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Effects of a straw layer over bare soil on surface and soil variables in Southern Brazil

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ABSTRACT

Changes in land use can have significant impacts on physical processes that act between the surface and atmosphere. Crop residues deposited on the soil surface can affect soil response to environmental variables. In this work, we analyze the effects of straw layers (SL) bare soil (BS) soil on surface and soil variables in a subtropical climate region in southern Brazil. We analyze measured data of surface temperatures, soil temperatures, soil volumetric water content and soil heat flux from May to November 2015, , with straw layer replaced three time. The presence of a straw layer increase soil volumetric water content *(VWC)* by 5% to 15%, decrease the surface and soil temperatures and the soil heat flux, besides present a lower thermal amplitude than bare soil. The soil and surface temperature are more sensitive to *VWC* variations in bare soil. These results can be applied in land surface and agricultural models to better represent the thermal soil behavior.

Introduction

Changes in land use can have significant impacts on physical processes that act between the surface and atmosphere, such as exchanges of water, energy and carbon (Bagley et al., 2015; Lagos et al., 2009; Law et al., 2002). Some changes in agricultural practices are being considered as possible ways of intervening in climate changes. One example is the no-tillage system, which can increase soil carbon storage (Schlesinger & Jasechko, 2014). However, crop residues deposited on the soil surface can affect soil response to environmental variables (Ramakrishna et al., 2006; Sarkar et al., 2007; Sarkar & Singh, 2007). Soil temperature, soil moisture, surface albedo and surface emissivity are immediately affected by the deposition of agricultural residues (Gascoin et al., 2009; Kumar & Dey

2014; Sándor & Fodor, 2012; Usowicz et al., 2016; Wang et al., 2005). The soil temperature has a significant impact on the enzyme activity of soil, further affecting the emergence rate (Li et al. 2013). Differences in the albedo and emissivity of the soil surface lead to changes in the radiation balance, i.e., differences in energy available to drive processes acting between components of the soil-surface-atmosphere system (Novak et al., 2000). Clearly, these processes are interconnected. Therefore, variations in soil water content also affect the mechanisms of energy exchange between the surface and atmosphere.

Studies have been conducted to quantify the influences of different land cover types on soil variables. In general, soil temperatures in uncovered soil are higher than those in covered soil (Wu et al., 2014)) and a negative correlation between surface temperature (T_{surf}) and soil volumetric water content (VWC) are observed (Jin & Mullens, 2014). However, these relationships are not generally represented by different climate and soil types. Therefore, the objective of this work was to study the influences of agricultural residues on soil and surface variables, specifically, surface temperatures, soil temperatures, soil moisture and soil heat flux in a subtropical climate in southern Brazil.

Materials and Methods

Experimental Site and Instrumentation

The experiment was conducted in Santa Maria, Rio Grande do Sul, Brazil (29°43'13"S, 53°42'23"W). The climate in this region is classified as Cfa (Köppen classification). The soil is a Rhodic Paleudalf with the following composition (0 to -0.21 m): 67% sand, 21% silt, and 12% clay. The soil bulk density (ρs) is 1670 kg m^{-3}. This type of soil is dominant in southern Brazil, in the Pampas Biome (Streck, 2002).

Two plots, each approximately 6 m^2 in area, were evaluated to determine the soil variables and surface radiation components. One of the plots was bare soil (BS), and chemical control was applied to eliminate spontaneous vegetation. A layer of oat straw (*Avena sativa* Schreb) was deposited on the other plot (SL) at a rate of 6 tons per hectare. This rate of coverage is the average amount of agricultural residue that results from growing of commercial crops southern Brazil. The study was conducted from 9 May to 30 November 2015. To maintain the straw's characteristics (color, thickness, and density) during this period, the straw layer was replaced 3 times: on 12 June, 12 August, and 22 October.

The instruments listed in Table 1 were installed in both plots, and these sensors collected data every minute. Unfortunately, problems occurred with the instruments that measured surface temperatures and ground heat flux between 14 and 29 September and 7 and 20 October. Therefore, these variables were not measured during the affected periods. A set of sensors was also installed near the plots to measure meteorological variables. Measurements of incident shortwave radiation, K↓ (Wm^{-2}), were obtained 2 km from the experimental area at a height of 3 m using an automatic weather station (MAWS301) operated by the National Institute of Meteorology (INMET).

