



Citation: T. Pogačar, L. Kafež Bogataj, R. Kuk, Z. Črepinšek (2022) Effects of heat waves on soil temperatures in Slovenia. *Italian Journal of Agrometeorology* (1): 41-48. doi: 10.36253/ijam-1388

Received: September 2, 2021

Accepted: January 24, 2022

Published: July 19, 2022

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Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

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Effects of heat waves on soil temperatures in Slovenia

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Abstract. Soil temperature regulates the rate of plant growth and tells us much about the climatic characteristics of a particular site. Climate variability and extremes need to be studied and there is a large gap in knowledge about soil temperature during heat waves. Agricultural land is highly dependent on heat waves, which are becoming longer, more intense and more frequent, and it is important to monitor soil temperatures in situ to understand their changes during heat waves. Therefore, the aim of this work was to investigate how soil temperatures change at different depths during and after heat waves. Average daily air and soil temperature data for the 25-year period 1992-2016 were evaluated at four agrometeorological stations in three climate zones in Slovenia and analyzed during heat waves determined according to the Slovenian definition. During the period 1992-2016, 53 (Lesce) to 76 (Ljubljana) heat waves were identified. Analysis of average air and soil temperatures before, during and after heat waves showed higher responsiveness of the upper part of the soils and an increase in the time lag between maximum air temperature and maximum soil temperature with depth. The maximum temperature during the heat wave was reached on average in three to nine days, depending on the depth. Only in Moderate climate of the hilly region, the average daily temperatures at a depth of 100 cm remained below 20°C during and after the heat wave. The temperature rise in the deeper layers of the soil lasts longer than in the shallower layers.

Keywords: soil temperature, heat wave, air temperature, climate change.

1. INTRODUCTION

Soil temperature is of great importance for soil decomposition, regulates various processes including the rate of plant growth, and as such is a very sensitive climate indicator (Jebamalar et al., 2021; Onwuka and Mang, 2018). In soils, carbon mineralization and sequestration can be severely affected by heat. Above a critical threshold of heat wave duration, biomass can be drastically depleted and soil microbial communities restructured, associated with a shift in physiological properties (Berard et al., 2011). Soil organic matter decomposition is controlled primarily by soil temperature during wet periods

and by the combined effect of soil water and soil temperature during dry periods (Yuste et al., 2007). Heat stress itself is a complex function of intensity, duration, and the rate of increase in air temperature.

As shown in a previous study, air temperatures in Slovenia were strongly correlated with upper soil temperatures, with coefficients decreasing rapidly with depth (Pogačar et al., 2018). Moreover, the effect of an increase in soil temperature may be even stronger if accompanied by a decrease in soil water content. The frequency of very hot days increases in summers with dry soils (Fischer et al., 2007a, 2007b; Hirschi et al., 2011). In addition to the well-known influence of soil moisture on heat wave intensity, it also plays the key role in the persistence of heat wave events (Lorenz et al., 2010). Case studies of selected large summer heat waves show that intraseasonal and interannual variability in soil moisture accounts for 5-30% and 10-40% of the simulated heat wave anomaly, respectively (Jaeger and Seneviratne, 2011). When soil temperatures are higher, soil water evaporation also increases (Aguilera et al., 2015). When soils are moist, heat transport is rapid, but more energy is required to change temperature (Manfredi et al., 2015). Increased soil surface temperature can lead to loss of subsoil carbon stocks, more carbon release to the atmosphere, increased soil respiration, and extended potential growing season (Soong et al., 2021; Zhang et al., 2016). Therefore, soil temperature with its influence on plant development is very important and should be monitored or analyzed if it is above a certain critical threshold (Mueller et al., 2010; Sviličić et al., 2016). Extreme air and soil temperature can alter the water transport rate due to reduced plant stomatal conductance, which reduces transpiration rate and consequently also yields (Irmak and Mutiibwa, 2010). Many agricultural crops are sensitive and vulnerable to changes in soil temperature. Research of Liao et al. (2016) showed that the temperature at the surface soil (20 cm soil depth), and the soil moisture content at 20–30 cm depth were the significant factors that affected potato yields. High soil temperatures negatively affected the photosynthesis of the maize plants due to decreased carboxylation rates (Nóia Júnior et al., 2018). The same research showed that short-term exposure to extreme soil temperatures affects the root system growth, leading to lower shoot dry mass accumulation. In addition, high soil temperatures reduced the relative water content of the leaves, causing an increased leaf temperature and cells rupture.

