Soil temperature analysis for various locations in Slovenia

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Abstract: *The increase in air temperature due to heat transfer on the ground means the rise in temperature of the soil, which impacts physical, biological and microbiological processes in the soil. In this research, yearly, seasonal and monthly averages of soil temperatures, seasonal correlations between air and soil temperatures, and long-term trends have been evaluated for six locations in Slovenia. We also determined soil thermal regimes and soils' vulnerability to low and high temperatures between 1971-2010 and 1986-2015. Air temperatures were strongly correlated to upper soil temperatures, with high correlation coefficients for spring and autumn at all depths, and weaker for summer and winter, coefficients rapidly decreasing with depth. Soil temperatures at all stations showed a positive trend, with the strongest warming in summer with average rates of increase of 0.75, 0.76, 0.62, and 0.73 °C per decade at depths of 5, 10, 30, and 100 cm, respectively. Soils' vulnerability to changing thresholds evaluation showed higher vulnerability to high temperatures.*
Keywords: *Soil temperature, air temperature, climate change, trend, correlation, vulnerability threshold.*

Riassunto: *L'aumento della temperatura dell'aria dovuto al trasferimento di calore sul terreno comporta la crescita della temperatura del suolo, che influisce sui processi fisici, biologici e microbiologici. In questa ricerca, sono state valutate per sei località della Slovenia le temperature medie del suolo annuali, stagionali e mensili, le correlazioni stagionali tra temperatura dell'aria e del suolo, e gli andamenti nel lungo periodo. Sono stati anche determinati i regimi termici del suolo e la vulnerabilità dei terreni alle basse e alte temperature tra il 1971-2010 e il 1986-2015. Le temperature dell'aria risultano fortemente correlate alle più alte temperature del suolo, con alti coefficienti di correlazione per la primavera e l'autunno a tutte le profondità, mentre più deboli per l'estate e l'inverno, con coefficienti rapidamente decrescenti con la profondità. Le temperature del suolo in tutte le stazioni hanno mostrato un andamento positivo, con un più alto riscaldamento in estate con tassi medi di aumento di 0,75, 0,76, 0,62 e 0,73 ° C per decennio a profondità di 5, 10, 30 e 100 cm, rispettivamente. La valutazione della vulnerabilità dei suoli al variare delle soglie ha mostrato livelli maggiori alle alte temperature.*
Parole chiave: *Temperatura del suolo, temperatura dell'aria, cambiamenti climatici, tendenza, correlazione, soglia di vulnerabilità.*

1. INTRODUCTION

Soil temperature is one of the key factors within the soil-plant-atmosphere system. As shown in recent studies, soil temperature is increasing in areas all over the globe, influencing subsurface processes under any cover – forested (Tierney *et al.*, 2001; Mellander *et al.*, 2007; Feng *et al.*, 2007; Urakawa *et al.*, 2014), agricultural (Kahimba *et al.*, 2009; Rodriguez *et al.*, 2010; Mueller *et al.*, 2010), and urbanized areas (Ferguson and Woodbury, 2007; Taniguchi *et al.*, 2008; Taylor and Stefan, 2009; Zhu *et al.*, 2015). Top soil temperature influences frost occurrence, presence or absence of snow cover, however, the absence of snow cover decreases soil temperature and accelerates the freeze-thaw process (Hardy *et al.*, 2001; Zanini and Freppaz, 2006). The freeze-thaw process of the top layer alters soil microbial biomass and enzyme activity (Feng *et al.*, 2007; Tan *et al.*, 2014), soil moisture, increases soil aggregate breakdown (Edwards, 2013) and susceptibility to wind erosion (Wang *et al.*, 2014).

On agricultural areas, soil temperature influences soils' heat and quality. Shallow soil temperatures are detrimental for attaining the necessary temperature thresholds for plant physiological development stages, influence nutrient cycle (Grogan *et al.*, 2004; Fekonja *et al.*, 2011), mineralization of organic matter (Harrison-Kirk *et al.*, 2014; Matzner and Borken, 2008) and influence success of conservation tillage (Ferrara *et al.*, 2017). Due to warmer winters mineralization of organic matter will increase through increased microbial activity or even shift in a microbial community (Feng *et al.*, 2007; Ferrara *et al.*, 2017) thus releasing nutrients stored in the organic matter at a higher rate. Soil thermic properties differ between degraded and reconstituted soils (Manfredi *et al.*, 2015).

