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Annual and daily pattern of soil temperature in an integrated crop-livestock system in the south of Brazil

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ABSTRACT

Considering the importance of soil temperature and the high spatial and temporal variability associated with soil types, types of vegetation cover, and applied management, this study aimed to determine the daily and annual patterns of soil temperature in a conservation crop-livestock integration system conducted under subtropical climate conditions in the southern Brazil. The experiment was conducted in a crop-livestock integration system cultivated with soybean in the summer and ryegrass in the winter and grazed by sheep. The measured data were NDVI and soil temperature at four depths, with characterization of the annual and daily cycle of the soil profile and daily thermal amplitude, used to calculate the thermal diffusivity. The results showed that the differences in energy availability throughout the seasons, associated with the humid subtropical climate, determines the annual pattern of soil temperature. In summer, the soil profile temperature and daily thermal amplitude are higher than in winter, especially under partial soil cover conditions. Soil thermal diffusivity is low, especially under lower soil moisture conditions, which determines a delay in the time of occurrence of minimum and maximum temperatures in the daily cycle.

Introduction

Daily variations in soil temperature represent one of the most important elements controlling the exchange of moisture and energy between the soil and the atmosphere. In the context of agricultural production, soil temperature has a direct influence on the germination of seed and the growth rate of roots, bulbs, and tubers. Indirectly, this element acts in defining the rate of chemical reactions and the activity of microorganisms responsible for the mineralization of organic matter, as well as fungi, insects, and other biological forms in the soil (Reichardt & Timm, 2004). Therefore, it is a relevant element to be considered in the delimitation of production regions, in the definition of agrometeorological zoning of climate risk and other actions related to the planning of agricultural activity associated with crop requirements (Monteiro, 2009). In this sense, studies that help understand daily and seasonal patterns of soil temperature in different production environments are important.

Heat conduction in the soil occurs through the transfer of thermal energy from one particle to another. Soil temperature is the result of meteorological conditions (solar radiation, air temperature, wind speed, rainfall, etc.) and the intrinsic thermal properties of the soil, especially the capacity to store heat (C – volumetric thermal capacity) and its ability to transfer heat (K – thermal conductivity) (Schoffel & Mendez, 2005), resulting in a meteorological element that is quite variable in time and space.

An important physical property of soils is the speed of advance of the heating front in the soil profile. This property, called soil thermal diffusivity (α), is obtained by the ratio between the physical properties K and C. The amplitude, phase, logarithm, and arctangent methods are available to estimate this parameter (Reichardt & Timm, 2004). The values obtained for the soil thermal diffusivity are low (in the order of 1 to 10^{-6} cm^{-2} s^{-1}) and present variations mainly related to with the composition of soil horizons, soil moisture, and the type of vegetation on the soil (Danelichen & Biudes, 2011; Carvalho et al., 2013).

The typical daily temperature variation approximately follows a periodic movement in which the thermal amplitude is exponentially damped with depth and the values at each depth oscillate sinusoidally with time around a mean value (Shoffel & Mendez, 2005; Oliveira et al., 2019). These patterns can be reconstructed, and future changes can be predicted through knowledge of the dynamics of soil thermal properties (Zeynodn et al., 2019).

Importantly, management practices, including conservation systems that use plant residues on the surface, can alter soil physical properties and can also modify soil microtopography, which can modify soil temperature (Shen et al., 2018). In integration production systems, such as crop-livestock integration, there is some concern about the potential reductionin the amount of biomass on the surface, that can occur due to grazing and animal trampling, which can affect soil moisture and temperature (Veiga et al., 2010).

Considering the importance of soil temperature and the high spatial and temporal variability associated with soil types, types of vegetation cover, and applied management, this study aimed to determine the daily and seasonal patterns of soil temperature, as well as dimension the thermal diffusivity parameter, in a conservationist crop-livestock integration system conducted under subtropical climate conditions in southern Brazil.

Material and methods

The experiment was conducted at the UFRGS Agricultural Experimental Station (Figure 1), located in Eldorado do Sul, a region of the Central Depression of the State, characterized by the occurrence of a rainy subtropical climate, according to Köppen (Alvares et al., 2013). The soil in the experimental area is a typical dystrophic red argisol, with a B horizon texture.

