surfaces without plants.

On the basis of the measurement results obtained, the average hourly values of *G/Rn* ratio were calculated for the three active surfaces respectively. Figure 2 presents the interrelations between *G/Rn* ratio and net radiation, *Rn* (W m^{-2}),

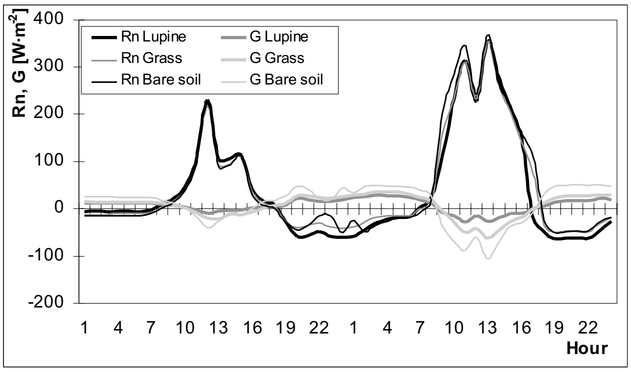

Fig. 1. Daily courses of the net radiation and soil heat flux for each active surface respectively, during the first two days of the measurement session.

for the surfaces examined (the flow directions of the energy fluxes were taken into consideration, hence the negative values). It is observable that for the active surface of lupine field, for small positive values of *Rn* (in the range from 0 to 50 W m^{-2}), the value of *G/Rn* ratio is prevailingly positive and may assume the value of 0.7. It stems from the fact that deficiency of energy for covering turbulent components of the heat balance, resulting from small values of the radiation balance, may be filled in 70% by the soil heat flux. At night or at dawn, when the radiation balance is negative and close to zero, the flux of heat energy coming from the soil can exceed the value of *Rn* even three times (for $Rn \cong 0$ $G/Rn = -3$). However, when the value of *Rn* falls below -30 W m^{-2}, the value of *G/Rn* ratio rarely exceeds -0.5 (Fig. 2).

the bare soil surface *G/Rn* ratios assume the highest values when compared with the surfaces with plant covers.

At small positive values of *Rn*, the values of *G/Rn* ratios are the highest, exceeding even the value of 2. Also for higher positive values of *Rn*, *G/Rn* ratio on the bare soil surface assumes the lowest values, dropping to -0.35. This indicates that on that particular active surface, even at high values of the net radiation, most of the heat energy is absorbed by the active surface and stored in soil. The energy flows to the active surface at night (at negative *Rn* values), which is shown by the layout of measurement points in Fig. 2 (bare soil). At negative values of *Rn* on the bare soil surface, the values of *G/Rn* ratios (even at very negative values of *Rn*) oscillate around the value of -1.

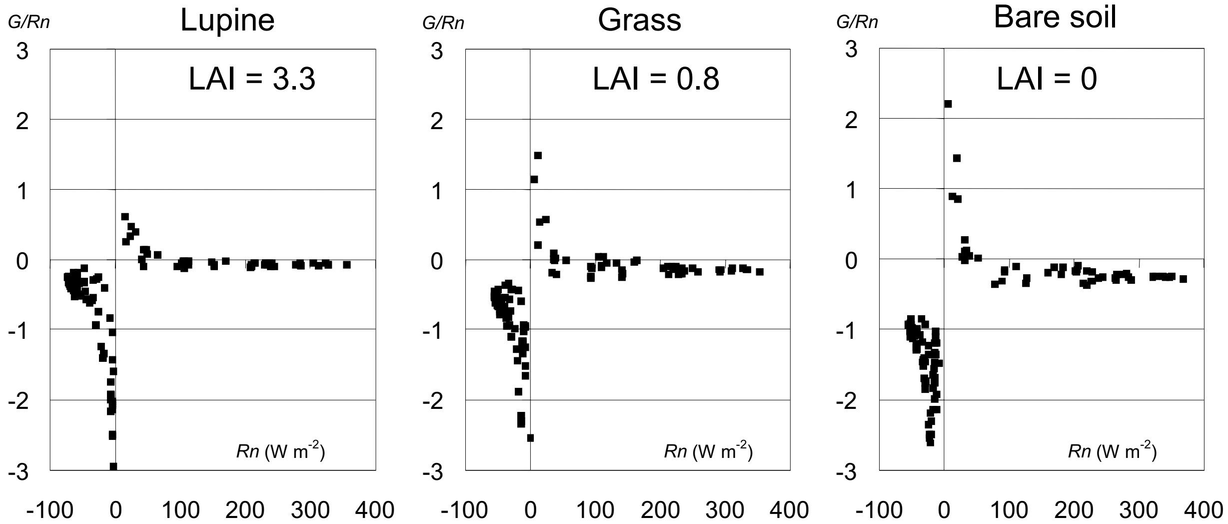

Fig. 2. The dependence of the *G/Rn* ratio on the value of the net radiation (*Rn*) over the lupine, grass and bare soil.

