Soil Temperature Strongly Increases: Evidences From Long-term Trends (1951 – 2018) in North-rhine Westphalia, Germany

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Abstract

Soil temperature (ST) is an important property of soils and driver of below ground biogeochemical processes. Global change is responsible that besides variable meteorological conditions, climate-driven shifts in ST are observed throughout the world. In this study, we examined long-term records in ST by a trend decomposition procedure from eleven stations in Western Germany starting from earliest in 1951 until 2018. Concomitantly to ST data from multiple depths (5, 10, 20, 50, and 100 cm), new snow cover (NSC), sunshine duration (SD), cloud cover (CC) and precipitation (PP) were measured and included in the multivariate statistical analysis to explain spatiotemporal trends in soil warming. A significant positive increase in temperature was more pronounced for ST (1.76 ± 0.59 °C) compared with AT (1.35 ± 0.35 °C) among all study sites. The impact of meteorological variables on trends in soil warming decreased in the order AT < PP < NSC < CD < SD. On average, soil temperatures increased by 0.29 ± 0.21 °C per decade and the trend accelerated from 1990 onwards. Especially the summer months (June to August) contributed most to the soil warming effect. Trends of ST were found up to +2.3 °C in 100 cm depth and are critical in many ways for ecosystem behavior, e.g., by enhanced mineral weathering or organic carbon decomposition rates. Spatiotemporal patterns of soil warming are embedded in a complex interplay of meteorological parameters and needs to be evaluated by trend decomposition procedures under a changing climate.

1 Introduction

The spatiotemporal distribution of soil temperature (ST) is inevitable affected by increased air temperature (AT) but in contrast, its trend due to climate change have been less widely propagated. Obviously, one reason is that unlike AT, humans do not feel the direct consequence of a warming soil. However, virtually all biogeochemical processes are directly dependent on the ST and therefore trends are of utmost importance to delineate. For instance, increased ST will enhance (i) metabolic activity of microorganisms, (ii) decomposition of soil organic matter and the supply of released nutrients for plant growth, and (iii) mineral weathering by enhanced feldspar dissolution, among other minerals (Schlesinger and Emily, 2013; Williams et al., 2010). All these processes are embedded within a changing climate with either a positive or negative feedback. Air temperatures constantly increased since 1850 and the "period from 1983 to 2012 was *likely* the warmest 30-year period of the last 1400 years in the Northern Hemisphere" (IPCC, 2014). Not surprisingly, a recent study highlighted a substantial increase in surface ST (0.47°C/decade; 0 cm depth) and deep ST (0.36°C/decade; 40 to 320 cm) in the Tibetan plateau (Fang et al., 2019). In addition to the Tibetan high altitude region, climate change has also been linked to soil warming in other parts of the world, such as Canada (Qian et al., 2011), the United States (Bradford et al., 2019), and Sweden (Mellander et al., 2007). In order to assess the vulnerability of soil warming under the aspect of climate change it is desirable to address three important aspects: (i) an altitude gradient should incorporate settings in lower terrain compared with mountainous terrain, (ii) long-term records (≥ 30 years) of ST must integrate a high vertical spatial distribution to differentiate between topsoil and subsoil layers, and (iii) the meteorological data set should include as many as possible parameters.

In most studies, AT is the master variable to explain the variability in ST, although other climate parameters regulate soil temperature as well. For instance, the sunshine duration shows a general upward trend within the last 40 years in Europe, which agrees well with rising AT in this period (European State of the Climate, 2019). Cloud cover acts as an antagonist because the presence of clouds can cut out 70 to 80% of the incident radiation and has a profound impact too (Saha, 2008), whilst being present during the night the long-wave radiation is reflected and potentially warm up the temperatures on Earth.

Soil temperature is a sensitive indicator of climate change and to delineate its trend is of highest importance. The overarching goal of this study was to (i) assess spatiotemporal trends in ST for the federal state North-Rhine

Westphalia and (ii) discuss the relationship with meteorological parameters. To achieve our goals, we employed long-term records of ST ranging from 1951 up to 2018 at high vertical resolution in 5, 10, 20, 50, and 100 cm soil depth. Another unique feature of our study is that we considered new snow cover (NSC), sunshine duration (SD), and cloudiness degree (CD), besides AT and precipitation (PP) as meteorological parameters.