Soil temperature changes in the root zone, such as shallow depths of 10 and 30 cm, influence soil moisture availability (Pavel and Fereres, 1998; Zupanc *et al.*, 2007; Fekonja *et al.*, 2011) and soil

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water flow, which influences nutrient availability (Freppaz *et al.*, 2007), plant nutrient uptake and growth (Steudle and Peterson, 1998; Fekonja *et al.*, 2011) and soil water storage (Zupanc *et al.*, 2007).

Soil temperature regime maps are used for estimation of potential productivity in a natural ecosystem, land suitability, and soil classification, and can more appropriately define climatic regions with regard to pedological processes (Takata *et al.*, 2011). Temperate region soils can typically be defined as having mesic or thermic STR regimes (those experiencing less than a 5 °C difference in soil temperature at 50 cm depth) (USDA soil classification, Keys to Soil Taxonomy, 2006). At large, temperate regions account for 7% of the surface area of the earth, and amass 40% of world's population, making anthropogenic influence the dominant soil-forming factor. Takata *et al.* (2011) determined a parallel relationship between mean annual soil temperature and mean annual air temperature, which was affected by elevation, and also wind speed and global irradiation. There were four classes of soil temperature regime in Japanese soils, namely frigid, mesic, thermic and hyperthermic (Soil Survey Staff, 1999; cited after Takata *et al.*, 2011), and just one in Finland, cryic (Yli-Halla and Mokma, 1998), yet some recent studies in STR showed high diversity on short distances, such as in Tenerife, Spain (Rodriguez *et al.*, 2010). Under global warming global scale soil temperature regime alterations are expected (De Sanctis *et al.*, 2008), indicating the northward shift of various croplands in regions where until now land cultivation was not possible (Grillakis *et al.*, 2016). There is increasing need to develop predictive models of future soil temperatures under different climate change scenarios (Eccel *et al.*, 2015; Loddo *et al.*, 2015).

Soil temperature is an important factor for crop development, therefore, it is also important to observe the consecutive duration of soil temperature that is higher than a certain critical threshold (Svilič ić *et al.*, 2016).

In Slovenia, soil temperature has been studied as a factor in CO_2 fluxes and soil respiration (Vodnik *et al.*, 2009; Eler *et al.*, 2013), mercury emissions and dispersion (Llanos *et al.*, 2011), soil thermal properties for long distance heating (Perpar *et al.*, 2012) and subsurface warming (Šafanda *et al.*, 2007; Strgar et al, 2017). However, as general soil temperature characteristics with regard to agricultural production have not yet been described for Slovenia, analysis has been done for the 30-year period 1986-2015 at six locations in Slovenia. Yearly, seasonal and monthly averages of soil temperatures, seasonal correlations between air and soil temperatures, and trends have been evaluated. Soil thermal regime was determined and changes in soil vulnerability to low and high temperatures between the periods 1971-2010 and 1986-2015 for three locations has been assessed.

2. MATERIALS AND METHODS

2.1 Data and basic analysis of averages, correlations and trends

Former standard approach for evaluation of soil temperature regime was the use of estimations based on air temperature data; however, this approach did not always produce good results (Yli-Halla and Mokma, 1998; Rodriguez *et al.*, 2010). Therefore analysis included raw soil temperature data. For six selected standard meteorological stations, namely Bilje, Ljubljana, Lesce, Maribor, Novo mesto and Šmartno near Slovenj Gradec (Fig. 1, Tab. 1) mean, minimum and maximum daily soil temperature data and mean air temperature data at 2 m above sea level (a.s.l.) were evaluated for the 30-year period 1986–2015. For comparison and threshold analyses soil temperature data for period 1971–2000 was used. Data were retrieved from the Slovenian Environment Agency (ARSO: http://www.meteo.si/).

Mean, maximum and minimum daily soil temperature is determined by ARSO at a specific depths: 2, 5, 10, 20, 30, 50 and 100 cm. 30-year average monthly soil temperatures for various depths were calculated to show the heat transfer in-depth (i.e. the upper level of soil is in the winter cooler than lower and in the summer vice-

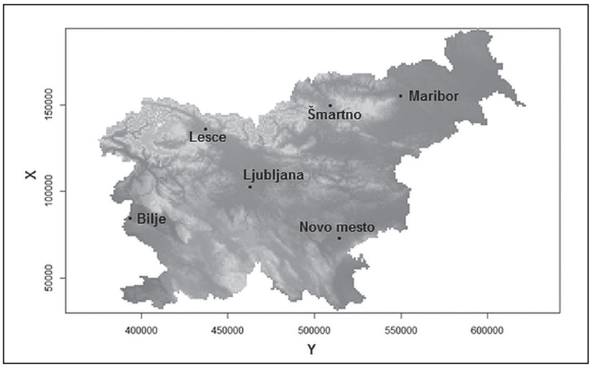

Fig. 1 - Map of Slovenia with denoted locations of selected meteorological stations.
Fig. 1 - Mappa della Slovenia con la localizzazione delle stazioni meteorologiche selezionate.

