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Estimating the Soil Thermal Conductivity Using Experimental Soil Heat Flux in a Rice Paddy Area

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Abstract The soil heat flux (*G*) is a key parameter for closing energy balance, and a significant variable to understand the surface processes, principally in meteorological applications. Fourier's Law for heat conduction is a simple methodology to obtain *G*. In this methodology it is necessary to know the soil thermal conductivity (*Ks*). In this study, we use the inversion of Fourier's Law, using experimental values for *G* and soil temperature in two layers to obtain *Ks*. The experimental data was measured over a year in a rice paddy area, located in the Paraíso do Sul, southern Brazil. The soil type is Dystrophic Hydromorphic Plainsoil. The *Ks* were obtained using data of hour 14:00 in two periods: fallow and rice growing season, *Ks* values were 1.44 and 1.31 W m^{-1} K^{-1}, respectively. The values of *Ks* estimated and suggested by literature (for clay soil saturated) were used to estimate *G*, comparing with *G* experimental data. The results showed the new values of *Ks* represent *G* satisfactory. Since there is no specific *Ks* in the literature for rice paddy in this soil type, we recommend the application of *Ks* found in this study.

Keywords Soil thermal conductivity, Soil heat flux, Rice, Fallow

1. Introduction

Estimating and comprehending the soil thermal properties are important activities in meteorological studies, such as the energy balance closure, weather forecast models and agricultural studies, as well as agricultural production forecast models and soil temperature estimations [1, 2]. The soil thermal properties influence the heat and mass transferring processes between the Earth surface and the soil interior. The soil thermal conductivity (*Ks*) is a key parameter to the estimation of the soil heat flux (G) [3]. It depends on other soil parameters, such as texture, humidity and soil porosity. However, these parameters can change with the different soil types in a small spatial scale [4], difficulting its precise determination, and the use in meteorological models, for example [5].

Currently, several models for the estimations of the thermal soil properties and the soil heat flux have been suggested [6-9]. However, few studies have handled the flooded ecosystems, with a water layer strongly affecting the energy balance components, and thus, the energy transfer to soil as soil heat flux [10-12]. The rice paddy is an example of agroecosystem in which the water needs to be abundant. The flooding affects the soil thermal properties, modifying the energy transferring to the soil. During approximately 80% of the rice growing season, the area stays under a 5 - 10 cm water layer.

In this study, the soil thermal conductivity is estimated using the soil temperature and soil heat flux experimentally measured in a rice paddy area, located in a subtropical region in the southern Brazil. The estimation is performed for two distinct periods: rice growing season and fallow. A simplified model for the conductivity using the soil humidity is also suggested.

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2. Materials and Methods

2.1. Site Description

The experimental data used in this study were collected in the period from July 2003 to July 2004. The observations were made in the municipality of Paraíso do Sul (29° 44' 39,6" S; 53° 8' 59,8" W; 108 m), in Rio Grande do Sul State, Southern Brazil. The experimental site is flat and homogeneous area, where irrigated rice has been cultivated by flooding since 1980. The soil is classified as Dystrophic Hydromorphic Plainsoil [13], typical from flooded areas for the rice cultivation in this region. The soil is characterized as: sand 23.7%, clay 14.9% and silt 61.4% (for 10cm depth) [14].

The typical weather in the regions is humid subtropical Cfa [15], with ENOS phenomena influence, affecting directly the precipitation, temperature and radiation.

About 30 days after the seeding (November 25th 2003) the soil was kept flooded with a water layer of 5 – 10 cm depth, until few days before the harvest (April 4th 2004). It was a rice cycle of 131 days. During the rest of the year the soil was not cultivated, remaining covered with a ground vegetation of spontaneous growing, characterizing a fallow period.

2.2. Experimental Measurements

The soil temperature and soil heat flux were experimentally measured using the STP01 sensor and Hukseflux sensor (HFP01SC-L), respectively. The soil heat flux was experimentally measured at 7cm depth and the soil temperature at 5cm and 10cm depth.

2.3. Soil Heat Flux Estimation

The soil heat flux (G) can be estimated using the soil temperature (T) and soil thermal conductivity (Ks) using Fourier's Law:

$$G = -Ks\left(\frac{(T2 - T1)}{(Z2 - Z1)}\right) \quad (1)$$

where T_2 and T_1 are the soil temperature in Z_2 and Z_1 soil depth, respectively, being $Z_2 > Z_1$. In this work we use $Z_1 =$ 5 cm and $Z_2 =$ 10 cm.