2 Material And Methods

2.1 Study sites

The study sites belong to the federal state North-Rhine Westphalia located in western Germany. It encompasses low-altitude plains of the Lower Rhine region up to mountainous terrain of the Central Uplands. A temperate climate prevails and the average AT depends on the altitude between 5 and 11°C and a mean precipitation of 920 mm for the climate period from 1979 to 2008 (LANUV, 2010). Criteria to investigate long term trend in ST were (i) a consecutive operation record for ~ 30 years, (ii) no long operational failures with < 5% missing data, (iii) stations which simultaneously measured meteorological parameters, and finally (iv) comprised a low- to high-altitude gradient (Table 1). From 39 observation stations in the federal district of North-Rhine-Westphalia, eleven of these met the prescribed features. Altitudes ranged from 37 up to 839 m asl, with spans from 25 up to 60 years of ST data. The monitoring for the study sites Herford and Aachen ended in 2007 and 2010, respectively. The stations are with the exception of Aachen and Münster-Osnabrück in rural areas, thus, a heat-island effect is of minor importance. Maintenance of the stations was done by the German Weather Service.

2.2 Data collection

The data was downloaded from a public-available portal hosted by the German Weather Service (DWD Climate Data Center (CDC), 2020). Only data that has been version-controlled and audited by end of the investigation period (December 2018) from the federal agency, e.g. due to changes of the measurement principle, was employed for the trend analysis. Meteorological data included the AT (°C), SD (h), CD (okta) and PP (mm). Soil temperatures were measured in 5, 10, 20, 50, and 100 cm soil depth. Whereas the temperature was conventional measured in the 1950s, platinum resistance thermometer (PT100) enabled hourly measurements from 1990 onwards, which is true for most of the stations. The raw data comprised $22 \bullet 10^6$ observations that were aggregated, when needed, to monthly or yearly averages or sums. All analysis including data manipulation, calculation and visualization were carried out in *Rstudio* (version 1.4.1103) (RStudio Team, 2021).

2.3 Trend analysis

Long-term trends were evaluated by applying the “Seasonal-Trend decomposition procedure based on Loess (STL)” (Cleveland et al., 1990). The STL algorithm enables to decompose a time series into a trend, seasonal and residual component by using a locally weighted regression (LOESS) technique. The method is robust to outliers so occasional unusual observations have no effect on the trend component. Since the trend in ST was the focus of our study we utilized a high t.window value, a “periodic” s.window and subsequent default arguments in order to delineate and smoothen the trend. Subsequent to the trend extraction, a linear fit ($f(x) = mx + b$) was applied on the trend to assess whether the parameter increased or decreased during the course of the investigation period. To determine if the trend is statistically significant, we employed the seasonal adjusted Mann-Kendall trend test, which is a non-parametric test (Hirsch and Slack, 1984). Our assumption is that a p value < 0.05 is statistically significant for the evidence of a trend in the data.

2.4 Statistical analysis

RStudio 1.4.1103 was used to compile the statistical results of the trend analysis (RStudio Team, 2021). To reduce the dimensionality of the data set with interrelated variables we employed a principle component analysis (PCA) using the FactoMineR package. The data was scaled to unit variance prior to the analysis. In addition, testing for differences between ST increase and soil depth we employed a one-way ANOVA following Tukey's test to compute pairwise differences of the mean. Spearman rank correlation coefficients were calculated and we considered variables being significantly correlated with a p value < 0.05.

3 Results And Discussion

3.1 Spatiotemporal trends of soil warming

The study sites were equally well distributed along the federal state North-Rhine Westphalia (Fig. 1) and the topography has a striking effect on the climatic conditions (Table 1, Fig. S1). For instance, the station Düsseldorf with the lowest altitude featured the highest AT, ST, SD, whereas NSC, CD, and PP were lowest (Fig. 2). At site Kahler Asten with the highest altitude, these climatic variables were inversely distributed (Table 1, Fig. 2). Generally, a statistically significant increase in AT was observed amongst all stations that was accompanied by an increase in ST throughout all depths (Fig. 2A and B). The only exception is the 5 and 10 cm depth for the study site Herford (Fig. 3A). On average, ST increased by 1.02°C in Münster-Osnabrück up to 2.23°C in Lippstadt-Bökenförde with on average 1.76°C (Fig. 3B). The trend is partially decoupled from the increase in AT (Fig. 3B). Interestingly, the strongest increase was found in the 20 cm depth with 1.87°C but this is not significantly different compared with the other depths (Fig. 3C). This indicates that trends in soil warming affect the complete soil profile and should not be isolated portrayed, e.g., with an emphasis on the topsoil. Among all study sites, the increase accelerated from 1985 onwards experiencing a shift towards higher soil temperatures, respectively (Fig. 4A to C). Thereby, each decade was warmer than the previous with a decadal increase up to 0.56 ± 0.28°C for the decade from 1991–2000 (Fig. 4A, Fig. S2B). Especially the last decade from 2011 to 2018 deviated from the long-term average (Fig. 4D), whereby the summer season contributed most to the overall increase in soil temperatures (Fig. 4E).