Station	Altitude (m a.s.l)	Geographical coordinates (longitude, latitude)	Area description	Soil type	Climate
Ljubljana	299	14°31′, 46°4′	Urban	Antroposols	Subcontinental
Maribor	264	15°41′, 46°29′	Urban	Distric	Subcontinental
Novo mesto	220	15°11′, 45°48′	Urban/peri urban	Antroposols	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
Šmartno	455	15°7′, 46°29′	Rural	Distric	Moderate climate of hilly region

Tab. 1 - Description of six measurement sites: altitude, geographical coordinates, surrounding land use, soil and climate zone.
Tab. 1 - Descrizione di sei luoghi di monitoraggio: altitudine, coordinate geografiche, uso del suolo, suolo e zona climatica.

versa) for each location. The correlation between air temperature and temperatures at various soil depths was analyzed on the daily scale for each season using Pearson correlation test implemented in R. Seasonal trends were also calculated in R, with QR decomposition to calculate the least squares fit.

2.2 Soil temperature regimes

Soil temperature regimes are defined in Soil Taxonomy using measurements taken at a depth of 50 cm (Soil Survey Staff, 1975; cited after Rodriguez *et al.*, 2010). Based on USDA Soil Survey Division, the mesic soil temperature regime has mean annual soil temperatures of 8 °C or more, but less than 15 °C, and the difference between mean summer and mean winter soil temperatures is greater than 5 °C at 50 cm below the surface. The thermic soil temperature regime has mean annual soil temperatures of 15 °C or more, but less than 22 °C; and a difference between mean summer and mean winter soil temperatures greater than 5 °C at 50 cm below the surface (USDA Soil Taxonomy).

2.3 Soils vulnerability

Sviličić *et al.* (2016) methodology was followed to determine the soil vulnerability to low and high temperatures, as their thresholds were chosen based on optimal temperature ranges at which plants are able to grow and develop: for minimal soil temperature, critical thresholds of 0 and –5 °C at 2, 5, 10, and 20 cm depths, and for maximal soil temperature, critical thresholds of 30, 35, 40, and 45 °C at 2, 5, and 10 cm; 25 and 30 °C at 20, 30, and 50 cm; and 20 °C at 50 cm. The condition is that critical soil temperature will appear in the duration of 10 or more consecutive days, and of 3 or more consecutive days for the critical threshold of –5 °C. According to Joint Research Centre soils are vulnerable when these conditions are fulfilled with 20 % probability (this means in at least 6 years within the observed 30-year period).

3. RESULTS

3.1 Soil temperature characteristics

This is the first research on soil temperature on a national scale in Slovenia. Average monthly soil temperatures by depth for each month during 1986–2015 for the selected stations are represented in Fig. 2. Annual air temperature averages for the 30-year period were for at least 1 °C lower than annual soil temperature averages at a depth of 2 cm. These were the lowest annual average temperatures in the soils (except for Šmartno, where the lowest average was at a depth of 20 cm), ranging from 10.4 °C in Šmartno and 10.6 °C in Lesce (both with the Moderate climate of hilly region) to 14.3 °C in Bilje (Submediterranean region, Fig. 2). The highest average annual soil temperatures were in Bilje at a depth of 50 cm (14.5 °C), followed by 12.5 °C in Novo mesto and 12.3 °C in Ljubljana at a depth of 100 cm, 11.9 °C in Maribor (50 cm), 11.2 °C in Lesce (50 cm) and 11.0 °C in Šmartno (100 cm). The highest monthly averages occurred in July to a depth of 30 cm and in August at depths of 50 and 100 cm, reaching to the maximum of 22 °C in Lesce and 27 °C in Bilje. The lowest monthly averages occurred in January (at a depth of 2 cm –0.6 °C in Šmartno and 2.7 °C in Bilje). In February, the lowest monthly averages were detected deeper, on 30 or 50 cm. Only in Šmartno and Lesce, the 30-year average January temperatures at a depth of 2 cm were negative, in Šmartno also at the depth of 10 cm (Fig. 2). In