The management used in the experimental area has been the crop-livestock integration system since 2017, with the cultivation of soybean in the summer and ryegrass in the winter, grazed by sheep. The soybean variety BRS 6105RR was sown on December 1, 2021, with a population of 292 thousand plants ha^{-1}. The ryegrass BRS Ponteio was sown by broadcast after the soybean harvest (April 27, 2022). Sheep entered the area from June 21, 2022, and stayed until November 4, 2022.

The study period covered a complete annual cycle, consisting of a crop period followed by a pasture period. Analyses were conducted using the complete data set and separately using data from the crop and pasture periods. A breakdown was also made within each of the periods, separating the data into partial and total soil cover. The criterion for defining the periods was based on the temporal profile of the NDVI (Normalized Difference Vegetation Index). Measurements were taken weekly during the crop period and monthly during the casture period, using a Trimble Greenseeker Handheld HCS-100. Total canopy cover consisted of the period when NDVI was high and stable over time.

Decagon 5TM and GS3 sensors were used to measure soil temperature and moisture and were connected to a Campbell CR1000 datalogger for data collection and storage every 10 minutes (Figure 1). Only temperature data referring to the hourly and daily mean of depths of 5 and 10 cm (GS3 sensors) and 20 and 40 cm (5TM) were analyzed in this study.

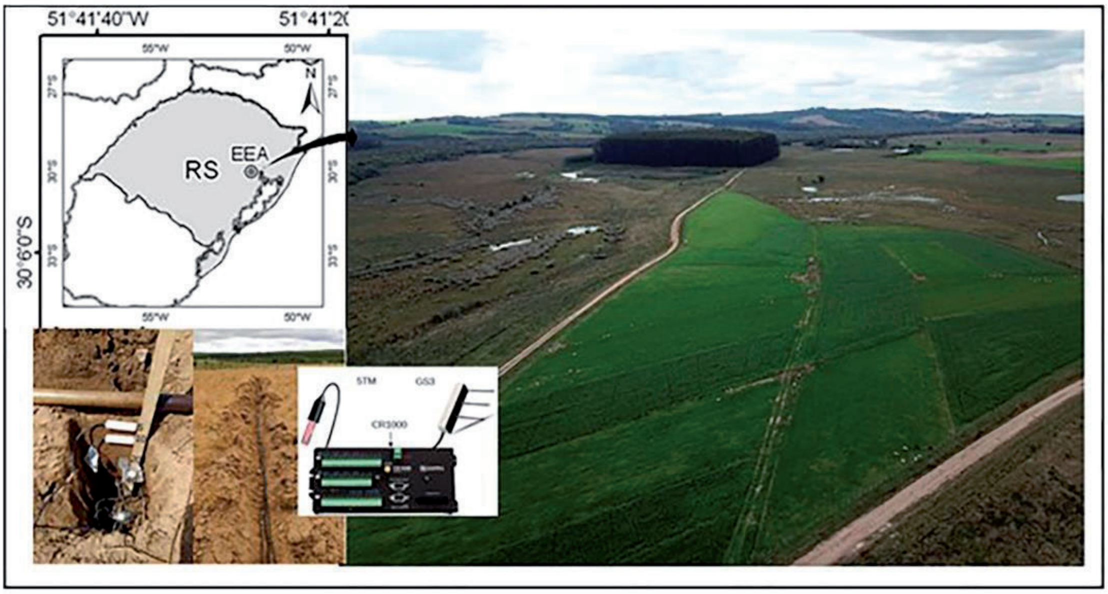
The annual cycle of soil temperature was characterized, and descriptive statistics (maximum, minimum, and mean values, thermal amplitude, standard deviation, and coefficient of variation) were calculated for the four depths in the crop and pasture periods under partial and total soil cover conditions. Hourly data were used to determine the mean daily course of soil temperature, the time of occurrence of daily maximum and minimum temperatures, and the frequency of occurrence of maximum and minimum daily temperatures throughout the period. The separation of the data into the crop and pasture periods with total and partial soil cover allowed the plotting of tautochrone curves for the maximum and minimum soil temperature.