3.2 Relationship with meteorological parameters

Obviously, the multifactorial complexity of soil warming cannot be explained solely by AT since, e.g., the NSC determines the temperature of the soil as well (Shreve, 1924). Snow cover certainly alters the energy budget of a soil due to its low thermal conductivity and high albedo (Zhang et al., 2008). Thus, the site Kahler Asten is particularly vulnerable to contribute to an overall trend in soil warming in the future, because the NSC decreased over time (Fig. 2, Fig. S3C and D). Soil temperatures may increase by several degrees due to changes in the duration the snow cover prevails (Zhang, 2005). In addition, the relationship between CD and SD is strong and generally shows a codependence (Matuszko, 2012). This is true on a daily basis but on the long-term, only the station Herford showed evidence that an increased trend in SD goes along with a concomitant decrease in CD (Fig. 2D and E). Finally, three of the eleven study sites revealed a decreasing trend in PP (Fig. 2F). This has implications for the study sites Kahler Asten and Lippstadt-Bökenförde, where soil moisture content is solely controlled by PP contrary to the groundwater influenced site Münster-Osnabrück (Table 1). If a study site becomes drier, e.g. due to shifts in PP and/or increased evapotranspiration rates, the heat transfer is strongly affected. Air-filled pores have a lower heat capacity than water-filled ones and favor a more rapid rise in temperature within the entire soil profile (Blume et al., 2016). At the same time, the heat transfer of a dry soil is limited and therefore, a topsoil might be disproportional more severe affected than the subsoil by warming. However, we do not have any evidence for this assumption at present (Fig. 3C).

In order to reveal the influence of climatic factors (AT, SD, NSC, and CD) on soil temperatures, a principal component analysis was conducted. About 90% of variation in the data could be explained by PC1 and PC2 (Fig. 5A). Air temperature and SD were positively correlated with ST but contrary to AT, SD had only a minor impact to the variation in the data (Fig. 5A). Precipitation, NSC and CD were negatively correlated with soil temperature (Fig. 5B) and contributed to the variation in descending order, respectively (Fig. 5A). The strongest influencing factor – PP – has a direct impact on soil moisture feedback mechanisms and a decrease plays a more important role in influencing ST than AT, especially during summer months (Zhang et al., 2001). Even though a decreasing trend in PP was only observed at three out of eleven stations (Fig. 2F), PP must be critically portrayed in the future.

3.3 Subsoil warming and implications for biogeochemical processes

Subsoil harbor an important reservoir of soil organic carbon (SOC) with turnover times of centuries to millennia. In this context it is even more serious that subsoil warming alters the stability of SOC and enhances decompositions rates due to associated shifts in the functional gene structure of microbial communities, as recently shown by artificial subsoil warming of ~ 2°C in 25 cm depth over a 10-year period (Cheng et al., 2017). Obviously, soil warming not only accelerates the decomposition of old SOC pools in subsoil, but also highlights the vulnerability of years-to-decades old SOC in topsoil, which accounts for the largest fraction of total SOC in terrestrial soils globally (Hopkins et al., 2012). We found a strong evidence of subsoil warming > 2°C in 100 cm soil depth at six out of eleven stations throughout the study area (Fig. 1). This is also reflected in an increase of phenological days > 5°C by 25 days in 100 cm soil depth on average (Fig. S4E). Soil warming not only influences the persistence of SOC as an ecosystem property (Schmidt et al., 2011), it contributes significantly to mineral weathering and ecosystem nutrition in general. In 2019, up to 25% of the land use in North-Rhine Westphalia constitutes forest and 47% is used agriculturally (LANUV, 2021). The productivity of forest ecosystems is reliant by efficient reutilization of organic-bound nutrients derived from litterfall, but it was highlighted recently that nutrient uptake from saprolite weathering constitutes an important geogenic nutrient pathway as well (Uhlig et al., 2020). Links to soil warming can also be established to mineral weathering by alteration of mineral reactivity and nutrient availability (Doetterl et al., 2018). Soil temperature was reported to be the main driver of silicate weathering rates compared with pCO_2 levels and organic acids (Brady and Carroll, 1994; Gwiazda and Broecker, 1994). Projected future increases in ST up to 5°C for the period from 2070–99 in forested sites of Quebec can be seen as a harbinger of what we have to expect with the associated impacts on biogeochemical cycles (Houle et al., 2012).