Similar analyses were conducted for grass and for the bare soil. On the grass, during the day at small values of net radiation, *G/Rn* ratio reached the value of 1.5, which means that the value of the soil heat flux exceeded the value of the net radiation (*Rn*) by 150%. When the value of *G/Rn* ratio is higher then one, it means that there is energy deficiency on a given surface resulting from a small value of the net radiation (lack of energy for covering turbulent fluxes *S* and *LE*). Under such conditions, lacking energy is taken from the deeper layer of the ground. For higher values of *Rn*, the *G/Rn* ratio assumed lower values oscillating, in most cases, between 0 and -0.1. On the grass, the share of *G* flux in the heat balance (in comparison to *Rn*) increased when compared with the surface covered with lupine (Fig. 2). This may indicate a smaller share of *LE* and *S* in the heat balance of grass than in that of lupine field, because evapotranspiration from the grass surface is smaller than from the surface covered with lupine (smaller flux of latent heat). On

It is clearly noticeable, after analyzing the layout of measurement points (Fig. 2) for all the active surfaces examined, that the value of *G/Rn* ratio under the same meteorological conditions depends substantially on the value of LAI. The higher the LAI, the lower the amplitude of *G/Rn* ratio fluctuations, whereas absolute values of *G/Rn* ratio are higher for the same values of the net radiation.

For the purpose of further analysis of the results obtained, the data sets for each active surface were divided into two parts. The first included average values of *G* and *Rn* during the time of day when *Rn* was above zero (they are called average daily values), the second part included the time of day when *Rn* values were below zero (they are called average night values). Table 1 presents average daily values of *G* and *Rn* fluxes as well as their ratios, for all three active examined, surfaces using the above division (Table 1a *Rn*>0, Table 1b *Rn*<0).

Table 1. Comparison of the daily average soil heat fluxes (G (W m^{-2})) and net radiation (Rn (W m^{-2})) as well as G/Rn ratios for each surface respectively.
a) for positive values of net radiation (Rn, daily values)

Date	Lupine (LAI = 3.3)			Grass (LAI = 0.8)			Bare soil		
	Rn	*G*	*G/Rn*	*Rn*	*G*	*G/Rn*	*Rn*	*G*	*G/Rn*
20.09	87	-1	-0.01	78	-8	-0.10	78	-9	-0.11
21.09	212	-13	-0.06	212	-29	-0.14	234	-52	-0.22
22.09	161	-16	-0.10	159	-31	-0.19	163	-50	-0.31
23.09	208	-9	-0.05	214	-26	-0.12	235	-53	-0.22
24.09	245	-14	-0.06	244	-29	-0.12	284	-63	-0.22
Average	159	-8	-0.05	157	-20	-0.13	171	-37	-0.22

b) for negative values of net radiation (Rn, night values)

Date	Lupine (LAI = 3.3)			Grass (LAI = 0.8)			Bare soil		
	Rn	*G*	*G/Rn*	*Rn*	*G*	*G/Rn*	*Rn*	*G*	*G/Rn*
20.09	-5	12	-2.20	-12	14	-1.22	-15	25	-1.74
21.09	-42	21	-0.50	-29	28	-0.96	-30	39	-1.29
22.09	-30	11	-0.38	-24	16	-0.68	-25	31	-1.24
23.09	-39	20	-0.50	-27	26	-0.96	-31	47	-1.54
24.09	-63	25	-0.40	-47	31	-0.66	-46	52	-1.14
25.09	-63	22	-0.35	-48	28	-0.58	-47	48	-1.02
Average	-40	18	-0.46	-31	24	-0.77	-32	40	-1.26

When analyzing average values of G and Rn fluxes for the whole measurement period, it must be remarked that on the surface covered with lupine, during the day, the value of G assumes 5%, and at night 46% of the Rn value (Table 1). For grass, these values assumed 13 and 77%, respectively, and for bare soil 22% for daily values and 126% for night values. The data in Table 1 indicate that the plants on the two surfaces covered with lupine and grass decrease substantially the value of soil heat flux. The difference between the surface covered with lupine and the one covered with grass probably stems from the differences in the density and height of the plants. Grass was much more dense but much lower than lupine. It also caused very big differences in LAI noted on the two surfaces (LAI for lupine was 3.3 and for grass 0.8, Table 1).

On the bare soil surface, substantial differences were observed in net radiation fluxes in comparison with the surface of lupine or grass. The reason for that is probably albedo. Higher values of albedo (more reflected short-wave radiation) were measured on the surfaces covered with plants (lupine 0.22, grass 0.23) than on the bare soil surface (0.19). Consequently, average daily values of the net radiation were as follows: on the surface covered with lupine 159 W m^{-2}, on the surface covered with grass 157 W m^{-2}, and on the soil surface without plant cover 171 W m^{-2}. Next, average daily values of the soil heat flux were as follows: for lupine -8 W m^{-2}, for grass -20 W m^{-2} and for bare soil -37 W m^{-2}, respectively.