The daily amplitude data were used to calculate the soil thermal diffusivity using the equation (1) (Reichardt & Timm, 2004).

$$\alpha= (\omega/2)[(z2-z1)/\ln(A2/A1)] \quad (1)$$

where α is the thermal diffusivity (m^2 s^{-1}), Ω is the angular

Figure 1. Location and aerial view of the experimental area, with details of the temperature and moisture sensors and their installation. UFRGS Experimental Station (EEA) in Eldorado do Sul/RS, Brazil.



frequency ($7.27x10^{-5}$ rads^{-1}), z1 and z2 are the depth of layers 1 and 2 (cm), respectively, and A1 and A2 are the daily thermal amplitudes in layers 1 and 2 (°C), respectively.

The thermal diffusivity values were calculated for the crop and pasture periods separately for to the layers 5–10 cm, 5–20 cm, and 5–40 cm and were represented graphically in a boxplot.

Results and discussion

Soil temperature showed important variation over the data collection period, with the season of the year determining the thermal pattern in the soil. The highest temperatures were observed in December 2021 and January 2022 at all soil depths, which were higher than those observed in June and July 2022 (Figure 2B).

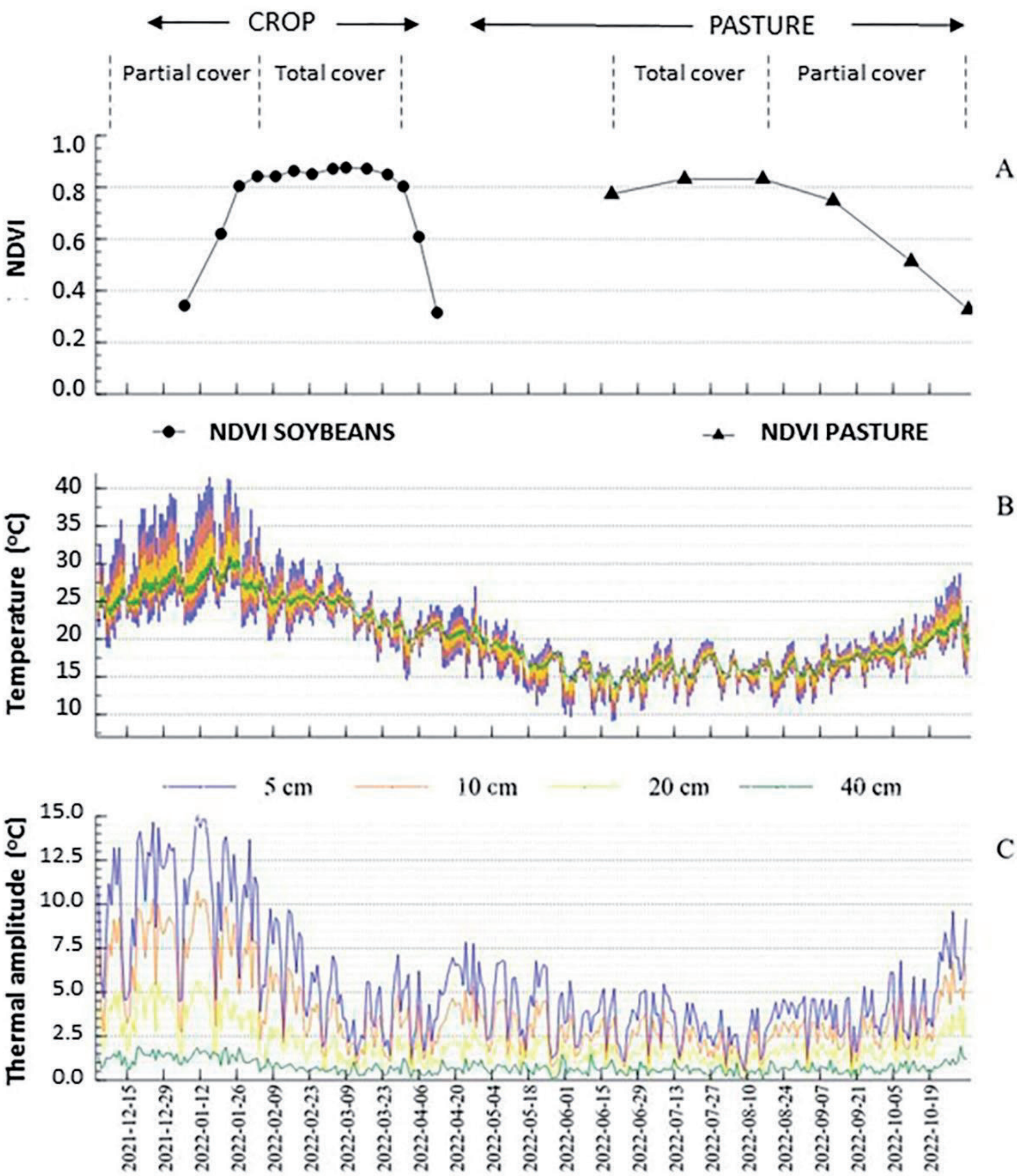
Solar declination in the summer is higher under the southern hemisphere resulting in a higher energy contribution. Solar radiation was not measured during the experimental period (sensor failure), but the climatological normal (Bergamaschi et al., 2003) indicated this trend, with values ranging from 21.6 to 8.7 MJ m^{-2} day^{-1} in January and July, respectively. The dataset obtained during this period showed an inverse and significant relationship between solar declination and soil temperature, with a correlation coefficient of −0.85. The daily thermal amplitude also showed an association with the season (Figure 2C), with the largest thermal amplitudes in the summer period at all depths, much higher than in the winter.