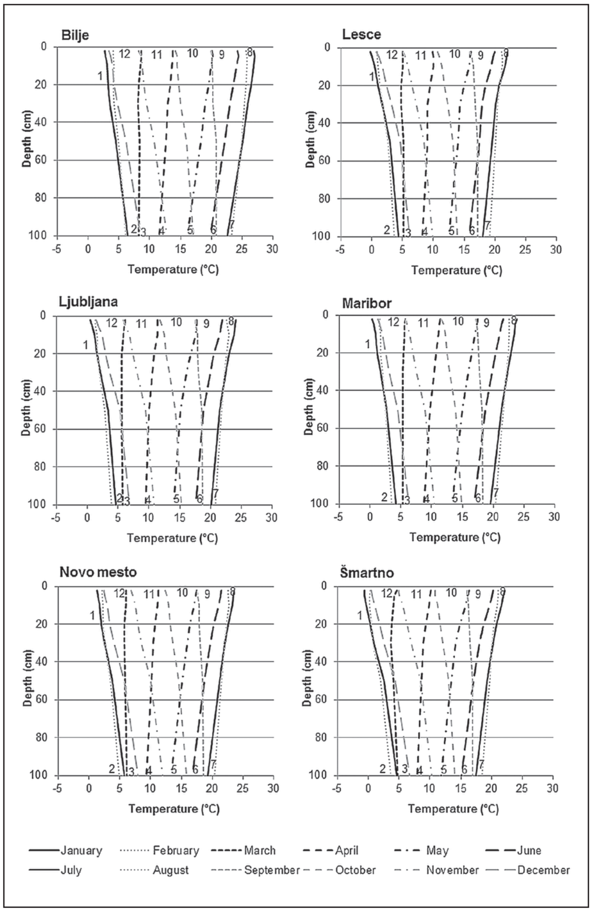

Fig. 2 - Course of average monthly soil temperature with depth (the numbers in the graph represent months (1 – January, 2 – February, etc.)) in the period 1986–2015 for 6 meteorological stations.
Fig. 2 - Andamento della temperatura del suolo media mensile in base alla profondità (i numeri nel grafico rappresentano i mesi (1 - gennaio, 2 - febbraio, ecc.)) nel periodo 1986-2015 per 6 stazioni meteorologiche.

the period 1986–2015 the highest measured soil temperature was 47 °C in Ljubljana (1988) and the lowest −13.5 °C in Šmartno, both at a depth of 2 cm (Tab. 2).

3.2 Correlations to air temperatures and seasonal trends of soil temperatures

Seasonal correlation coefficients between air temperatures and soil temperatures at various depths were calculated for the selected six locations (Tab. 3). The lowest is correlation coefficient (0.07) for winter in Šmartno between air temperature and soil temperature at a depth of 100 cm. The highest is correlation coefficient (0.96) for autumn in Lesce (2 cm) and Ljubljana (2 and 5 cm). The highest coefficient (0.95) for spring is in Bilje (2, 5 and 10 cm), Lesce and Ljubljana (2 and 5 cm), Maribor and Šmartno (2 cm), for summer (0.94) in Ljubljana (5 cm), and for winter (0.89) in Bilje (2 cm).
Trends in seasonal air temperature and soil temperature at various depths in the period 1986–2015 are in majority statistically significant (Fig. 3). Exceptions are trends of winter air temperature at all locations and spring air temperature in Šmartno, trends of winter soil temperature at a depth of 5 cm in Bilje and Novo mesto, at a depth of 10 and 30 cm in Bilje, at a depth of 100 cm in Lesce, Ljubljana in Šmartno, and trends of summer soil temperature at a depth of 30 cm in Lesce and at a depth of 100 cm in Novo mesto.
In addition to less significant changes detected in winter, the magnitudes of significant trends are also lower, from 0.33 °C per decade in Maribor at a depth of 100 cm to 0.78 °C per decade in Novo mesto also at 100 cm. All autumn trends are significant, ranging from 0.32 °C per decade in Maribor at a depth of 30 cm to 0.98 °C per decade in Šmartno at 5 cm. In spring soil temperature increase was significant in all cases with the greatest warming in Lesce at a depth of 5 cm, at a rate of 1.31 °C per decade, and the smallest was observed in Ljubljana at 100 cm, at a rate of 0.44 °C per decade. Summer significant trend magnitudes were a little lower, between 0.42 °C per decade in Novo mesto at a depth of 30 cm and 1.1 °C per decade in Šmartno at 10 cm.