In the further stage of the analysis, an attempt was made to calculate statistical dependence of the soil heat flux value as a function of net radiation. In order to conduct this kind of analysis, all the results for all the surfaces examined were presented in the relation $G= f(Rn)$ (Fig. 3). The layout of measurement points clearly indicated linear type of this correlation. After conducting linear regression analysis, three equations were obtained which allow the estimation of the value of the soil heat flux on the basis of the net radiation (Fig. 3). Determination coefficient for all three data sets was high (r^2 in the range from 0.84 to 0.94), indicating the statistical relevance of the given dependencies. The dependencies indicate that y-intercepts (G=0) are different and assume the following values: for lupine surface 103 W m^{-2}, for grass surface 76 W m^{-2} and for bare soil surface 77 W m^{-2}. These points statistically determine the value of net radiation at which soil heat flux changes the flow direction (from that value the flux comes in the direction of the active surface and above that value it comes from the direction of the active surface).

The slope of the straight lines of the determined linear dependences differ from one another and assume the following values: for the lupine surface -0.12, for the grass surface -0.21 and for the bare soil surface -0.35. It indicates that by fluctuating values of the net radiation the biggest changes in the values of the soil heat flux are observed on the surface of the bare soil (irrespective of the sign of the net radiation). To put it differently, the slope of the straight line

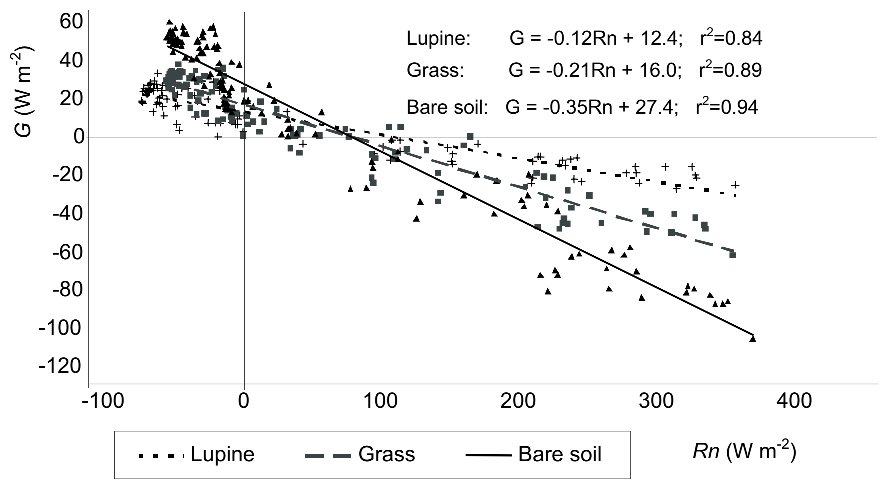

Fig. 3. The dependence of the value of the soil heat flux (G) on the value of the radiation balance (Rn) for three different active surfaces.

of the given equations is dependent on the share of the soil heat flux in the whole heat balance of the active surfaces (Table 1).

The y-intercept in the determined equations also differs substantially and assumes the following values: 12.4 W m^{-2} for lupine, 16 W m^{-2} for the grass and 27.4 W m^{-2} for bare soil. This indicates that at night or at dawn, when the radiation balance drops to zero, soil heat flux directed towards the active surface is observed. The value of the flux, however, varies and for the bare soil surface it is almost twice as big as for the surface covered with lupine.

It seems justified to claim that the differences in the dependencies $G = f(Rn)$ described above, for the three examined surfaces, are the result of different LAI values which characterize each of the examined surfaces (Table 1). Field experience acquired during the research of the heat balance structure of the active surface teaches that soil heat flux measurements are technically difficult and hence mistakes can happen. They can take place particularly during measurements of that energy flux on the active surfaces covered with plants in a heterogeneous way (*eg* row crops). On the other hand, when the active surface has a plant cover which gets more and more dense (since the beginning of the vegetative season to the full development stage of the plant cover), the share of the soil heat flux in the heat balance of the active surface decreases. However, during measurement of the heat balance structure in shorter periods of time (an hour, a day, a decade, a month), the share of the soil heat flux can be substantial and requires particularly accurate measurement, as far as the method is concerned.

CONCLUSIONS

1. Plant cover decreases the density of the soil heat flux in comparison with other surfaces without plants. This regularity occurs both during the day and at night.

2. Not only the existence of the plant cover, but the kind and size of the plants as well, have an influence on the heat balance structure of the active surface, specifically on the G/Rn ratio. Particularly important is the value of leaf area index LAI which characterizes a given surface.

3. The soil heat flux is less important on surfaces covered with plants than on the surface of bare soil, where the share of G flux in the heat balance of the active surface may even reach 35% of the radiation balance.

4. There is a possibility of estimating soil heat flux values on the basis of the measurement of the radiation balance and information about the condition of the plant cover (or its lack) on the surface examined.

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