Soil Energy

Soil heat flux, Fg, was estimated as the sum of the ground heat flux, G, and the soil and straw heat storage (ΔG). ΔG between the surface and a depth of 0.05 m was calculated using the equation (Heitman et al., 2010; Meyers, 2004)

$$\Delta G = \frac{C_T \Delta z \Delta T}{\Delta t} \tag{1}$$

where ΔT (°C) is the difference between soil temperatures

Table 1. Instrumentation (measured variable, sensor model and vertical position) placed in plots with bare soil (BS) and with a straw layer (SL) and installed in the automatic weather station at the experimental site.

Variable (symbol) [unit]	Sensor model and manufacturer	Position (m)
Instrumentation in (SL) and (BS) plots.		
Surface temperature (T^{surf}) [°C]	SI-111; Campbell Scientific	0.15
Ground heat flux (G) [Wm^{-2}]	HFP01SC; Hukseflux Thermal Sensors	-0.10
Soil temperature (Tsoil) [°C]	Tipo T; Thermocouple	-0.05
Soil volumetric water content (VWC) [m^3m^{-3}]	CS616; Campbell Scientific	-0.05
Automatic Weather Station		
Precipitation (Prec) [mm]	TR-525 M	2
Air temperature (Tair) [°C]	CS215; Campbell Scientific	2
Relative humidity (RH) [%]	CS215; Campbell Scientific	2
Incoming shortwave radiation* (K↓) [Wm^{-2}]	CNR4; Kipp & Zonen	3

* Measurements performed 2 km from the experimental area at an automatic meteorological station maintained by the Brazilian National Meteorological Institute (INMET).

measured at a depth of 0.05 m at two times (in this case, Δt was 1 hour), Δz (m) is the thickness of the layer, and C_T $Jm^{-3}°C^{-1}$ is the soil volumetric heat capacity. CT was estimated using the equation

$$C_T = \rho_s C_s + VWC\,\rho_{H_2O} C_{H_2O} \qquad (2)$$

where ρ_s is the dry soil density, which was determined experimentally at the study site (ρs=1670 kg m^{-3}; C_s is the gravimetric specific heat of the dry mineral soil, and C_s=840 Jkg^{-1}K^{-1}, as obtained from (Hanks, 1992); ρ_{H2O} is the density of water ρ_{H2O}=1000 kg m^{-3}; C_{H2O} is the gravimetric specific heat of water (C_{H2O}=4190 Jkg^{-1}K^{-1}; and VWC is the experimentally determined volumetric water content of the soil (Table 1)).

The first term on the right side of eq. (2) represents the thermal capacity of a dry soil, while the second term represents the influence of soil moisture on the thermal conductivity of the soil C_T. Data needed to calculate the thermal capacity of the straw and heat storage in the straw layer were not available. Therefore, eq. (1) was used to estimate ΔG in the soil layer from the surface to a depth of 0.05 m, using the same physical soil parameter for both SL and BS. The difference between C_T influence of the straw layer on energy storage in the soil in SL and BS was due to VWC measured, according to table 1, in each plot.