All over the world, the latest scenarios show increased uncertainty in climate conditions, which are important for agriculture (Pariße et al., 2020).

The increasing duration of extreme heat waves is having a major impact on agricultural land (Hansen et al., 2018). For example, row crops are particularly susceptible to heat stress under hot and dry conditions because of excessive heating due to heat fluxes in the soil and very limited capacity for leaf cooling (Costa et al., 2019). Mortality due to drought is far more likely for trees than mortality due to heat stress, but its severity and rate of development, is greatly increased at high temperatures (Teskey et al., 2015). In the Mediterranean region, extreme events caused by climate change, such as prolonged and more intense heat waves, have an impact on soils and their functions through changes in the biomass, composition and activities of edaphic microbial communities (Berard et al., 2011).

In Slovenia, soil temperatures at all stations showed a positive trend in the period 1971-2015, with the strongest warming in summer (Pogačar et al., 2018). Average annual air temperatures have already increased by 2°C since 1961, and projections show an average increase of 1 to 4°C (with the 1981-2010 reference period) for the average summer air temperature by the end of the century. The projected increase in average soil temperatures from July to September is even slightly higher, by 2 to 4.5°C (ARSO, 2020).

Average values give us only a superficial idea of warming, as it is difficult to translate them into real change. In addition, climate variability and extremes need to be studied and there is a large gap in our knowledge of soil temperature during heat waves. Therefore, the intent of this paper is to investigate how soil temperatures change at different depths during and after heat waves.

2. MATERIALS AND METHODS

Four standard agrometeorological stations, namely Bilje, Ljubljana, Lesce and Novo mesto from three different climatic zones and on three different soils were selected (Tab. 1). All four stations belong to the official meteorological network from the Slovenian Environment Agency (ARSO: <http://www.meteo.si/>).

Average daily soil temperature data and average air temperature data at 2 m above sea level were evaluated for the 25-year period 1992-2016. Data were retrieved from ARSO and for soil temperatures the calculation of daily averages was performed using the climatological standard. The period was chosen because the number of days with fulfilled criteria for dangerous heat-related conditions due to the meteoalarm has especially increased since 1990 (Pogačar et al., 2020), and after

Table 1. Description of four measurement sites: altitude, geographical coordinates, surrounding land use and climatic zone.

Station	Altitude (m a.s.l)	Geographical coordinates (longitude, latitude)	Area description	Soil type	Climate
Ljubljana	299	14°31', 46°4'	Urban	Antrosols	Subcontinental
Novo mesto	220	15°11', 45°48'	Urban/peri urban	Antrosols	Subcontinental
Lesce	515	14°11', 46°22'	Rural/peri-urban	Rendzina	Moderate climate of hilly region
Bilje	55	13°38', 45°54'	Rural	Eutric fluvisol	Submediterranean

2000 heat waves in Slovenia are much more frequent, intense and longer than before (Pogačar et al., 2019). The upper year was set to 2016, because since 2017 there are no more measurements of soil temperatures at depths of 2 and 100 cm in Slovenia.

The Slovenian definition of heat wave was used, where the average daily air temperature must be higher than or equal to the threshold (in graphs marked with the red line) for at least three consecutive days. For Subcontinental climate (Ljubljana, Novo mesto) the threshold is 24°C, for Moderate climate of hilly region 22°C (Lesce) and for Submediterranean climate 25°C (Bilje) (Ključevšek et al., 2018). First, periods in heat waves were identified based on the definition using air temperatures. The first day of each heat wave was identified. Then, soil temperatures at a given depth of 2, 5, 10, 20, 30, 50 and 100 cm were averaged for each consecutive day before, during and after the heat wave. There is quite some missing data of soil temperatures, so we checked it carefully and eliminated these days (only for specific depths) from averages: at Bilje days around 24.6.2005 (20 cm), 9.7.2016 (10 cm); at Ljubljana around 14.7.2007 (30 cm), 11.8.2013 (5 and 10 cm); at Lesce around 3.8.1993 (2 cm), 27.7.2006, 22.6.2008, 26.7. and 29.8.2009 (2, 5, 10, 20, 30, 50 cm); and at Novo mesto around 2.7. and 30.7.2006 (100 cm). According to a sensitivity analysis, these specific dates do not change the averages significantly.

