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Evidences of soil warming 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), various meteorological variables 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 air temperature (AT; 1.35 ± 0.35 °C) among all study sites. Air temperature was the best explanatory variable to explain trends in soil warming by an average 0.29 ± 0.21 °C per decade and the trend peaked during the period from 1991–2000. Especially, the summer months (June to August) contributed most to the soil warming effect, whereby the increase in maximum ST (ST_{max}) was nearby fivefold with 4.89 °C compared with an increase of minimum ST (ST_{min}) of 1.02 °C. This widening between ST_{max} and ST_{min} fostered enhanced diurnal ST fluctuations at ten out of eleven stations. Subsoil warming up to + 2.3 °C in 100-cm depth is critical in many ways for ecosystem behavior, e.g., by enhanced mineral weathering or organic carbon decomposition rates. Thus, spatiotemporal patterns of soil warming need to be evaluated by trend decomposition procedures under a changing climate.

Keywords Soil temperature · Subsoil warming · Trend analysis

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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 has 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 USA (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 (SD) 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 2020). Cloudiness degree (CD) 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 influenced by new snow cover (NSC) and seasonal duration of snow cover as well (Sokratov and Barry 2002) and since dry soils heat more easily than wet ones, climate change related impact on precipitation (PP) and evapotranspiration modifies soil moisture and thereupon ST (Weil and Brady 2017).

Overall, ST is a sensitive indicator of climate change and to delineate its trend is of highest importance. The goals of this study were to (i) assess spatiotemporal trends in ST for the federal state North Rhine-Westphalia, (ii) discuss the impact by intrinsic, external, and meteorological variables on soil warming, and (iii) outline the possible consequences of soil warming on biogeochemical processes. 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 and further employed NSC, SD, and CD, besides AT and 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 the 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 analyses 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

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	Years	Altitude (m asl)	Soil type [a]	Textural class	PAW ($L\ m^{-3}$) [b]
Düsseldorf	RA[c]	1986–2018	33	37	Gley-Parabraunerde	Sandy loam	166
Münster-Osnabrück	UA[d]	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]plant available water

[c]rural area

[d]urban agglomeration

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 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 mean annual ST (Table 1, Fig. S1B and S1C). For instance, the station Düsseldorf with the lowest altitude featured the highest ST throughout all depths, whereas the site Kahler Asten with the highest altitude featured the lowest ST (Table 1, Fig. 2A). Virtually, among all stations and depths, a statistically significant increase in ST was evident with the only exception for the 5 and 10-cm depth for the study site Herford (Fig. 2A, Fig. S2). Interestingly, the increase was strongest in the 20-cm depth with 1.87 °C but this is not significantly different compared with the other depths (Fig. 2B). Thus, soil warming affected the complete soil profile and should not be isolated and portrayed, e.g., with an emphasis on the topsoil. This is different from observations by Subedi and Fullen (2009), who found that soil at 0-cm depth, warmed twice the rate of soil at 100-cm depth between 1982 and 2006. While in our study, the ST increase was on average 1.77 °C, maximum ST (ST_{max}) rose faster with 4.89 °C increase compared with the minimum ST (ST_{min}) trend of 1.02 °C (Fig. 2C). Even though Wang et al. (2018) explored only surface soil temperatures throughout China, they found the opposing trend that ST_{min} rose at a faster pace than ST_{max} after 1998. This finding suggests that differences between diurnal ST fluctuations (ΔST; $ST_{max} - ST_{min}$) decreased but actually none of this pattern was evident in our data. Whereas the ΔST was 4.11 ± 0.61 °C from 1951–1960 it rose towards 7.46 ± 0.88 °C from 2010–2017 for the study site Essen-Bredeney in the 5-cm depth (Fig. 2D). An increase in ΔST was evident among all stations, with the exception of the site Herford (Fig. S3). Obviously, enhanced diurnal fluctuations not only control water transport during day–night cycles but also have implications for various ecological processes. On a seasonal basis, the summer season from June to August of each year contributed most to an increase in ST and the last decade from 2010–2018 deviated most from the long-term average. Enhancement of soil warming during the summer season was also found for stations in Ireland (García-Suárez and Butler 2006) and Iran (Araghi et al. 2017). However, the setting is important since continental cool sites exhibited the largest warming during the spring months and settings featuring a melting season e.g., the Icelandic highlands, and warming was found throughout all seasons except