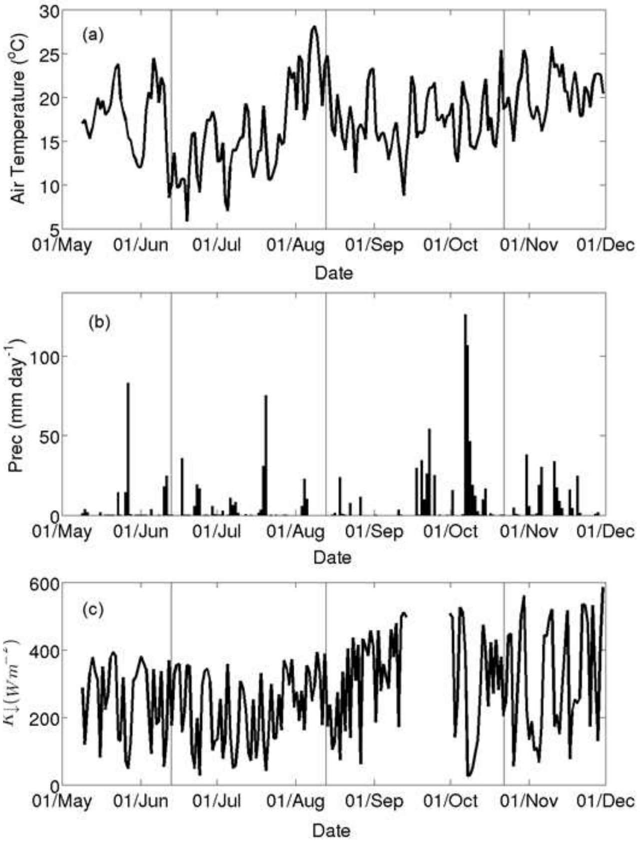
Results and Discussion

Meteorological Conditions

The analyzed data correspond to the autumn, winter, and spring seasons. The average daily air temperature (Tair) during the period covered by the experiment was 17.5 °C (Figure 1a), which is greater than the climatological average for the same period (16 °C). The minimum daily air temperature was 0.4 °C (recorded on 5 July), and the maximum value was 33.8 °C (recorded on 30 August.). As expected, the daily average temperatures increased near the end of the analyzed period, due to the approach of summer, with the increase of the incoming shortwave radiation (Figure 1c). However, after the second straw replacement (12 August), the temperature increased by approximately 10 °C for two days and remained high for almost a week. This increase in temperature was caused by the 'north wind' phenomenon, which is typical in the region at the end of winter. This phenomenon is characterized by intense warm north winds and low relative humidity (Arbage et al., 2008).

In 2015, the El Niño phenomenon affected southern Brazil. The main effect of this phenomenon is an increase in precipitation (Prec). During the study period, the total precipitation was 1234 mm; the climatological average for the same period is approximately 926 mm. The precipitation was well distributed throughout the analyzed period, as shown in Figure (1b). In the first straw cycle, the accumulated precipitation was 169 mm, i.e., average 4.8 mmday^{-1} in the second straw cicle, the accumulated precipitation was 265 mm, i.e., 4.3 mmday^{-1} the third straw cycle, between 12 August and 22 October, had more intense precipitation, accumulating 586 mm, leading to an average of 8.3 mmday^{-1} The fourth cycle had 214 mm of accumulated precipitation, with an average of 5.4 mmday^{-1}. These events had a strong influence on the distribution of incident solar radiation, because the sky remains cover by clouds most of the day; however, the incident solar radiation presents a well-defined seasonality (Figure 1c).

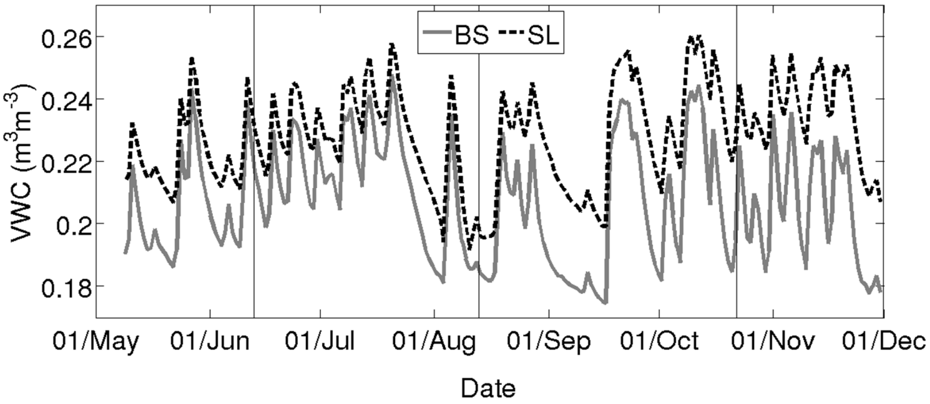
Figure 1 - Meteorological conditions: (a) air temperature; (b) recipitation (Prec) and (c) incoming shortwave radiation (K↓).