However, in addition to the energy supply, some other important factors that determine the soil thermal pattern are collected in the seasonal analysis, such as variations in soil moisture and variations in the type of vegetation cover on the soil.

Soil moisture and temperature are known to be related to each other (Oliveira et al., 2019; Vieira et al., 2021), as the presence of water in the soil affects its thermal properties, both K and C, as well as the radiation balance partition between the evapotranspiration and soil and air heating components (Reichardt & Timm, 2004). Soil moisture duringan annual cycle tends to be lower in the summer given the "subtropical rainy" climate condition predominant in Rio Grande do Sul (Alvares et al., 2013). With average monthly precipitation exceeding 110 mm throughout the year (Bergamaschi et al., 2003), variations in the atmospheric evaporative demand (higher in the summer and lower in the winter) help to explain soil moisture variations (lower in the summer and higher in the winter) and, consequently, variations in soil temperature (higher in the summer and lower in the winter).

The known influence of the type and amount of vegetation cover on the soil (Zeynoddin et al., 2019) is evident in the differences between the temperature measured in the soil profile and the observed daily thermal amplitude, especially at the beginning of the soybean cycle and at the end of the cropping period when the soil was partially covered by plants. The criterion for using NDVI (Figure 2 A) to determine total soil cover is based on its "saturation," when it loses sensitivity to detect variations in biomass, which occurs when the index presents high values or an optimal leaf area index (Fontana et al., 2019). The smaller the vegetation cover, the higher the energy input that reaches the soil surface and the higher the temperature and thermal amplitude throughout the soil

Figure 2. Variations in NDVI, hourly soil temperature, and daily thermal amplitude at different soil depths. Period: December 2021 to October 2022, Eldorado do Sul/RS, Brazil.



profile (Dalmago et al., 2010; Bergamaschi & Matzenauer, 2014; Oliveira et al., 2019).

Table 1 quantifies the differences in soil temperatures between periods of analysis and depths of measurement. It shows that the biggest differences occurred between the crop (soybean–summer) and pasture (ryegrass–winter) periods, especially when soil cover was partial. The mean soil temperature was generally 15 °C higher in the crop period compared to the pasture period at all depths, and this difference increased in the partial cover period. There was also a decrease in thermal amplitude with increasing depth.

Figure 3 also shows the differences between the crop and pasture periods. It shows the average daily cycle of soil temperature under conditions of complete soil cover (crop: February 2, 2022, to March 23, 2022, and pasture: June 19, 2022, to August 16, 2023). Soil temperature in both the crop and pasture periods showed a typical pattern of periodic movement in which the thermal amplitude is exponentially damped with depth and the values at each depth oscillate sinusoidally with time around a mean value, as described by Schoffel & Mendez (2005). The mean value of the collected data was different between the periods but the sinusoidal characteristic remained in both. The crop period showed much higher values than the pasture period, especially due to the energy available for the soil heating process associated with the summer season, as already mentioned (only the periods of total surface cover were used for the preparation of this figure). The temperatures at 5, 10, and 20 cm were lower than at 40 cm during the last hours of the night until the last hours of the morning (from 9 p.m. until 10 a.m.), characterizing

Table 1. Descriptive statistics of daily soil temperature (maximum, minimum, and mean values, thermal amplitude, SD–standard deviation, and CV–coefficient of variation) at four depths in the Crop and Pasture periods under partial and total soil cover conditions. Period: December 2022 to October 2023, Eldorado do Sul/RS, Brazil.