The experimental soil heat flux (G_{exp}) was compared with estimated soil heat flux (G) by two methods:

Method (1): using a known Ks from literature for for clay soil in saturated conditions (Ks = 1.58 W m^{-1} K^{-1}) [16].

Method (2): using Ks estimated using the inversion of the eq. (1), with $G = G_{exp}$. To estimate Ks we used the average of experimental soil temperature at 14h for each period analyzed. This hour represents the highest difference between the soil temperatures at 5 and 10 cm.

The analyses were realized in two periods: fallow (July 22nd 2003 - November 25th 2003) and rice paddy (march 04th 2004 – July 22nd 2004).

3. Results and Discussions

Significant changes of soil cover occur between the fallow and the rice paddy period. In the fallow period the soil is covered by harvest cultured residues, or sparse plants, being vulnerable to great daily thermal variations in the 5cm and 10cm deep layers, bringing on differences in the soil temperature up to 5 °C between these layers (Figure 1), principally in the end of spring period (november and december).

These differences decrease during the rice cultivation. Between January and March, period in which the water layer predominate in the crop (soil humidity greater than 0.4 m^3 m^{-3} in Figure 1), the soil temperatures present even smaller differences between the layers. This is due to the fact that the water layer makes the soil become soaked, modifying its conductivity. After the harvest, when the water layer on the crop vanishes, the temperature differences in both layers are not very accentuated as in the fallow before the planting, mainly because this is the winter season in this region.

The average daily cycle for soil temperature in rice paddy and fallow period is presented in Figure 2. The soil temperature variations are similar through the average day in both periods. However, the absolute values are greater in the rice paddy period, principally because the cultivation occurs in the summer.

The soil thermal conductivity Ks = 1.58 W m^{-1} K^{-1} proposed by [16], was used to estimate the soil heat flux using Method (1). Figure 3 shows the relation between the daily average experimental and the estimated G using Method 1 for rice paddy and fallow period. Both periods present good harmony between the experimental and simulated data. For the fallow period, a greater overestimation of the model is noticeable for values greater than 10 W m^{-2}. The RMSE for the fallow period was smaller than in the rice paddy (Table 1), showing the better representation of experimental data in the fallow period.

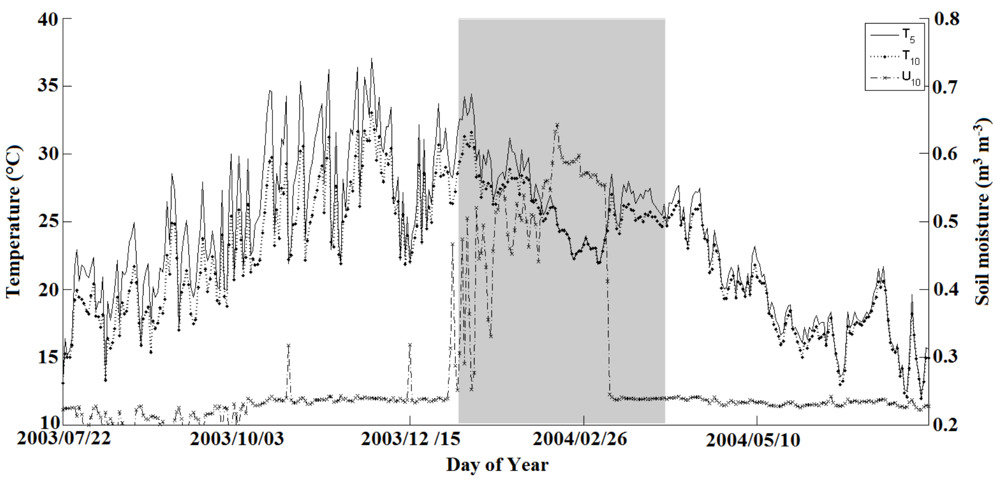

Figure 1. Daily mean of soil temperature in 5 cm and 10 cm depth. The hatched area in the plot represent the rice growing season