Soil Volumetric Water Content

The soil VWC, at a depth of 0.05 m was higher within the straw-covered (SL) plot throughout the time period of the experiment (Figure 2). In the BS plot, VWC ranged from 0.17 to 0.24 m^3 m^{-3}, whereas in the SL plot, these values ranged from 0.19 to 0.25 m^3 m^{-3}. After precipitation events, VWC decreased faster in the BS plot. Because the two plots are close to each another, their soil properties are similar. Therefore, the differences in VWC between the two plots can be attributed to the effects of the straw layer, which hinders water loss by evaporation. Dalmago

Figure 2. Volumetric water content (VWC) at a depth of 0.05 m in the bare soil (BS) plot and the plot with a straw layer (SL).



et al. (2010) indicate that, on non-vegetated surfaces, evaporation of straw-covered soil is lower in the first days after precipitation events, and also they concluded that this trend is reversed 2 to 5 days after precipitation.

Moreira et al. (2015) evaluated the difference in soil variables in two plots that were near each another and had been cultivated for over 20 years. One of these plots had been cultivated using the no-till system (which leaves a layer of agricultural residues), whereas the other had been cultivated using the conventional system. The differing soil management practices, which had been in place for so many years, caused changes in soil properties. These alterations caused differences in VWC between the plots. However, based on these results, the authors were unable to assess what proportion of the differences in soil water content was due to the straw layer. In this study, we were able to quantify this difference. On days with precipitation, the difference in VWC between BS and SL was less than 0.01 m^3m^{-3}. However, during drier periods, the difference increased to more than 0.03 m^3m^{-3}, as was observed at the beginning of September (Figure 2). Therefore, the presence of a straw layer can lead to an increase of 5% to 15% in VWC. These results agree, including quantitatively, with those presented by Zhao et al., 2014, which indicates an increase between 2.1 and 10.4% in the 0-20 cm of soil layer.

Surface and Soil Temperatures

The daily average soil temperatures (T_{soil}) measured at a depth of 0.05 m during the study period ranged from 10.2 °C to 29.5 °C within the BS plot and from 12.2 °C to 24.3 °C within the SL plot (Figure 3(a)). During the autumn and winter seasons (from May to September), daily average soil temperatures were very similar in the two plots. In spring (from September to December), the soil temperatures in the BS plot were higher. During the day, T_{soil} in the BS plot reached peak values that were up to 6 °C higher than the corresponding values in the SL plot. At night, this trend was reversed; soil temperatures measured in the SL plot were up to 4 °C higher than those measured in the BS plot (data not shown). This behavior may be due to the presence of the straw layer on the soil, which decreases energy input to the soil during the day and reduces energy loss from the surface at night (Furlani et al. 2008) and discussed in the next section. When precipitation occurs, these differences are minimized.

The daily average surface temperatures (T_{surf}) in the BS plot were generally higher than those in the SL plot (2 °C on average; Figure 3(b)). Assuming that the bare soil and straw layer have the same emissivity, ε_s, this difference in T_{surf} represents a difference of approximately 10 Wm^{-2} in emitted longwave radiation (L↑) between the BS and SL plots (determined using the Stefan-Boltzmann law, $L\uparrow = \varepsilon_S \sigma T^4$, where the Stefan-Boltzmann constant σ=5.6697 x Wm^{-2} k^{-4}). However, the emissivity must be different. In general, straw has a smaller emissivity than bare soil (Olioso et al., 2007), increasing the difference in longwave radiation emitted by the two surface types.

The relationship between the daily T_{soil} and T_{surf} and the daily VWC are shown in Figure 4. The figure shows that both temperatures decrease with soil moisture in both plots. T_{soil} and T_{surf} in the BS plot present a greater negative slope (regression coeficient) than SL plot". In all cases, the R-squared coefficient (r^2) was less than 0.2 due to the high variation in temperature for the same VWC. Similar relations have also been showed by (Lakshmi et al., 2003).