Table 1 Relevant information about the study sites where soil temperature monitoring was conducted. The sites were sorted according to their topographic position from low to high altitude.

Study site	Area type	Monitoring period			Altitude	Soil type [a]	Textural class	PAW (L m^{-3}) [d]
		From	To	Years	(m asl)			
Düsseldorf	RA [c]	1986	2018	33	37	Gley-Parabraunerde	sandy loam	166
Münster-Osnabrück	UA [b]	1990	2018	29	48	Gley	loamy sand	106
Herford	RA	1951	2007	57	77	Gley	silt loam	115
Köln-Bonn	RA	1961	2018	58	92	Podsol-Braunerde	sand	81
Lippstadt-Bökenförde	RA	1981	2018	38	92	Parabraunerde	silt	237
Bad-Salzuflen	RA	1981	2018	38	135	Pseudogley-Braunerde	silty clay loam	161
Essen-Bredeney	RA	1951	2017	67	150	Parabraunerde	silt	237
Bad-Lippspringe	RA	1981	2018	38	157	Braunerde	loamy sand	103
Aachen	UA	1951	2010	60	202	Regosol	loamy sand	112
Lüdenscheid	RA	1994	2018	25	387	Braunerde	silty clay loam	115
Kahler Asten	RA	1981	2018	38	839	Ranker-Braunerde	silty clay loam	39

[a] soil type and textural class were determined according to German classification (AG Boden, 2005)

[b] urban agglomeration

[c] rural area

[d] plant available water

Conclusions

Long-term ST trend data in North Rhine-Westphalia revealed a significant increase over the last decades with on average 0.29 ± 0.21 °C per decade. The summer months contributed most to the overall soil warming effect which is also indicated by enhanced maximum ST throughout the investigation period being responsible for shifts in the thermal regime of the soils. Subsoil warming in 100 cm depth up to 2.3 °C is an important observation and needs to be included with emphasize on soil organic carbon dynamics and under the aspect of mineral weathering rates and nutrition supply for plants. Small changes of ST already impact belowground biological processes such as priming and this could have a significant impact on forested and agricultural used ecosystems, as indicated by a successive extension of phenological days with temperatures > 5 °C. We expect a long-term impact by increasing ST that might be of relevance for scientific fields dealing with root phenotyping, greenhouse gas emission, nutrient fluxes and displacement of flora due to projected warmer soils. To decipher trends in soil warming temporally and spatially is important as a metric and should be linked to not only meteorological-dependent climate change observations.