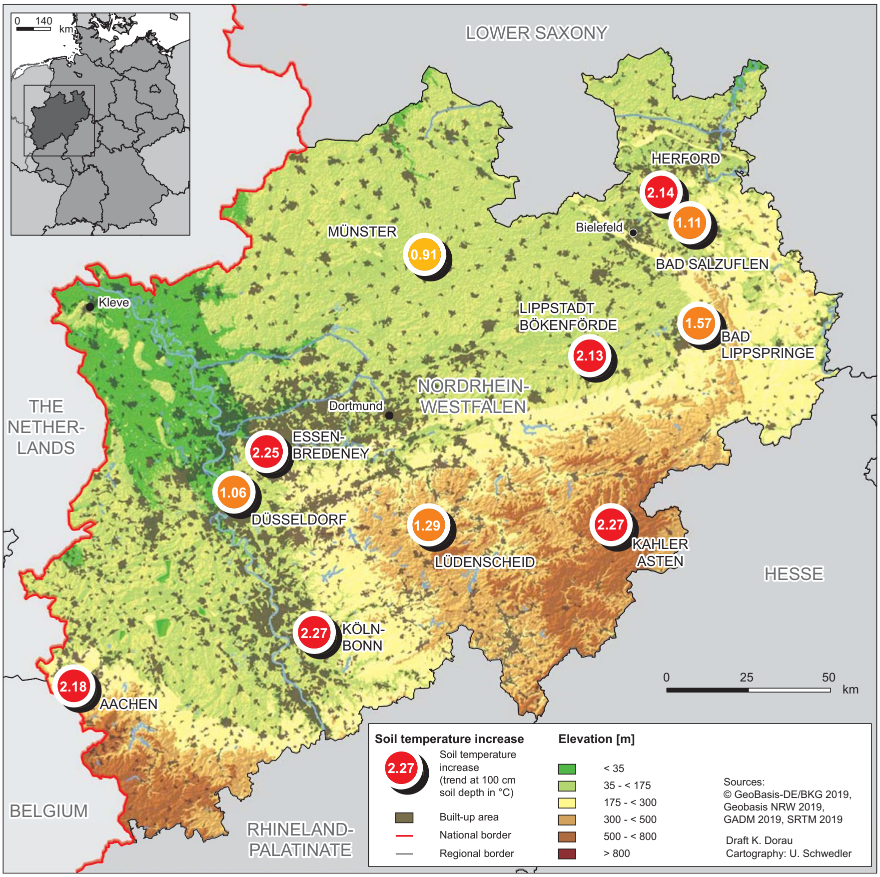

Fig. 1 Location of the study sites in North Rhine-Westphalia with temperature increase in 100-cm soil depth

the spring season from May to June (Petersen 2021). Among all study sites in the present study, the increase accelerated from 1985 onwards experiencing a shift towards higher ST, respectively (Fig. 2C). The decadal increase in ST was strongest from 1990–2000 with 0.56 ± 0.28 °C (Fig. 3A) but the long-term increase with 0.29 ± 0.21 °C per decade is below the values reported in literature from other regions of the northern Hemisphere (Fig. 3B).

3.2 Influencing factors on soil warming

Air temperatures significantly increased among all stations (Fig. 4B) and AT was the best explanatory variable to decipher trends in soil warming (Fig. 5A and B). However, the strongest increase in AT did not necessarily match with the strongest increase in ST (Fig. 5C), which highlights the multifactorial complexity of soil warming. Especially, snow depth and seasonal duration of snow depth are important factors (Chudinova et al. 2006). We verified a decrease in new snow depth at two out of eleven stations (Fig. 4D)

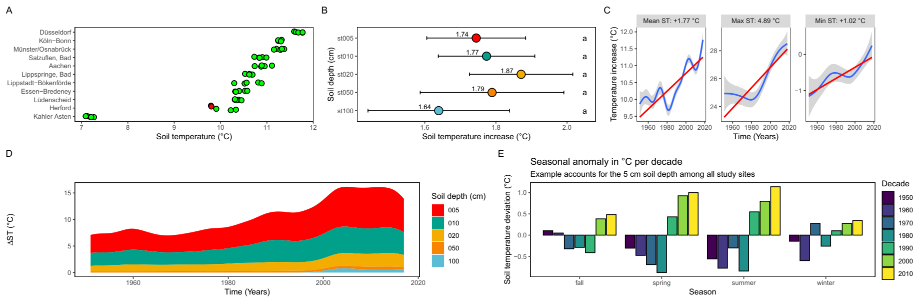

Fig. 2 **A** Summary statistics of soil temperature (ST) trends with the mean ST across the study sites with green colors indicating a statistically significant ($p<0.05$) increasing and red colors indicating no trend according to the seasonal adjusted Mann–Kendall test. The depth-specific increase in ST as mean and standard error of the mean among all study sites is shown in **B**. Panel **C** shows the decomposed trend line among all stations and depths (blue line) with the 95% confidence level (grey band) and the linear model (red line) differentiated for the average, maximum, and minimum ST. **D** The stronger increase in maximum ST than minimum ST favored an increase in ΔST over time (daily ST_{max} – daily ST_{min}) visualized as stacked area chart for the study site Essen-Bredeney. **E** Finally, seasonal anomalies from the long-term average are colorized by decadal groups starting from 1950