Soil Heat Flux

Soil thermal capacity values for the SL and BS plots were estimated using eq. (2). Because the VWC values were higher in the SL plot, C_T was also larger in this plot. The mean values during the study period were C_T=2.35 x 10^6 $Jm^{-3}k^{-1}$ and C_T=2.26 x 10^6 $Jm^{-3}K^{-1}$ for the SL and BS plots, respectively. Therefore, the soil thermal capacity in the SL plot was 4% greater than that in the BS plot. These values and methodology are consistent with those reported in studies of sandy soils, which vary from 1.28 × 10^6 $Jm^{-3}k^{-1}$ to 2.96 × 10^6 $Jm^{-3}k^{-1}$ (Arya, 2001; Xie et al., 2019).

The soil energy storage (ΔG) was greater in the BS plot (Figure 5a). Although the soil C_T was larger in the BS plot, the lower temporal variations in soil temperatures (ΔT)

Figure 3. (a) Daily average soil temperature at a depth of 0.05 m and surface temperature in the BS and SL plots; (b) differences between surface Surface temp and soil temp temperatures in the BS and SL plots.

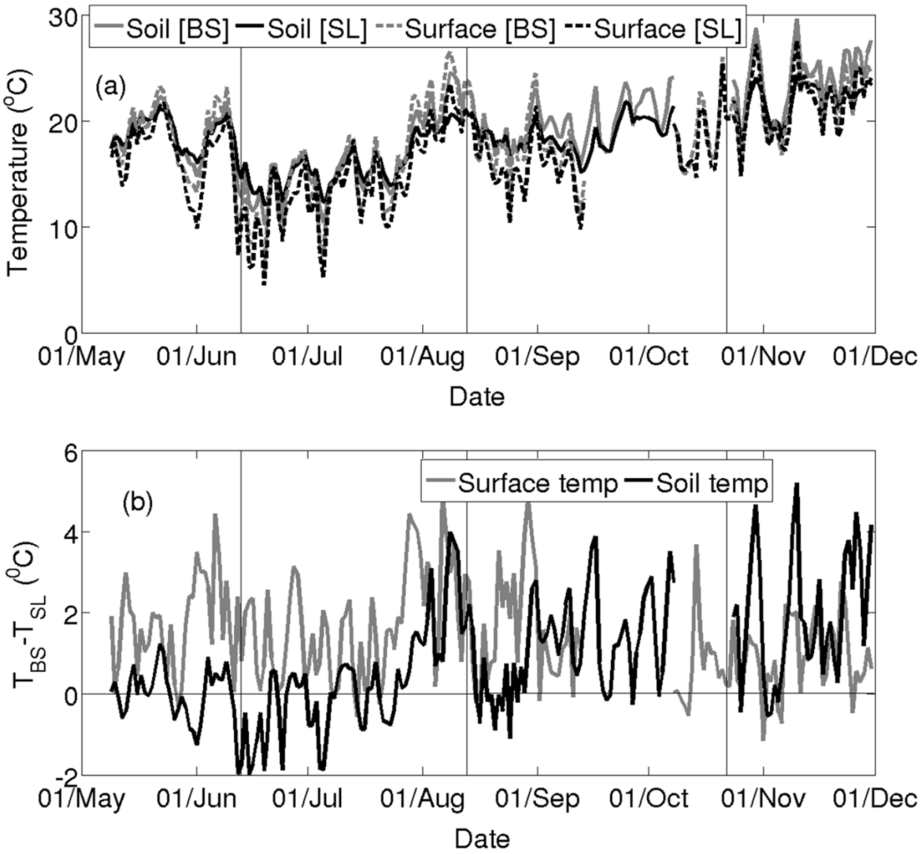
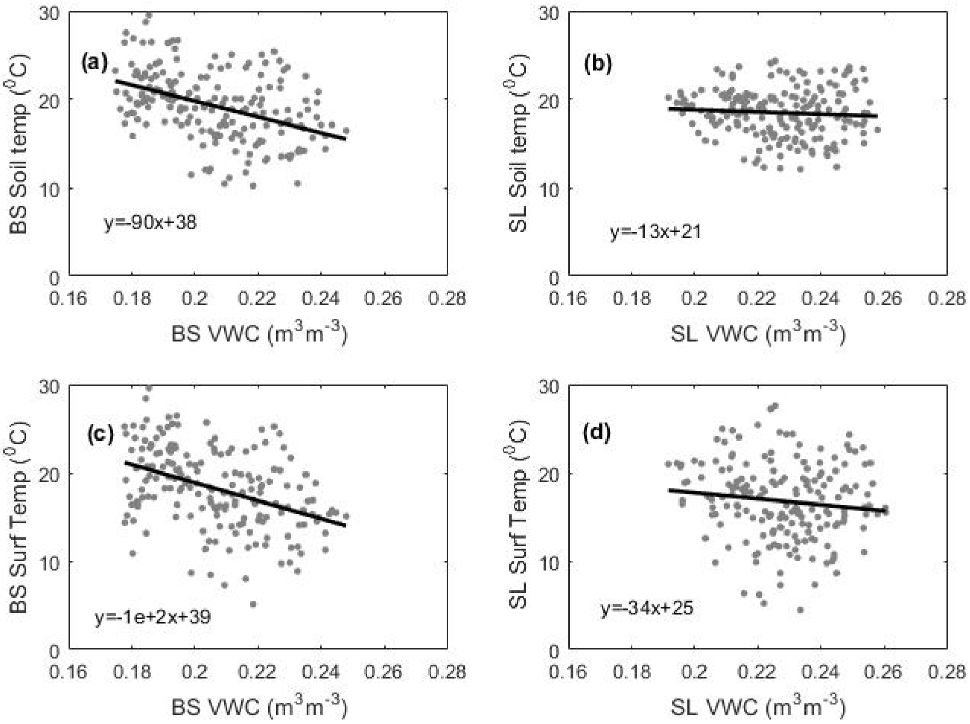