Location	Tmin 2 cm [°C]	Tmin 20 cm [°C]	Tmax 2 cm [°C]	Tmax 20 cm [°C]
Bilje	−6.4	−1.9	41.2	35.0
Lesce	−11.7	−4.1	43.0	28.1
Ljubljana	−11.5	−4.7	47.0	30.6
Maribor	−9.1	−2.5	43.7	31.6
Novo mesto	−7.2	−2.4	41.1	29.7
Šmartno	−13.5	−4.9	43.9	27.4

Tab. 2 - Absolute minimum and maximum soil temperatures at 2 and 20 cm depths in the period 1986–2015 for 6 meteorological stations.
Tab. 2 - Temperature assolute minime e massime del suolo a 2 e 20 cm di profondità nel periodo 1986-2015 per 6 stazioni meteorologiche.

BI	Spring	Summer	Autumn	Winter
2 cm	0.95	0.92	0.95	0.89
5 cm	0.95	0.92	0.95	0.87
10 cm	0.95	0.92	0.94	0.85
20 cm	0.93	0.89	0.93	0.80
30 cm	0.92	0.85	0.91	0.74
50 cm	0.89	0.74	0.86	0.60
100 cm	0.85	0.55	0.82	0.35

LE	Spring	Summer	Autumn	Winter
2 cm	0.95	0.91	0.96	0.80
5 cm	0.95	0.90	0.95	0.77
10 cm	0.94	0.89	0.94	0.70
20 cm	0.91	0.82	0.92	0.59
30 cm	0.89	0.73	0.89	0.51
50 cm	0.86	0.63	0.86	0.37
100 cm	0.80	0.40	0.81	0.21

LJ	Spring	Summer	Autumn	Winter
2 cm	0.95	0.93	0.96	0.82
5 cm	0.95	0.94	0.96	0.79
10 cm	0.93	0.92	0.95	0.73
20 cm	0.90	0.86	0.92	0.62
30 cm	0.87	0.78	0.90	0.52
50 cm	0.83	0.61	0.86	0.36
100 cm	0.79	0.43	0.82	0.20

MB	Spring	Summer	Autumn	Winter
2 cm	0.95	0.92	0.95	0.78
5 cm	0.94	0.90	0.94	0.74
10 cm	0.93	0.88	0.93	0.69
20 cm	0.91	0.82	0.91	0.61
30 cm	0.88	0.76	0.89	0.54
50 cm	0.84	0.58	0.85	0.35
100 cm	0.79	0.37	0.80	0.17

NM	Spring	Summer	Autumn	Winter
2 cm	0.94	0.93	0.94	0.81
5 cm	0.94	0.93	0.94	0.79
10 cm	0.92	0.91	0.93	0.74
20 cm	0.89	0.84	0.90	0.65
30 cm	0.87	0.75	0.88	0.56
50 cm	0.82	0.57	0.83	0.37
100 cm	0.75	0.32	0.74	0.17

ŠM	Spring	Summer	Autumn	Winter
2 cm	0.95	0.89	0.95	0.73
5 cm	0.94	0.90	0.95	0.70
10 cm	0.92	0.86	0.93	0.62
20 cm	0.89	0.79	0.90	0.46
30 cm	0.86	0.68	0.88	0.34
50 cm	0.82	0.48	0.83	0.20
100 cm	0.77	0.28	0.76	0.07

Tab. 3 - Seasonal correlation coefficients between air temperature and soil temperature at various depths in the period 1986-2015 at six meteorological stations (BI-Bilje, LE-Lesce, LJ-Ljubljana, MB-Maribor, NM-Novo mesto, ŠM-Šmartno).
Tab. 3 - Coefficienti di correlazione stagionale tra temperatura dell'aria e temperatura del suolo a varie profondità nel periodo 1986-2015 per sei stazioni meteorologiche. (BI-Bilje, LE-Lesce, LJ-Ljubljana, MB-Maribor, NM-Novo mesto, ŠM-Šmartno).

3.3 Soils temperature regime and vulnerability to low and high temperatures

Calculations showed that all the soils in lowlands or hilly areas in Slovenia (no measurements for mountainous areas were available) classify as the mesic regime according to USDA taxonomy.