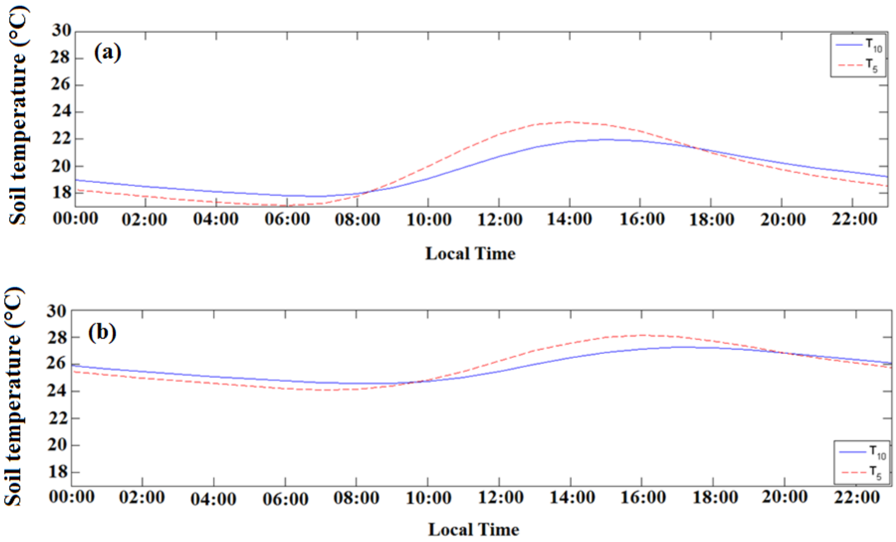

Figure 2. Average daily cycle for soil temperature in 5 cm and 10 cm depth for (a) Fallow and (b) rice paddy period

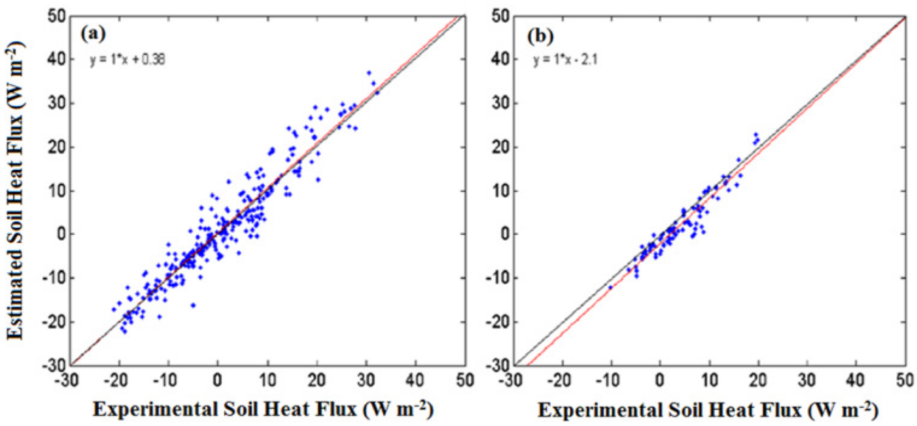

Figure 3. Scatter plot of daily mean of experimental *G* and simulated experimental *G* using Method 1 for: (a) fallow and (b) Rice paddy. Red line represents the linear fit of the data. For reference, the 1:1 line is also shown (solid black line)

The estimated values for *Ks*, using Method 2 were inferior to the values suggested in the literature (Method 1) for both periods (Table 1). Smaller values were obtained in the rice paddy period. Although the soil presents a greater amount of water in the rice paddy period, this was not enough to shift values closer to the water conductivity, which is 0.61W $m^{-1} K^{-1}$.

Figure 4 shows the relation between the daily average experimental *G* and the estimated *G* using *Ks* obtained by Method 2 for the rice paddy and fallow periods. For the fallow and the rice paddy periods, is noticeable that for negative values of experimental *G*, the model underestimates, and for positive values the model overestimates the experimental *G*. The RMSE for the fallow period was smaller than rice paddy period (Table 1), showing the better relation between model and experiment for the fallow period.

The Figure 5 represents the average daily cycle of experimental and estimated soil heat flux for Method 1 and Method 2. There is a delay between the experimental data and estimated data for fallow and rice paddy periods. This behavior was also observed by [17, 18]. These authors estimated the soil heat flux using distinct methods under different climatic conditions. By using the estimated *Ks* (Method 2), the daily cycle soil heat flux is better represented by the model principally in nocturnal period.