3. RESULTS

Soil temperatures during heat waves have never been analyzed in Slovenia. In the period 1992-2016, 76 heat waves were identified in Ljubljana, 56 in Novo mesto, 55 in Bilje, and 53 in Lesce. As an example of temperature distribution on days before, during and after a heat wave, we took the case of a heat wave in Bilje in June 2003 (Fig. 1). It can be seen that the heat threshold (marked with red line) was reached on 8 June and the heat wave lasted until 17 June. Only the soil temperatures at a depth of 100 cm were lower than the air tem-

peratures throughout the heat wave and higher only for two days after the heat wave. Temperatures at a depth of 50 cm were very similar to air temperatures, but remained high longer after the air had already cooled. At shallower depths, temperatures rose higher, reaching over 30°C, although average air temperatures did not. The highest maximum average daily soil temperature was at a depth of 2 cm, about 5°C higher than the highest maximum average daily air temperature.

Average air and soil temperatures (1992-2016) before, during and after heat waves at 4 sites (Fig. 2) showed similar characteristics, in Bilje especially similar as in the heat wave shown above. At other sites, air temperatures exceeded soil temperatures for a short time at depths greater than 10 cm. The upper part of the soils was more sensitive to air temperature changes, and the time interval between maximum air temperature and maximum soil temperature increased with depth. The maximum temperature during the heat wave was reached on average in three days for air temperature and soil temperatures at shallower depths below 10 cm, in three to four days at a depth of 20 to 30 cm, in four to five days at a depth of 50 cm, and in six to nine days at a depth of 100 cm.

The smallest difference between the maximum average air and soil temperature was in Novo mesto, less than 2°C, followed by Ljubljana, both of Subcontinental climate. In Lesce the difference was about 3.5°C and in Bilje about 5°C. Only in Lesce, due to Moderate climate of hilly region, the average daily temperatures remained below 20°C at the depth of 100 cm, maintaining an adequate environment for drinking water quality, as water pipes are usually installed at this depth.

In Novo mesto and Ljubljana, soil temperatures after the heat wave averaged just above 20°C at the 100 cm depth and about 22°C at the 50 cm depth. In Bilje (Sub-Mediterranean climate) the situation was most critical, with average soil temperatures after the heat wave at the depth of 100 cm reaching above 24°C, and at the depth of 50 cm even up to almost 28°C. For an average heat wave that lasted 5 days, the elevated soil temperatures