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Figures

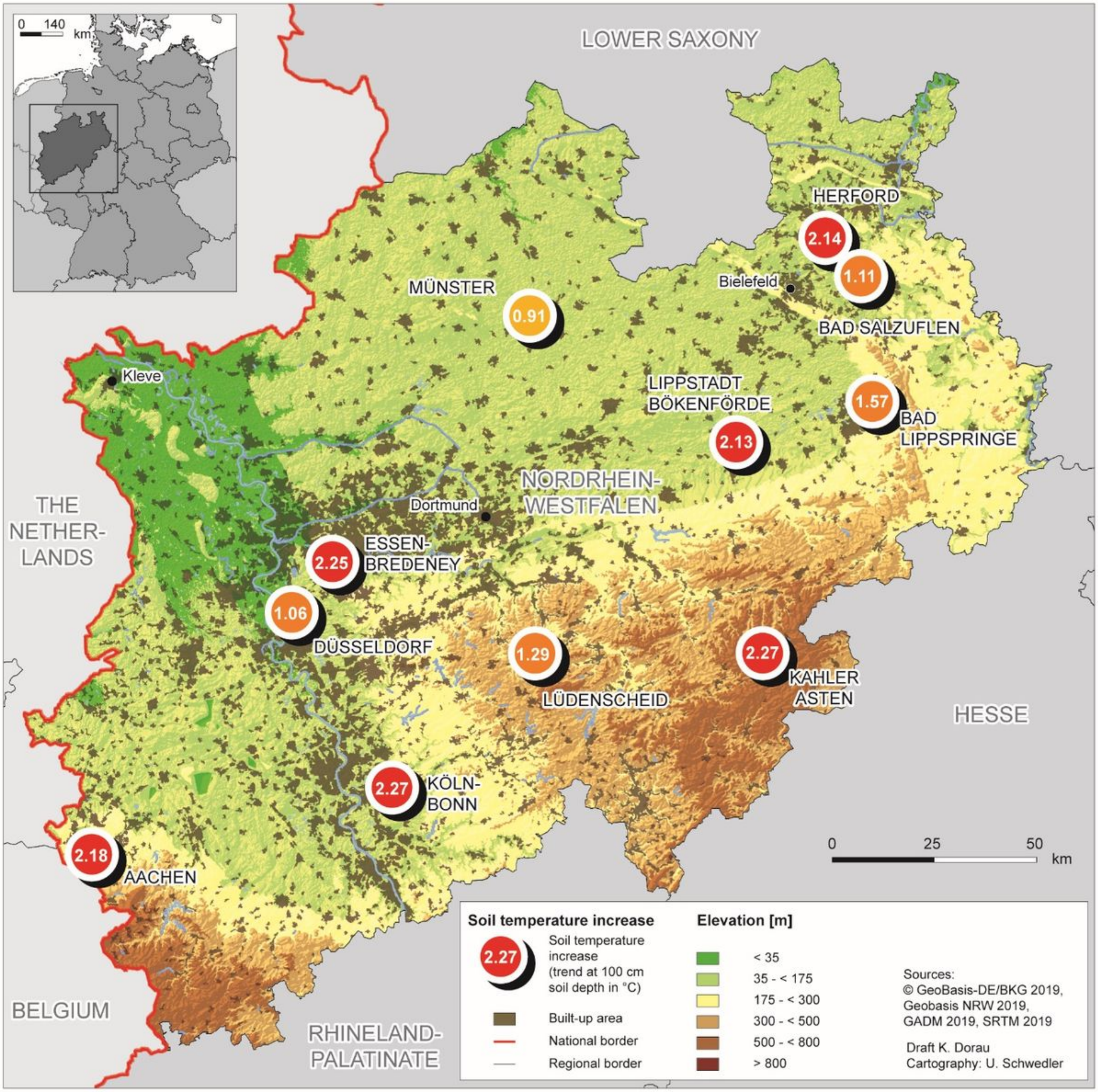


Figure 1

Location of the study sites in North-Rhine-Westphalia with temperature increase in 100 cm soil depth.