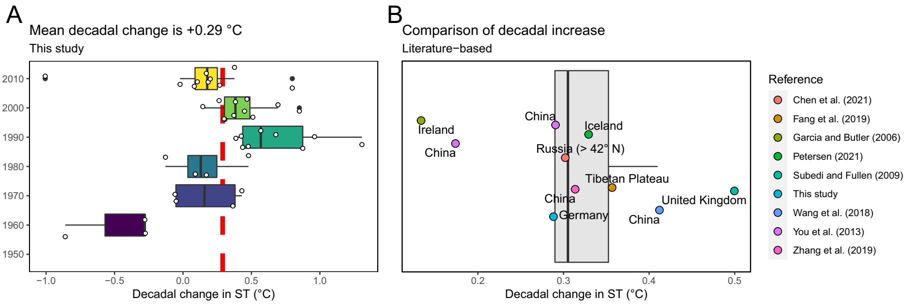

Fig. 3 Mean decadal change in soil temperature within this study (**A**) and comparison with literature-based data (**B**). Please note the different scaling of the *x*-axes. Sources: Chen et al. 2021; Fang et al. 2019; García-Suárez and Butler 2006; Guangyong et al. 2013; Petersen 2021; Subedi and Fullen 2009; Wang et al. 2018; Zhang et al. 2019

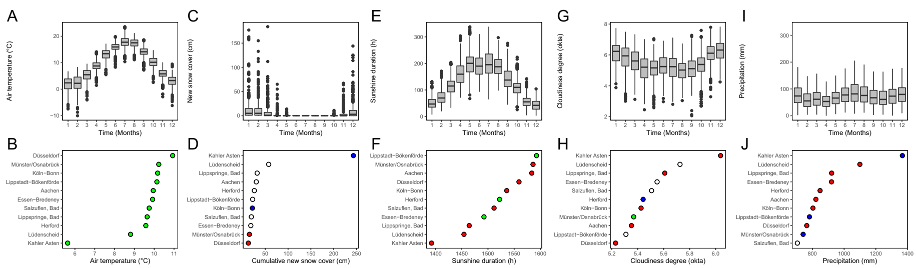

Fig. 4 Summary statistics of meteorological variables on a monthly basis among all study sites and for the overall mean for air temperature (**A** and **B**), new snow cover (**C** and **D**), sunshine duration (**E** and **F**), cloudiness degree (**G** and **H**), and precipitation (**I** and **J**). Green colors indicate a statistically significant ($p<0.05$) increasing trend over time, blue colors a decreasing trend, and red colors indicate no trend according to the seasonal adjusted Mann–Kendall test (**B**, **D**, **F**, **H**, **J**). Hollow circles indicate > 5% of missing data for a particular variable and, thus, this data was not further evaluated

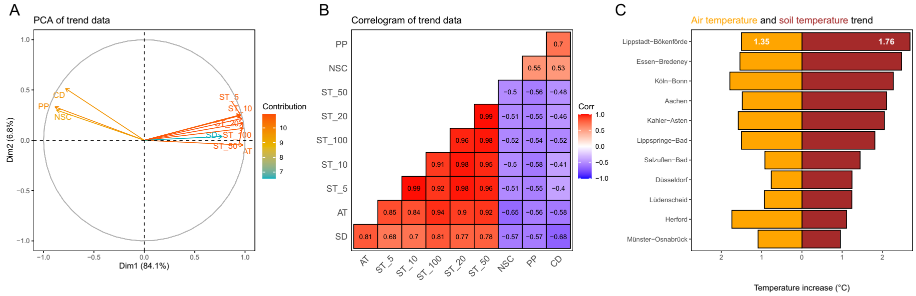

Fig. 5 Principal component analysis (PCA) of trend data from the study sites under investigation (**A**), a correlogram with the spearman correlation coefficients (**B**), and a pyramid chart that integrates air and the averaged soil temperature trend sorted by decreasing soil temperature (**C**)