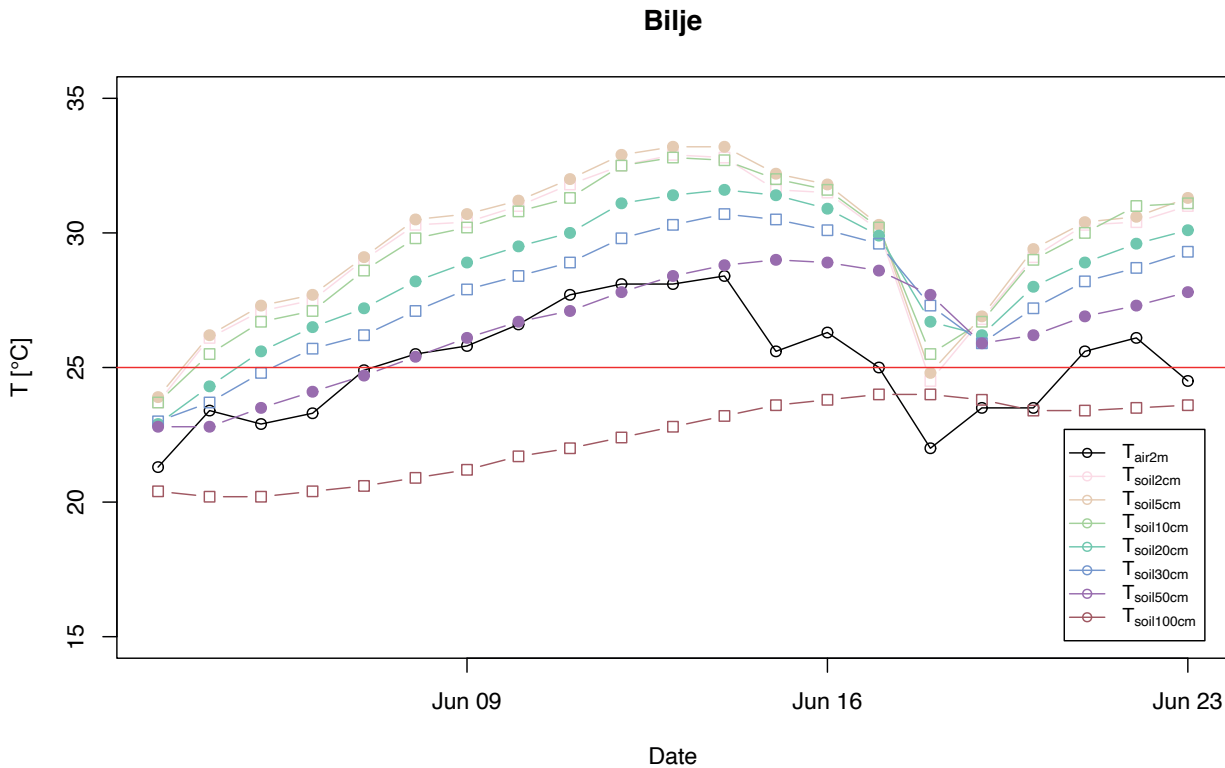


Fig. 1. An example of the time course of the daily average air and soil temperature at different depths before, during and after the heat wave (threshold – red line) in June 2003 at the Bilje station.

lasted only a few more days at shallower depths, and even more than 15 days at greater depths.

Further analysis of the slopes between the points in the graphs in Fig. 2 showed that the temperature in the upper soil layers and in the air increased the fastest (large positive slope) and decreased the fastest (large negative slope) (Fig. 3). It can also be seen that the zero slope, where the maximum temperature is reached, moves to the right with depth. Thus, the temperature rise in the deeper layers of the soil takes longer than in the shallower layers.

4. DISCUSSION

Changes in soil temperature affect many agricultural practices, so we wanted to examine changes during heat waves. The similar number of heat waves at 3 sites (except Ljubljana as an urban heat island) over the 25-year period confirms that the thresholds are appropriately set because in different climates all living organisms are acclimated to their usual conditions, so the threshold may not be the same everywhere (Wang et al., 2020). Air temperatures are strongly correlated with

upper soil temperatures, and in Slovenia warming was observed at all depths in all seasons, but the threshold of 45°C was not (yet) reached at any depth (Pogačar et al., 2018).

We have shown how the time lag of a heat wave is longer when going deeper, with the maximum temperature delayed by as much as four to five days. With slower responses and less influence of air temperature changes, the highest average annual soil temperatures are measured at a depth of 50 or 100 cm (Pogačar et al., 2018). Soil warming is more pronounced in summer, as also shown in a study for the Mediterranean region (Aguilera et al., 2015), which means more heat stress during heat waves that negatively affect crop production (Lasram and Mechlia, 2015; Melkonyan, 2015), as well as more changes in soil microbial community composition (Acosta-Martinez et al., 2014). It is important to monitor as early as the first seasonal heat waves that may occur in early June, as soil surface temperature is the dominant factor influencing vegetation variation in March–July (Xu et al., 2011), as well as throughout the summer, as soil water content must be maintained at appropriate levels during extreme heat periods to ensure plant uptake and minimize the effects of heat stress.