There is an increase in soil moisture in the rice paddy period (Figure 1), which significantly affects the soil thermal conductivity (values in Table 1).

Table 1. Statistical Analysis Method 1 and 2 in relation to the experimental data

	Method 1			Method 2		
	Ks ($Wm^{-1}K^{-1}$)	RMSE (Wm^{-2})	R^2	*Ks* ($Wm^{-1}K^{-1}$)	RMSE (Wm^{-2})	R^2
Fallow	1.58	3.19	0.92	1.44	1.72	0.96
Rice	1.58	3.51	0.91	1.31	2.10	0.91

The Figure 6 presents the relation between the thermal conductivity estimated using the Method 2 and the soil moisture to 10 cm layer, both to 14:00h.

The soil humidity variation in the fallow period was smaller than 0.01 $m^3 m^{-3}$ (values around 0.2 $m^3 m^{-3}$), which can make the analysis of the relation between the soil thermal conductivity and soil humidity more difficult in this period. However, we can estimate a negative linear relation between soil thermal conductivity and soil moisture. The equation that describes the soil thermal conductivity variation with the soil moisture was $Ks = -0.64\, U_{10} + 1.7$.

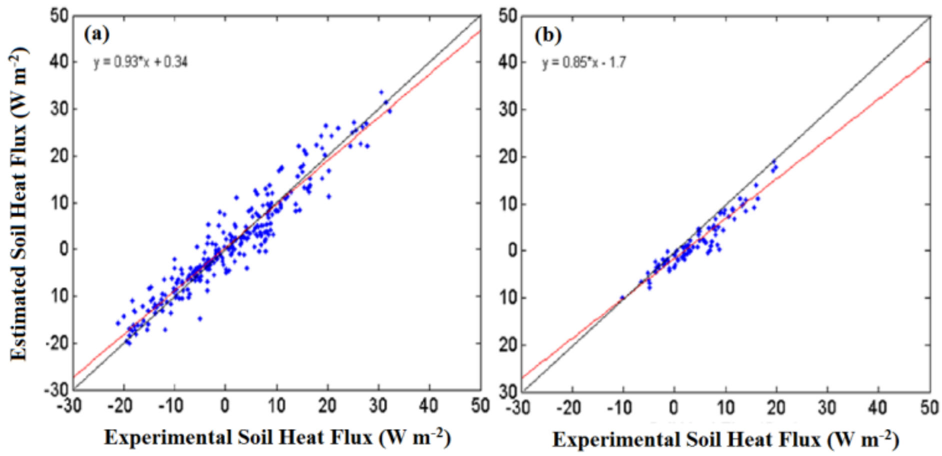

Figure 4. Scatter plot of the daily mean of soil heat fluxes (experimental (G_{exp}) and estimated (G_{mod}) using Method 2) computed for: (a) non Flooded and (b) Flooded with Rice. Dashed black line represents the linear fit of the data. For reference, the 1:1 line is also shown (solid black line)