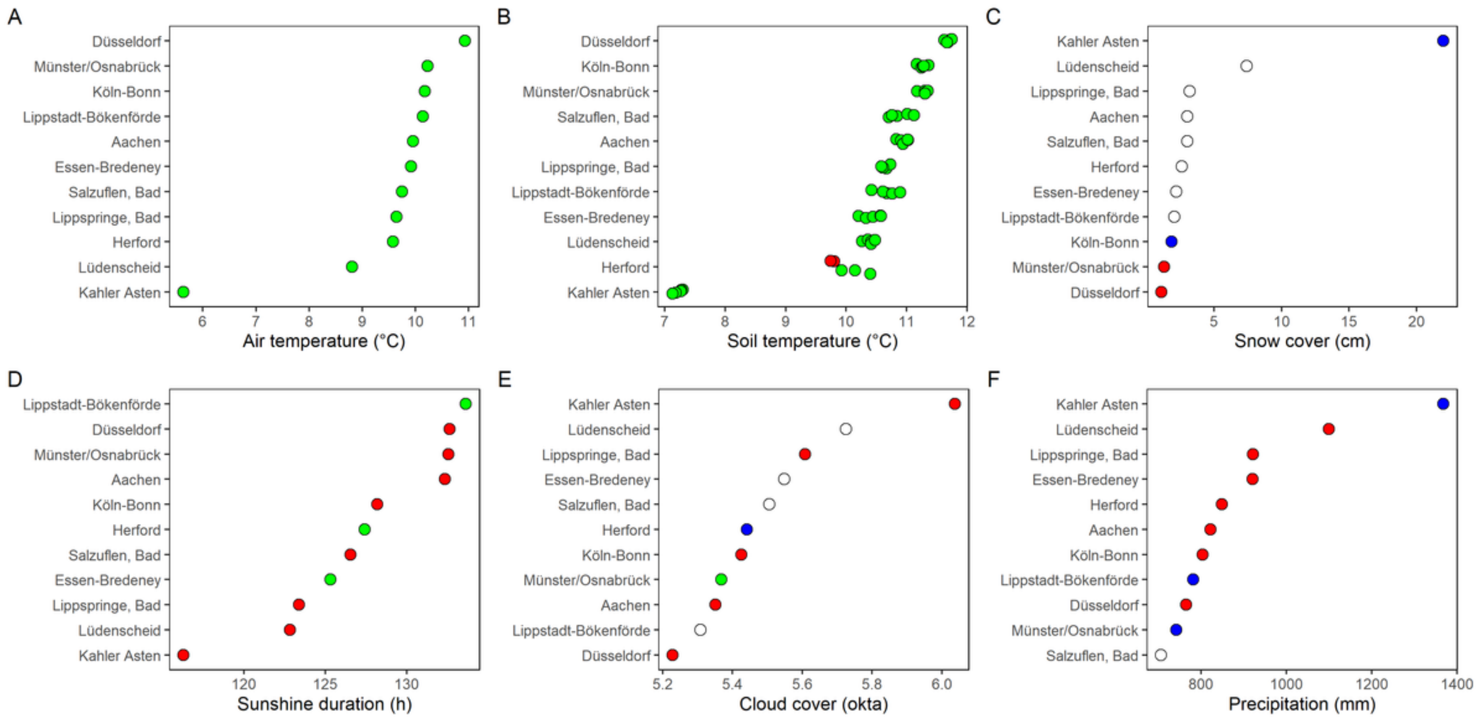


Figure 2

Summary statistics of air (A) and soil temperature across the depths from 5 to 100 cm (B), new snow cover (C), sunshine duration (D), cloud cover (E), and precipitation (F) for the study sites. The data accounts for the yearly mean for the total investigation period with green color indicating a statistically significant ($p < 0.05$) increasing and blue color decreasing trend according to the seasonal adjusted Mann-Kendall test. Red colors indicate no trend whereas a hollow circle indicates > 5% of missing data for a particular variable and, thus, this data was not further evaluated.