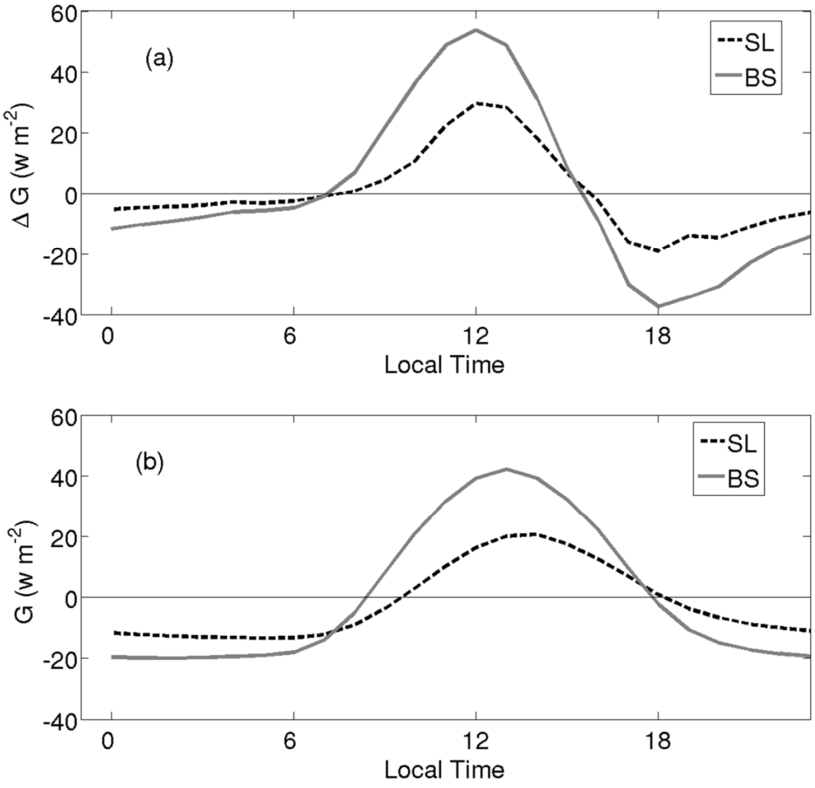
Figure 4. Soil temperature versus soil volumetric water content (VWC) for (a) BS and (b) SL and surface temperature versus VWC for (c) BS and (d) SL.



in the BS plot at a depth of 0.05 m dominate the energy storage term, causing the greater energy storage in BS plot; the difference in ΔG between BS and SL was approximately 14 Wm^{-2} around midday. The BS and SL plots yielded daily average values of ΔG close to zero (0.07 Wm^{-2} and 0.03 Wm^{-2} for the BS and SL plots, respectively).