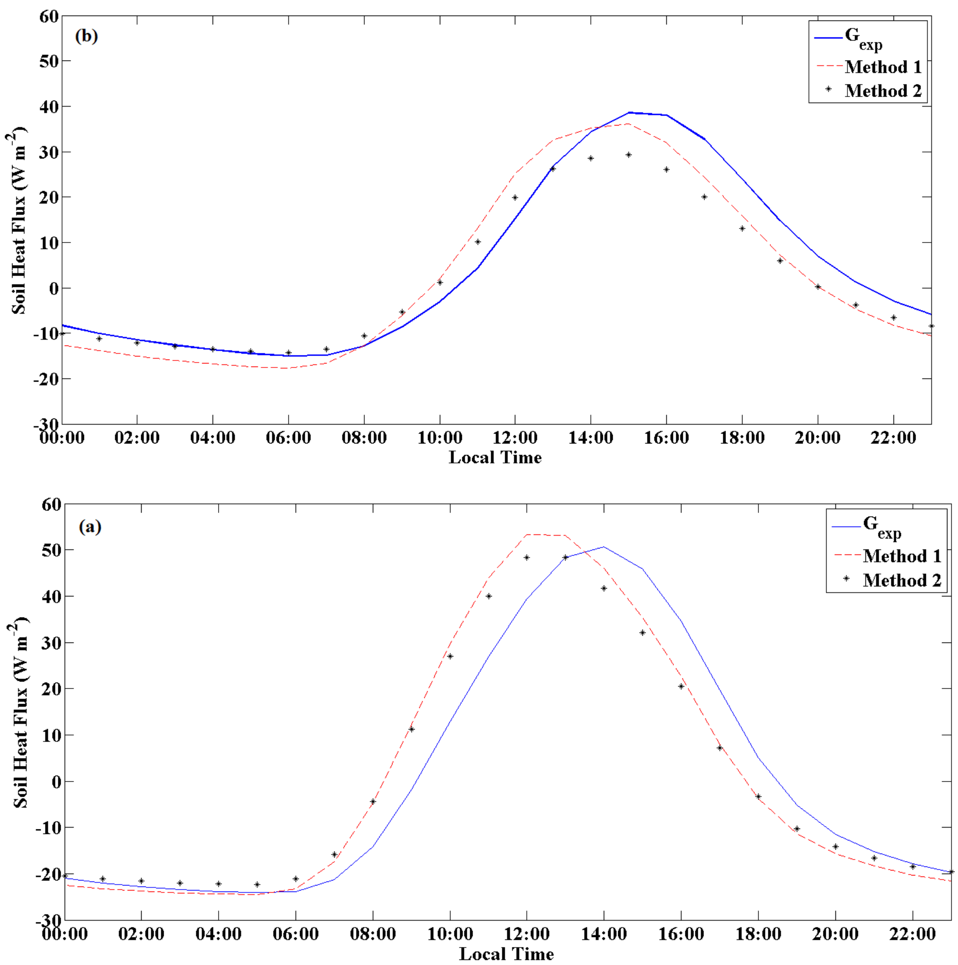

Figure 5. Average daily cycle for experimental *G* (G_{exp}) and estimated *G* using *Ks* from Method 1 e Method 2 for (a) fallow and (b) rice paddy periods

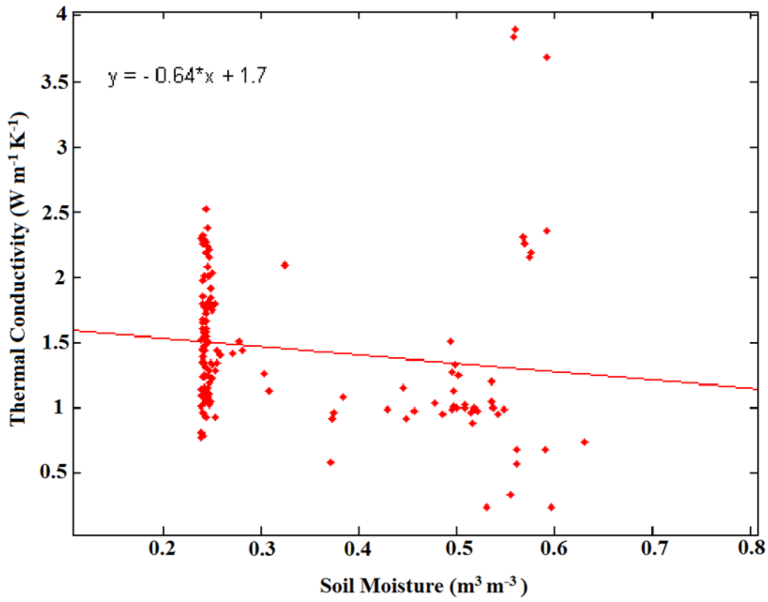

Figure 6. Soil thermal conductivity versus soil moisture for daily hour of 14:00

4. Conclusions

This study presented an estimation for the soil thermal conductivity value, *Ks*, for a rice paddy area located in Southern Brazil. The estimated value for *Ks* for the fallow period was 1.44 W m^{-1} K^{-1} and for the rice paddy was 1.31 W m^{-1} K^{-1}. The soil heat flux estimated using this *Ks* values satisfactorily represent the experimental soil heat flux values. Since there is no specific *Ks* in the literature for rice paddy in this soil type, we recommend the application of *Ks* found in this study.

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