Depths (cm)	5	10	20	40	5	10	20	40
	Crop – partial cover				Pasture – partial cover			
Maximum	41.48	38.08	34.33	31.01	28.73	27.03	25.32	23.36
Minimum	21.56	22.55	23.77	24.38	13.51	14.29	15.45	16.17
Mean	29.11	28.79	28.47	27.73	19.17	19.09	19.15	18.97
Amplitude	19.92	15.53	10.56	6.63	15.22	12.74	9.87	7.19
SD	4.58	3.44	2.30	1.54	2.72	2.38	2.04	1.67
CV (%)	16	12	8	6	14	12	11	9
	Crop – total cover				Pasture – total cover			
Maximum	34.86	32.36	29.62	27.82	20.10	19.25	18.68	18.03
Minimum	19.70	21.07	22.84	24.35	9.11	10.23	11.62	13.42
Mean	25.64	25.59	25.69	25.72	15.32	15.38	15.63	15.89
Amplitude	15.16	11.29	6.78	3.47	10.99	9.02	7.06	4.61
SD	2.87	2.06	1.26	0.79	1.98	1.69	1.36	0.96
CV (%)	11	8	5	3	13	11	9	6

that the heat transfer occurred from the deeper layers to the most superficial, and hence the heat flux in the soil was negative. A flux in the opposite direction occurred for the remainder of the daily cycle.

According to Bezerra et al. (2016), the variations on the soil surface are higher than those inside the soil due to absorption, energy loss, and lower propagation rate in the lower layers. In the collected data series, the delay in the time of occurrence of the maximum and minimum temperatures with increasing in depth in the soil profile was observed. This is the expected pattern given the already known low soil thermal diffusivity (Diniz et al., 2014). The information provided in the data presented is the definition of the magnitude of delays.

There was variability between days (Figure 4) but the minimum temperatures most frequently occurred during the crop period at 7 a.m., 8 a.m., 9 a.m., and 1 p.m. for depths of 5, 10, 20, and 40 cm, respectively. The lowest temperatures in the early morning occur because of the loss of long wave radiation throughout the night. In contrast, the times for the maximum temperature were 3 p.m., 4 p.m., 7 p.m., and midnight (the following day) for the same depths.

In this case, the temperature increase is a consequence of the absorption of solar radiation, which, on average, was maximum around noon, when the zenith angle is the lowest. Considering the entire soil profile (40 cm), there was a delay of around 6 hours in minimum temperatures and 9 hours in maximum temperatures. The lowest input of solar radiation into the system during the pasture period also caused a slower heat flux in the soil. In this sense, a delay of around one hour was generally observed for both the maximum and the minimum values compared to what occurred in the crop period.

Figure 3. Variation in soil temperature after 24 hours at four depths, with means for the Crop and Pasture periods under total soil cover conditions. Period: December 2022 to October 2023, Eldorado do Sul/RS, Brazil.