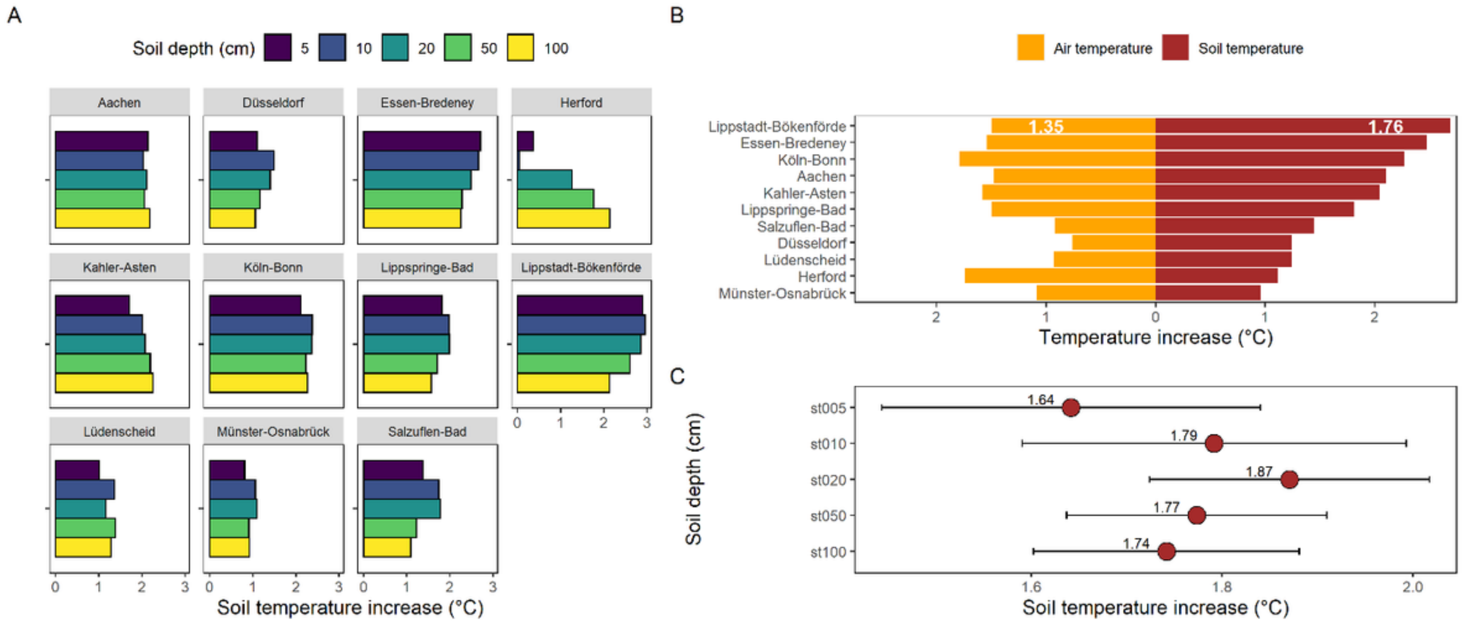


Figure 3

Increase in soil temperature per soil depth of the study sites derived from the trend analysis (A). The pyramid chart integrates air and averaged soil temperature sorted by decreasing soil temperature (B) with the depth-specific increase as mean and standard error of the mean among all study sites (C).