As there are too many missing data in the period 1971-2000 in Bilje, Šmartno and Lesce, and the stations have been moved during the observational period, only results for Ljubljana, Maribor, and Novo mesto are presented (Tab. 4). The threshold –5 °C was never reached at the depth of 20 cm and at the depth of 10 cm in Maribor and Novo mesto. The most vulnerable to low temperatures were soils in Ljubljana, followed by Maribor and then Novo mesto. With exception of 20 cm depth in Maribor, soils at all depth and locations were less vulnerable due to the threshold of 0 °C in the period 1986–2015 than in the previous period. On the other hand, it is interesting that soils were more or same vulnerable due to the threshold of –5 °C in the period 1986–2015, additional analysis would be needed to maybe assign the effect to fewer days with snow cover in this period. Also, the threshold of 45 °C was never reached at any depth, and the thresholds of 40 °C at 2 cm depth and 35 °C at 5 cm depth were only reached for less than 10 days in the hottest years of 2003, 2013 and 2015. In Ljubljana, soils in both evaluated periods were vulnerable to high temperatures due to the threshold of 30 °C at depths of 2 and 5 cm, due to the threshold of 25 °C at a depth of 20 cm and in the more recent period already also at a depth of 30 cm. In Maribor, soils were less vulnerable to high temperatures, but still in the first period due to the threshold of 30 °C at a depth of 2 cm, and in the second period like the soils in Ljubljana, although with lower percentages. The soils in Novo mesto were not vulnerable to high temperatures in the first period, however in the more recent two thresholds were exceeded: 30 °C at a depth of 2 cm and 25 °C at a depth of 20 cm.

4. DISCUSSION

From August to February soil temperatures were lower in the upper half of the soil and vice versa from March to July. The difference between warmer and cooler half of the soil profile was about 2 °C. The shift from warmer to cooler temperature happens about at a depth of 50 cm. Very similar monthly and yearly ranges were determined for soils in Croatia for the period 1981–2010 (Husnjak *et al.*, 2014). According to Sviličić *et al.* (2016), the highest measured soil temperatures in Croatia from 1951 to 2014 were higher than Slovenian absolute maximum at eight out of nine presented stations, reaching from 45.1 °C to even 57 °C, while the lowest of them was −14 °C, similar as in Slovenia. As it was observed before, the warmest soils were in Submediterranean region (Bilje), which was confirmed with absolute minimums and maximums at 2 and 20 cm depths. The only exception is the