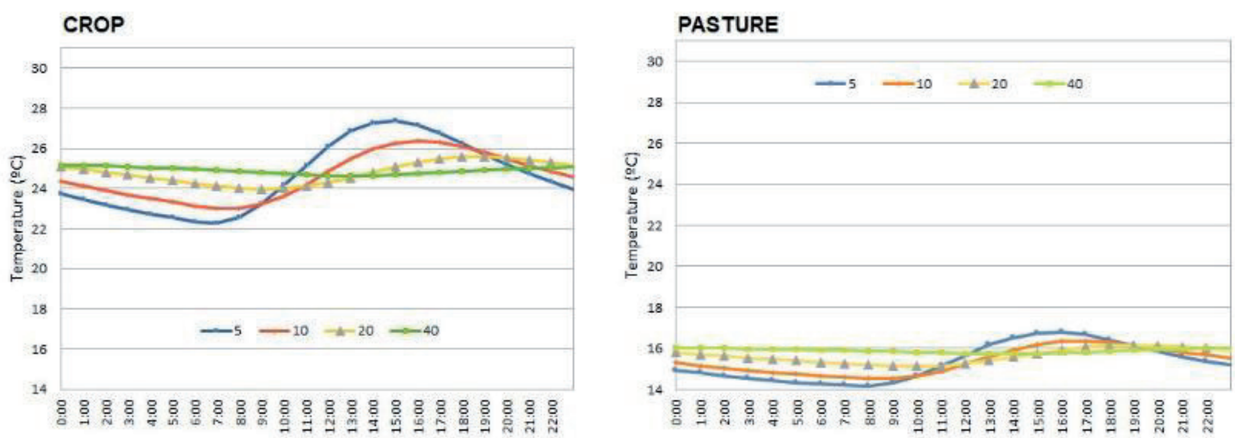
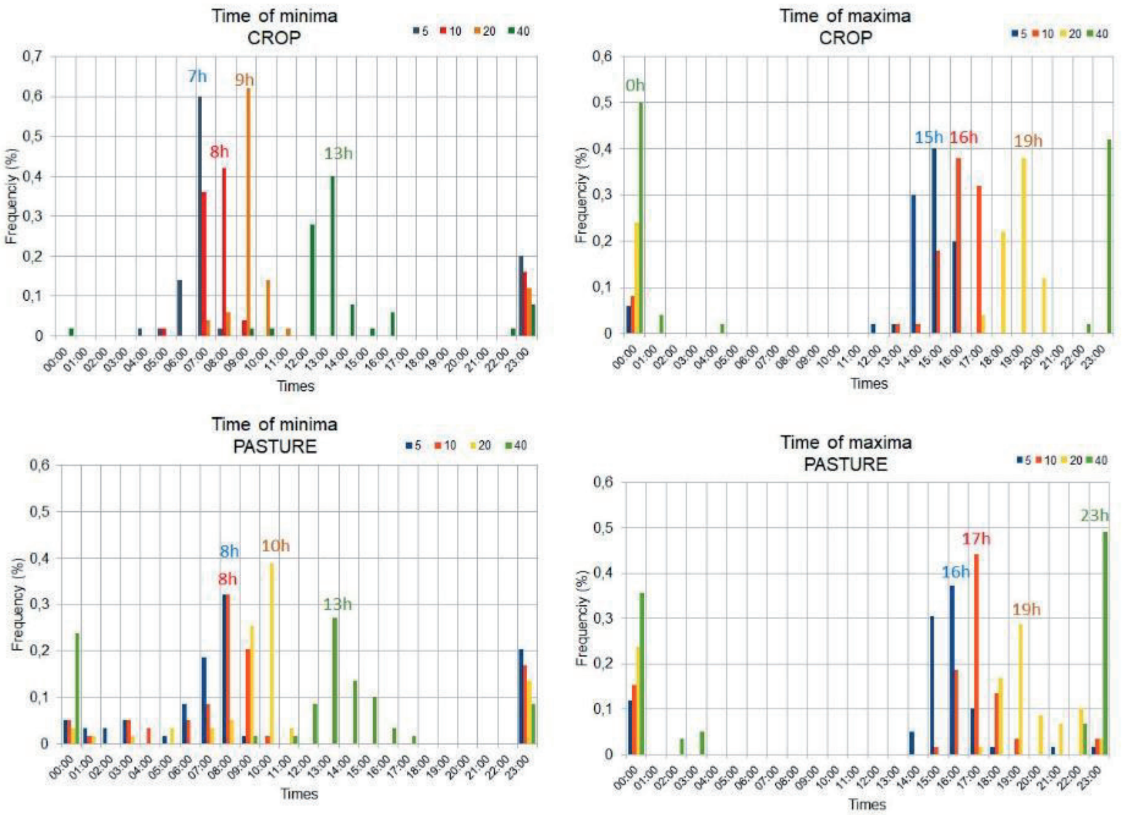


Figure 4. Frequency of times of occurrence of maximum and minimum soil temperatures at four depths for the Crop and Pasture periods. Period: December 2021 to October 2022, Eldorado do Sul/RS, Brazil.



The tautochrones (Figure 5) show the variation of the maximum and minimum soil temperature along the soil measurement profile, evidencing the characteristics of the thermal amplitude in relation to three factors: (i) depth – the amplitude decreases with increasing depth; (ii) amount of vegetation cover – the amplitude decreases under conditions of total soil cover; (iii) season: temperatures are lower across the entire profile in the pasture period, cultivated in the Autumn-Winter but the magnitude of the amplitude was similar to that observed in the crop period.