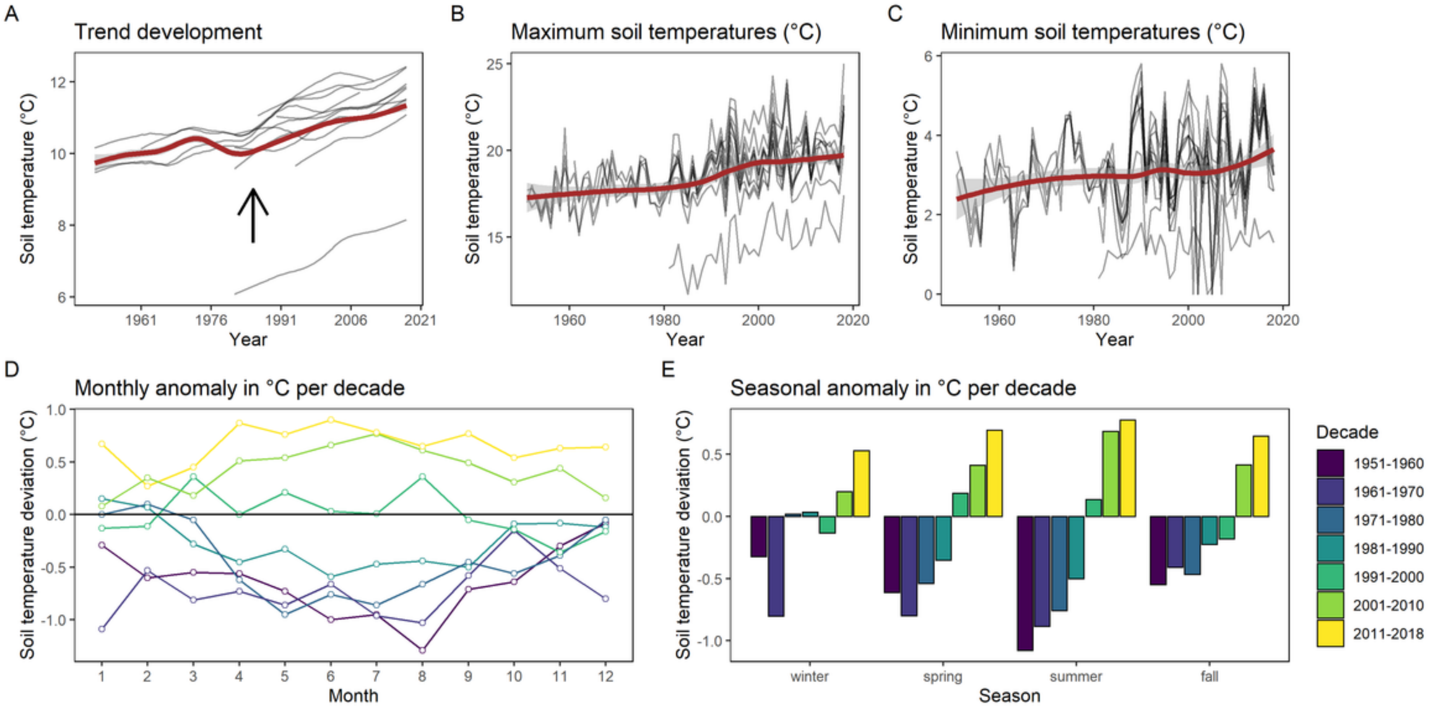
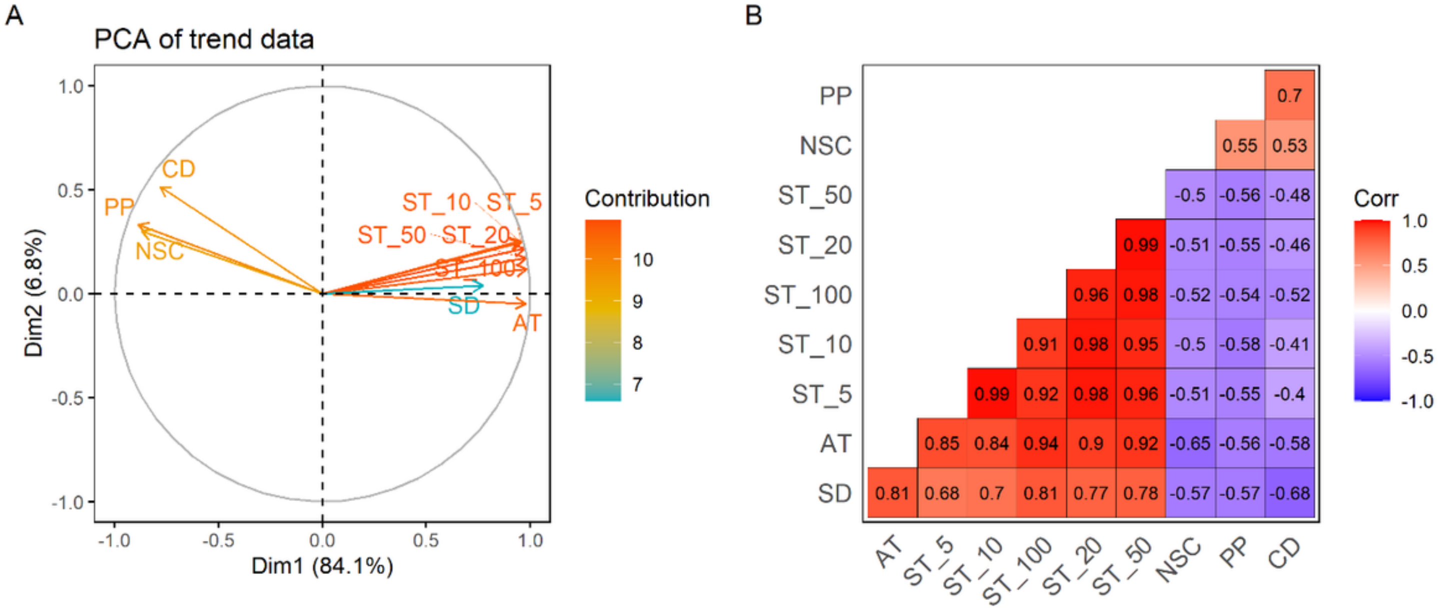


Figure 4

Development of the decomposed soil temperature trends across all study sites (brown line) throughout the investigation period (A) and for the maximum (B) and minimum (C) temperatures. The black arrow (A) indicates the steep increase of the trend from 1985 onwards. In addition, the monthly (D) and seasonal (E) anomalies from the long-term average are colorized by decadal groups starting from 1951.



	AT	ST_5	ST_10	ST_100	ST_20	ST_50	NSC	PP	CD
PP									0.7
NSC								0.55	0.53
ST_50							-0.5	-0.56	-0.48
ST_20						0.99	-0.51	-0.55	-0.46
ST_100					0.96	0.98	-0.52	-0.54	-0.52
ST_10				0.91	0.98	0.95	-0.5	-0.58	-0.41
ST_5			0.99	0.92	0.98	0.96	-0.51	-0.55	-0.4
AT		0.85	0.84	0.94	0.9	0.92	-0.65	-0.56	-0.58
SD	0.81	0.68	0.7	0.81	0.77	0.78	-0.57	-0.57	-0.68

Figure 5

Principal component analysis (PCA) of trend data from the study sites under investigation (A) and a correlogram with the spearman correlation coefficients (B).

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