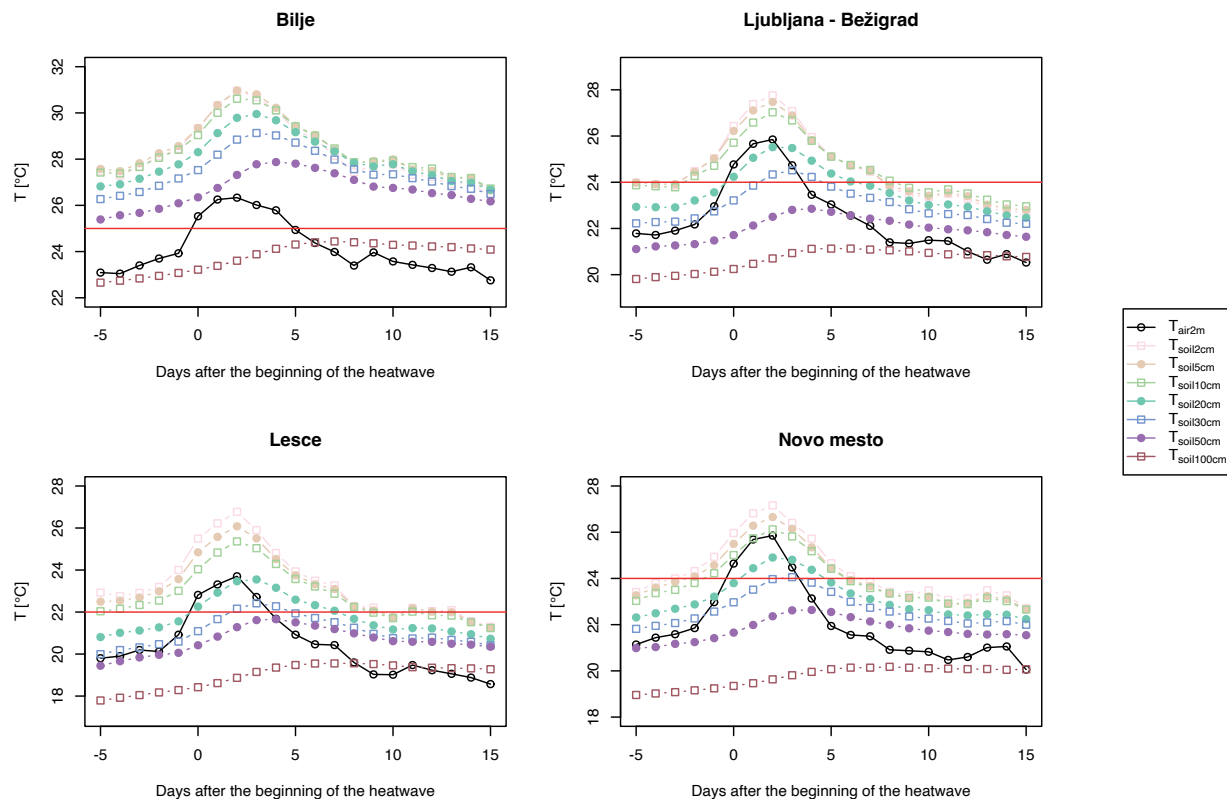


Fig. 2. The courses of average air and soil temperature at four sites in Slovenia. Temperature per individual day is the average value for all heat waves in the period 1992–2016, negative days meaning days before the start of the heat wave.

One way to reduce soil temperature during heat waves is to provide additional residue on the soil surface in reduced and no-till fields, which can minimize radiation interception on the soil surface, which lowers soil temperature and is beneficial for improving root growth and water and nutrient uptake during heat wave periods (Lipiec et al., 2013).

Since the altered contributions of circulation and soil moisture to temperature anomalies include enhanced feedbacks in the surface energy budget (Gessner et al., 2021), which increase sensible heat fluxes and reduce latent cooling over dry soils (Miralles et al., 2014; Seneviratne et al., 2006), the latter should also be investigated in additional studies for Slovenia to better plan agrotechnical measures in the near future.

The limitation of the study is only a small number of sites, however these four are good representatives of three different climatic zones in Slovenia and as such suitable to use. Due to the large amount of data over a period of 25 years, average daily values were studied, but they give us an insight into the usual spread of heat in the soils.