The last parameter characterized by experimental data was the thermal diffusivity, which expresses the rate of advancement of the heating front in the soil profile (Reichardt & Timm, 2004). The values obtained for the soil thermal diffusivity were low (Figure 6), which is expected and similar to the magnitude of the values calculated by other authors in different soil types (Souza et al., 2006, Diniz et al., 2014,). The variation observed during the experimental period was mainly associated with the layer depth, soil moisture, and the type of vegetation on the soil.

Figure 5. Tautochrones of maximum and minimum soil temperatures for the Crop and Pasture periods under partial and total cover conditions. Period: December 2022 to October 2023, Eldorado do Sul/RS, Brazil.

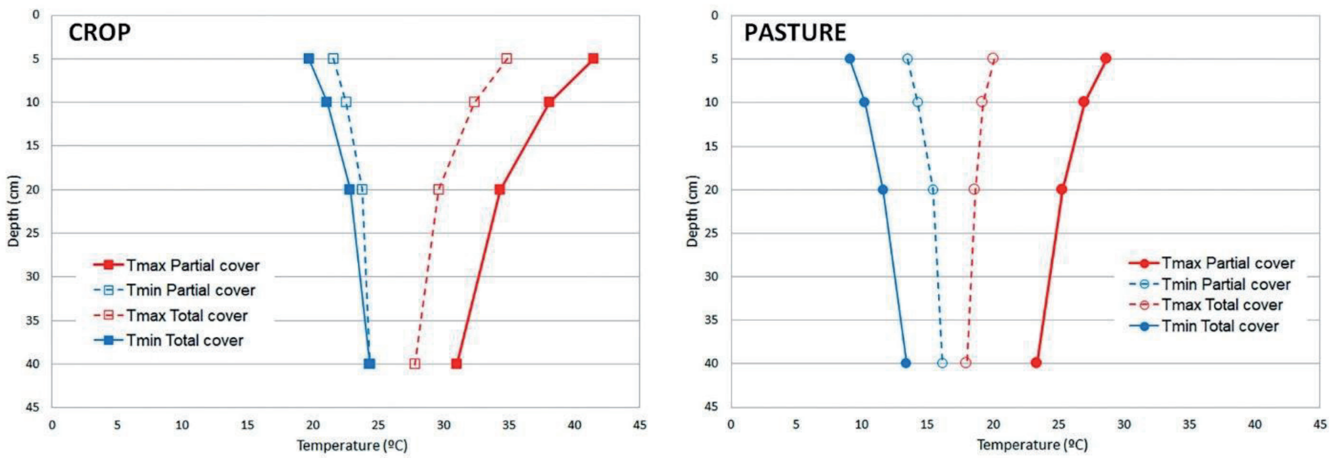
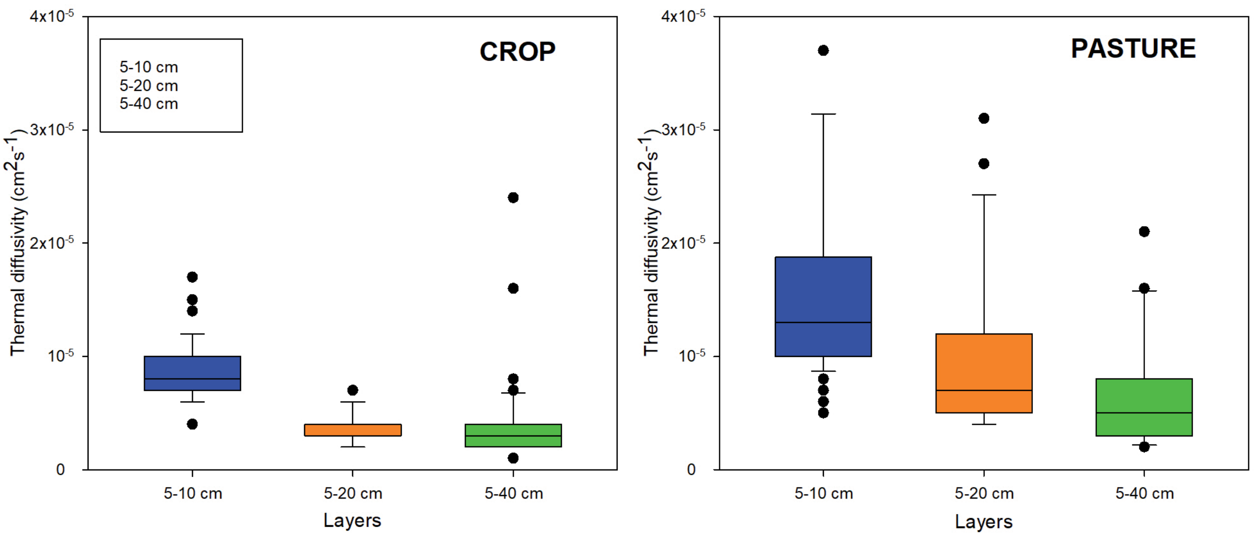