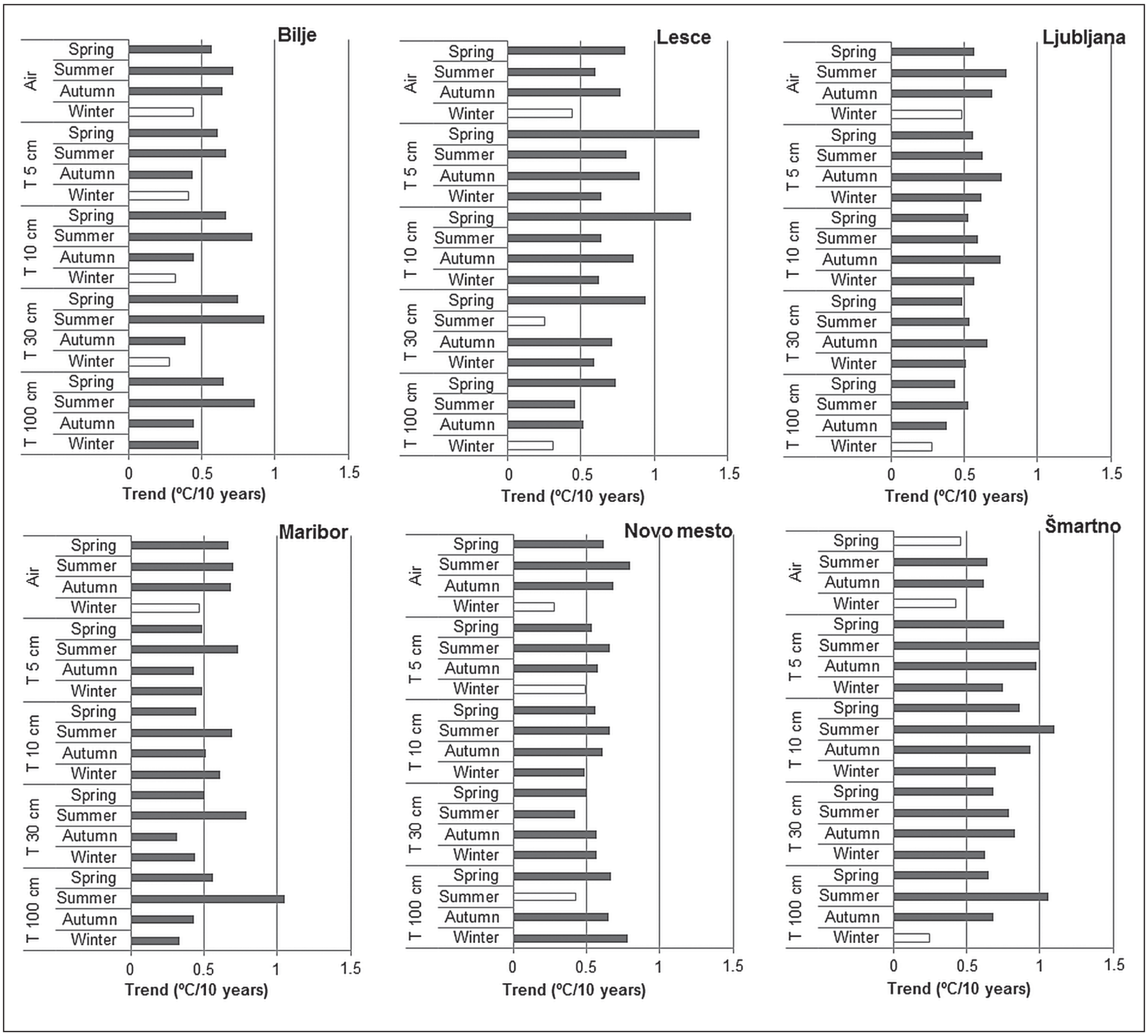

Fig. 3 - Magnitudes of trends of seasonal air temperature and soil temperature at various depths in the period 1986-2015 at six meteorological stations. Significant trends at 5% level are shown with the gray full column.

Fig. 3 - Trend stagionale della temperatura dell'aria e del suolo a varie profondità nel periodo 1986-2015 in sei stazioni meteorologiche. Le tendenze significative al livello del 5% sono mostrate con l'intera colonna grigia.

(a)

%		Threshold 0 °C				Threshold -5 °C			
		2 cm	5 cm	10 cm	20 cm	2 cm	5 cm	10 cm	20 cm
Ljubljana	1971–2000	100	83	80	50	27	7	3	0
	1986–2015	93	77	57	40	33	10	3	0
Maribor	1971–2000	93	93	77	40	10	0	0	0
	1986–2015	83	83	60	53	17	3	0	0
Novo mesto	1971–2000	77	77	50	23	3	3	0	0
	1986–2015	63	60	40	20	7	3	0	0

(b)

%		Threshold 35 °C		Threshold 30 °C			Threshold 25 °C	
		2 cm	5 cm	2 cm	5 cm	10 cm	20 cm	30 cm
Ljubljana	1971–2000	7	0	57	30	3	30	7
	1986–2015	10	0	80	63	13	60	23
Maribor	1971–2000	0	0	30	13	3	10	7
	1986–2015	10	0	50	33	3	47	33
Novo mesto	1971–2000	0	0	13	10	0	10	0
	1986–2015	0	0	47	17	0	30	7

Tab. 4 - Percentages of years in which the thresholds of critical soil temperature were reached: (a) threshold for minimum soil temperature, (b) thresholds for maximum soil temperatures. Fields where soil are determined as vulnerable (>20%) are colored in grey.

Tab. 4 - Percentuali di anni in cui sono state raggiunte le soglie della temperatura critica del suolo: (a) soglia per la temperatura minima del suolo, (b) soglie per la temperatura massima del suolo. I settori in cui il suolo è determinato come vulnerabile (> 20%) sono colorati in grigio.

absolute maximum at a depth of 2 cm, which is, surprisingly, almost the lowest in Bilje. This could be due to the rural area around the meteorological station in Bilje that is not exacerbating the summer accumulation of heat. In Croatia, in relation to the 2-cm depth values, at 20 cm depth absolute maximal soil temperature has decreased generally by about 20 °C along the coastline and eastern Croatia and by 10 °C in northwestern Croatia (Sviličić *et al.*, 2016), while in Slovenia the differences were somewhere in between, with already mentioned Bilje as an exception due to lower maximum at a depth of 2 cm.

Air temperatures are strongly correlated to upper soil temperatures, as it was expected due to the heat transport principles. Correlation coefficients are very high for spring and autumn at all depths, while the correlation is weaker for summer and winter, with coefficients very quickly decreasing by depth. Yesilirmak (2014) showed a clear effect of air temperature on soil temperature in Turkey based on the strong correlations between them, but particularly in summer.