4. CONCLUSIONS

During more than 50 heat waves over a 25-year period, at 4 sites, on average, the time interval between maximum air temperature and maximum soil temperature increased with depth. We have shown that the upper part of the soil is the most sensitive, reaching maximum temperatures within three days after the onset of the heat wave. At greater depths, up to 100 cm, the maximum was reached in up to nine days. Moreover, the temperature rise lasted longer in the deeper layers and only in Moderate climate of hilly region the average daily temperatures at the depth of 100 cm remained below 20°C during and after heat waves. Maize and potato are widely grown in the regions of our studied agrometeorological stations (SURS, 2021). Both crops are sensitive and vulnerable to changes in soil temperature, as the temperature at the upper soils is the significant factor that affects potato yields, and high soil temperatures negatively affect the photosynthesis of the maize, lead to lower shoot dry mass accumulation and reduce relative water content of the leaves. Due to the strong influence of soil temperatures on agricultural production, it is of great importance

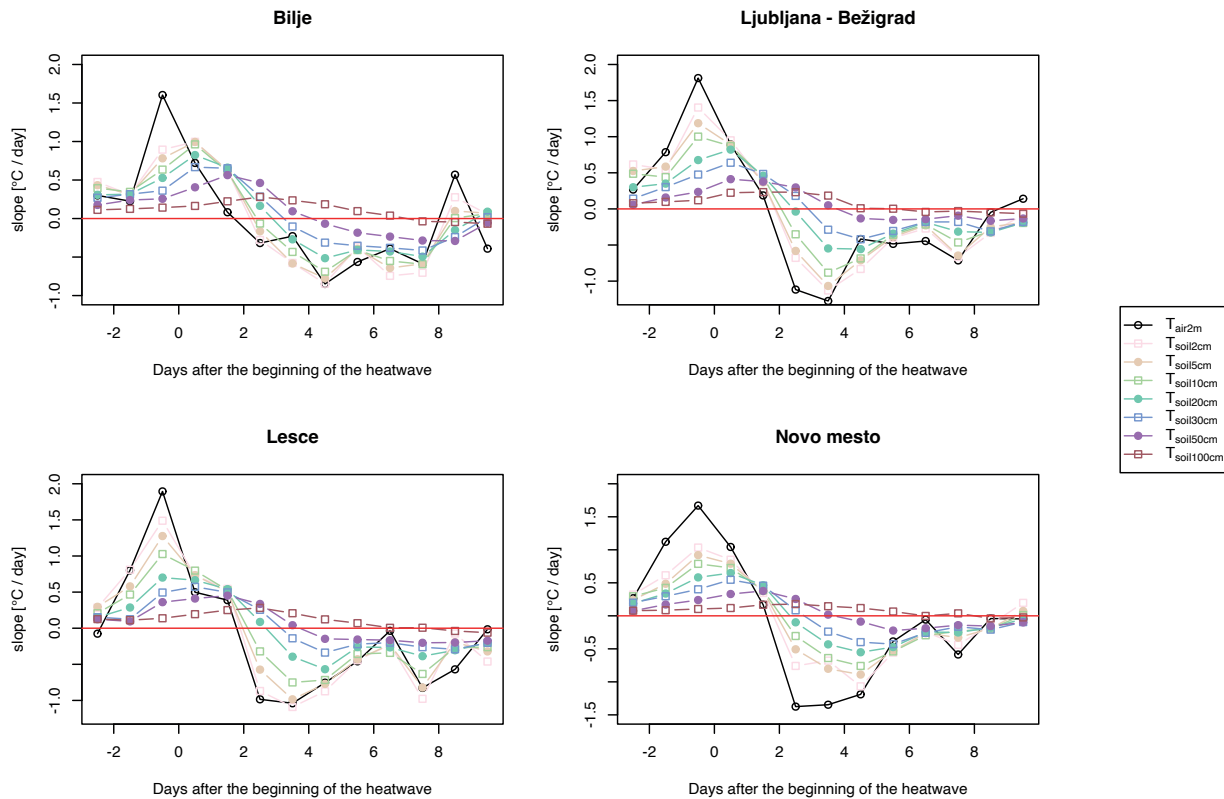


Fig. 3. The slopes of the lines between the points on Fig. 2.

to understand their evolution during heat waves. We recommend monitoring them in situ if only possible.

ACKNOWLEDGEMENTS

This work was supported by the Slovenian Research Agency, Research Program P4–0085.

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