Figure 6. Box plot of thermal diffusivity in the different soil layers considering the Crop and Pasture periods. Period: December 2022 to October 2023, Eldorado do Sul/RS, Brazil.



Soil thermal diffusivity was higher in the surface layer (5–10 cm) regardless of the period analyzed, with median values of 0.000008 and 0.000014 $cm^2\ s^{-1}$ for the crop and pasture periods, respectively. However, the pasture period had a higher thermal diffusivity than that observed in the Crop period. The highest moisture in the system during the Winter period was analyzed by the research group and partially explains the higher diffusivity values in the surface layers and the Autumn-Winter period, in agreement with related studies (Danelichen et al., 2011; Carvalho et al., 2013).

Conclusion

The differeces in energy availability throughout the seasons, associated with the humid subtropical climate, determines the annual pattern of soil temperature.The temperature across the entire soil profile in the summer, as well as the daily temperature amplitude, is higher (more than 10ºC) than that observed in the winter, especially under partial soil cover conditions.

Also, variations in soil moisture and variations in the type of vegetation cover on the soil determines the soil thermal pattern. In conditions of lower soil moisture, the temperature tends to be higher, which also occurs when the vegetation cover is lower.

Soil thermal diffusivity is low (median values of 0.000008 and 0.000014 $cm^2\ s^{-1}$), especially under low soil moisture conditions, which determines a delay in the time of occurrence of minimum and maximum soil temperatures in the daily cycle. Near the surface (5cm) the minimum temperature occurs around 7-8 a.m., with a delay of approximately 1h for every 5cm increase in depth. Also close to the surface, but for the maximum temperature, the time of occurrence is close to 3-4pm and the delay is longer.

Author contributions

D. C. FONTANA designed the experiments and wrote the manuscript. B. RADIN designed the experiments, analyzed the data and review the manuscript. G. A. Oliveira designed the experiments, conducted the experiments, performed the statistical analysis and review the manuscript. V. BELFANTE JUNIOR conducted the experiments and analyzed the data. C. BREMM performed the statistical analysis and review the manuscript.

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Padrão anual e diário da temperatura do solo em sistema integrado de produção agropecuária no sul do Brasil

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RESUMO

Considerando a importância da temperatura do solo e a alta variabilidade espacial e temporal associada aos tipos de solo, tipos de cobertura vegetal e ao manejo aplicado, este trabalho teve como objetivo determinar os padrões diário e anual da temperatura do solo em sistema conservacionista de integração lavoura pecuária conduzido em condições de clima subtropical no sul do Brasil. O experimento foi conduzido em sistema integrado lavoura pecuária, cultivado no verão com soja e no inverno com azevém, sendo pastejado com ovinos. Os dados medidos foram: NDVI e temperatura do solo em quatro profundidades, tendo sido caracterizados: o ciclo anual e diário do perfil do solo e a amplitude térmica diária, utilizada para o cálculo da difusividade térmica. Os resultados mostraram que a disponibilidade de energia variável ao longo das estações do ano, associada ao clima subtropical úmido, determina o padrão anual da temperatura do solo. No verão, a temperatura em todo o perfil do solo e a amplitude térmica diária é superior a observada no inverno, especialmente em condições de cobertura parcial do solo. É baixa a difusividade térmica do solo, especialmente em condições de menor umidade no solo, o que determina, no ciclo diário, um atraso no horário de ocorrência das temperaturas **mínimas e máximas**.

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