The daily mean value of G was -1.97 Wm^{-2} and 0.28 Wm^{-2} for the SL and BS plots, respectively. Midday local time, the difference between the G in BS and SL plots was approximately 20 Wm^{-2}. The amplitude of diurnal variations in G were greater in BS than (up to 22 Wm^{-2}) in the SL plot (Figure 5b), indicating lower energy transport through the soil layer within the SL plot. There is a discrepancy between the G peaks of around one hour. It

Figure 5. (a) Heat storage and (b) ground heat flux (G) at a depth of 10 cm in the SL and BS plots.



can be explained by a delay in energy input in the soil due to the straw layer being a physical barrier of the energy transport.

The soil heat flux (Fg = G + ΔG) is the energy transferred through the soil between the surface until the G measurements. The behavior of G is similar to Fg. Overall, Fg was greater in bare soil than in SL. The daily mean value of Fg was -1.90 Wm^{-2} and 0.31 Wm^{-2} for the SL and BS plots, respectively. The negative value indicates that the subsoil warms the surface layers, while the positive value indicates the surface warms the subsoil. Therefore, the solar energy arriving in BS is easily transferred to subsoil.

Conclusions

The effects of a straw layer over bare soil are evaluated in terms of soil and surface variables measured from May to November 2015 in southern Brazil. The soil with the straw layer is wetter, colder and present a lower thermal amplitude than bare soil. The surface temperature and the soil heat flux were greater in bare soil.

Based on the experimental data, equations are obtained that relate soil temperature and surface temperature to VWC. The soil and surface temperature are more sensitive to VWC variations in bare soil. Due to the short observation period in this study, the equations obtained might be site-specific and should be tested before extrapolated to locations with completely different soil and climatic conditions.

The storage of energy and water in the straw layer was not evaluated. Future studies should include these measurements to better describe the physical processes that occur within the straw layer. The results presented in this study can be applied in land surface and agricultural models.

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Authors Contributions

Conceptualization: Webler, G.; Roberti, D. R.; Diaz, M. B.; Zwirtes, A. L.; Gubiani, P. I.; Teichrieb, C. A. Data acquisition: Webler, G.; Diaz, M. B.; Zwirtes, A. L.; Teichrieb, C. A. Data analysis: Webler, G.; Roberti, D. R.; Diaz, M. B.; Zwirtes, A. L.; Buligon, L.; Gubiani, P. I.; Reinert, D. J.; Teichrieb, C. A. Design of Methodology: Webler, G.; Roberti, D. R.; Diaz, M. B.; Zwirtes, A. L.; Gubiani, P. I.; Reinert, D. J.; Teichrieb, C. A.

Writing and editing: Webler, G.; Roberti, D. R.; Diaz, M. B.; Zwirtes, A. L.; Buligon, L.; Gubiani, P. I.;

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Efeitos de uma camada de palha sobre solo nu nas variáveis da superfície e do solo no Sul do Brasil

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RESUMO

Mudanças no uso do solo podem causar impactos significativos nos processos físicos que governam as trocas de energia e massa entre a superfície e a atmosfera. Os resíduos das culturas depositados sobre a superfície do solo podem afetar a resposta do solo às variáveis ambientais. Neste trabalho, foram analisados os efeitos das camadas de palha sobre o solo nu sobre variáveis de superfície e solo em uma região de clima subtropical no sul do Brasil. Analisaram-se dados observados de temperatura da superfície, temperatura do solo, conteúdo volumétrico da água no solo e fluxo de calor no solo entre maio e novembro de 2015, em parcelas de solo nu e solo coberto por palha. A presença de uma camada de palha aumenta o teor volumétrico da água no solo (VWC) de 5% a 15%, diminui a temperatura de superfície e do solo e o fluxo de calor do solo, além de levar a uma menor amplitude térmica em relação ao solo nu. A temperatura do solo e da superfície é mais sensível às variações do VWC no solo descoberto. Esses resultados podem ser aplicados em modelos agrícolas e de interação superfície atmosfera para melhor representar o comportamento térmico do solo e suas consequências.

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