Warming was observed at all depths in all seasons all over Slovenia. In practice, this implies increased soil water evaporation and drought threat throughout the year (Aquilera *et al.*, 2015). When the magnitudes of trends are averaged over all stations for each depth it is seen that the warming trend was the strongest in summer with average rates of increase of 0.75, 0.76, 0.62, and 0.73 °C per decade at depths of 5, 10, 30, and 100 cm, respectively. Very similar results obtained Yesilirmak (2014) for Turkey, with an exception of a lower trend at a depth of 100 cm. In terms of trends magnitudes, summer is followed by spring, autumn and winter, only at a depth of 30 cm was average spring trend stronger than summer trend. In Turkey (Yesilirmak, 2014), the weakest soil warming since the 1970s were detected in winter and spring and the highest in summer, as also in Croatia (Sviličić *et al.*, 2016). Average trend magnitudes of soil temperatures are very similar at depths of 5 and 10 cm and are comparable to average trends of air temperatures in summer and autumn. In spring and winter, average trend magnitudes of air temperature are weaker and more comparable to trend magnitudes of soil temperatures at depths of 30 and 100 cm.

Based on the measurements, soil temperature regime in Bilje, (Submediterranean climate) is shifting from mesic to the thermic regime: soil temperatures at a depth of 50 cm reflected thermic regime in years 2001, 2003, 2007, 2009 and from 2011 to 2015. For comparison, in Croatia were in the period 1981-2010 soils in seven sub-regions classified as mesic temperature regime and soils in two subregions as thermic. According to Grillakis *et al.* (2016), model simulations of three well-established global climate models, spanning from 1981 to 2120, show significant shifts in the soil temperature regime, especially in the northern hemisphere, with the mesic and thermic soils gaining large areas.

Warming of the soils is far more pronounced during summer high temperatures than during winter low temperatures. As expected from absolute maximum soil temperatures, soils in Croatia are mainly far more vulnerable to high temperatures than in Slovenia, while Slovenian soils are mainly more vulnerable to low temperatures or similar to northwestern part of Croatia in the period 1981-2010 (Sviličić *et al.*, 2016), which was the only comparable study made in the surrounding region. However, a study for Mediterranean region showed higher thermicity index, with higher temperatures in summer and autumn (Aguilera *et al.*, 2015), which can lead to heat stress and impact plant production (Lasram and Mechlia, 2015). Increased soil temperatures will have a direct impact on water demand and crop yield (Melkonyan, 2015) and further amplify susceptibility of crop production to weather extreme conditions. On one hand, increased soil temperatures shift spring temperature threshold, indicating potential longer vegetative period and earlier yield and subsequent secondary crop yield (Potopova *et al.*, 2017). However, in case of sudden temperature decrease, low air temperature would cause a substantial setback in plant growth and potential yield loss (Stehli *et al.*, 1999; Fekonja *et al.*, 2011).

4. CONCLUSIONS

The lowest annual soil temperature averages, which were observed at a depth of 2 cm, were in the period 1986-2015 for at least 1 °C higher than annual air temperatures. Values reached from around 10 or 11 °C in the Moderate climate of hilly region to 14.3 °C in the Submediterranean region. The highest average annual soil temperatures were measured at a depth of 50 or 100 cm. The highest measured soil temperature was 47 °C in Ljubljana and the lowest −13.5 °C in Šmartno, both at a depth of 2 cm. Air temperatures were in spring and autumn at all depths strongly correlated to soil temperatures, however, the correlation is weaker for summer and winter, with coefficients very quickly decreasing by depth.

This was the first evaluation of soil temperature with regard to agricultural production on a national level in Slovenia. Soil temperature was mainly increasing at a quicker pace than air temperature, with the majority of trends being statistically significant. Less significant were changes in winter and the magnitudes of significant trends were lower. Overall the warming trend was strongest in the summer, which is comparable to previous results for the neighboring region.

Soil temperature regime in the Submediterranean region was thermic instead of mesic in nine years after the year 2000, indicating the soil thermal regime is changing. Soils vulnerability to changing thresholds evaluation for the period 1986–2015 and 1971–2000 showed higher vulnerability to high temperatures and less to low temperatures, with an exception in the threshold of –5 °C. This implies that efficient water balance management of agricultural soils will become imperative for sustainable agricultural production.

The thermal regime of soils is affected by various climatic variables, in addition to air temperature, other variables, e.g. rainfall, snow cover, freezing and thawing, can influence soil temperature variability. Since soil temperature changes may affect many agricultural practices, additional studies of the variability and trends of long-term soil temperatures are necessary to understand the causes and consequences of changing climate.

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