whereby the months from May to October were virtually snow-free across the federal state (Fig. 4C). An early snow melt at the site Kahler Asten rendered the month April snow-free at present contrary to the early decades from 1980 to 1990 (Fig. S5I) and, thus, a shortening of the snow season is certainly a warming agent by increased solar absorption (Lawrence and Slater 2010). High-altitude sites such as Kahler Asten are particularly vulnerable to contribute to an overall trend in soil warming in the future, since snow cover alters the energy budget of a soil due to its low thermal conductivity and high albedo (Zhang et al. 2008). In addition, the relationship between SD and CD is strong (Fig. 5A and B) 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. 4F and H). Even though only a few stations revealed a significant trend in SD and CD for the federal state North Rhine-Westphalia at present, anomalies in cloudiness and record high sunshine hours derived by satellite observations since 1980s were evident for Europe (European State of the Climate 2020) and will likely contribute towards accelerated soil warming in conjunction with the rising AT. Despite the rising AT, careful consideration must be addressed to soil moisture feedback mechanisms (Zhang et al. 2001), which were the main reason that summer ST decreased by up to 4 °C due to changes in rainfall at Irkutsk under special circumstances (Zhang et al. 2001). Our findings that ST showed a stronger increase than AT (Fig. 5C) and that the summer season contributed most to the increase in soil warming (Fig. 2E) match with findings from a study in Ireland (García-Suárez and Butler 2006). They formulated that increased ST is not only a result of warming but also of drier conditions in summer. In our study, three out of eleven stations revealed a decrease in PP (Fig. 4J) that was most pronounced at the site Kahler Asten with a decrease of > 30 mm (Fig. S5E). Drier soils are more easily heated than wet soils due to changes in the heating capacity and if the soil is not affected by capillary rise from shallow groundwater — which is the case for Düsseldorf, Münster-Osnabrück, and Herford (Table 1) — these settings receive their soil moisture exclusively by PP. If a study site becomes drier, e.g., due to shifts in PP and/or increased evapotranspiration rates, the heat transfer is strongly affected. The soil texture modifies this behavior, which is a sandy substrate at Herford up to more fine-textured soils, e.g., at Kahler Asten (Table 1). However, we cannot disentangle any trends due to differences in soil texture from the given data set. Overall, the influence of meteorological variables on trends in ST decreased by AT < PP < NSC < CD < SD as indicated by the PCA, from which about 90% of variation in the data could be explained by PC1 and PC2 (Fig. 5A). Even if intrinsic and meteorological factors are incorporated in the evaluation of soil warming, external factors such as soil management, e.g., tillage systems, crop rotation, clear cutting, have a direct impact on the thermal properties of a soil and consequently on the response of soil warming in the future (Table 2).

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 decomposition 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 by an increase of phenological days > 5 °C by 25 days in 100-cm soil depth on average (Fig. S4E), which would potentially increase biomass production. 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 an 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 to 2099 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). The linkage between subsoil warming and some of the before mentioned biogeochemical processes can certainly be transferred to other regions on the world and is not specifically tailored for the study site under investigation.

4 Conclusions

Long-term ST trend data in North Rhine-Westphalia revealed a significant increase with an average 0.29 ± 0.21 °C per decade. Thereby, we identified important aspects that cover the following: First, soil warming affected the whole soil profile among the study sites. Second, soil warming in the summer months contributed most to the overall soil warming effect and trends in ST_{max} values exceeded ST_{min} values. Third, thereupon ΔST ($ST_{max} - ST_{min}$) rose across ten of eleven sites until now and this highlights that shifts in the thermal regime of the soils are taking place at rapid pace, e.g., intensification of diurnal temperature cycles. Finally, subsoil warming in 100-cm depth up to 2.3 °C is an important observation and needs to be included with emphasis on biogeochemical processes that cover soil organic carbon dynamics and mineral weathering rates modifying the nutrition supply for plants. A

Table 2 Intrinsic, external, and meteorological factors and how they contribute or mitigate to soil warming

	Factor	Impact on thermal properties[a]
Intrinsic	Soil texture	Sand absorbs heat from shortwave radiation very well but has a very low diffusivity with 3.75×10^{-7} m^2 s^{-1}
	Soil water content	Moist soils absorb much energy and soil water cools the soil during evaporation
	Albedo	Dark-colored surfaces absorb incident radiation very well compared with smooth, light-colored surfaces
	Compaction	Soil compaction enhances heat-transfer rates by extended particle-to-particle contact
External	Slope angle	Soil temperature is greatest when the incoming rays are perpendicular to the soil surface
	Soil cover	Bare soil, vegetation, mulch, or snow determines the amount of solar radiation reaching the soil
	Management	Tillage produces a loose surface with lower heat capacity compared with non-tilled soil
	Altitude	Elevation has a strong impact on the quantity and distribution patterns of rainfall and snow
Meteorological	Precipitation	Rain and irrigation water cools the soil in the summer but in spring warms surface soil within a short period
	Evapotranspiration	Reduces soil water content and dry soils are 3–6 °C warmer in the spring than poorly drained wet soils
	Snow depth	Reduction of snow depth and seasonal duration of snow cover (i) enhances soil warming due to increased solar absorption (ii) whereas a shallowing snowpack in the winter mitigates soil warming by attenuated insulating properties from cold air
	Cloudiness degree	Clouds attenuate downward longwave radiation at night while during day decrease incoming solar radiation
	Sunshine duration	Proxy for shortwave forcing at the Earth's surface and inversely related with cloudiness degree

[a]The information were summarized from Chesworth (2008), Lawrence and Slater (2010), Wang et al. (2018), andWeil and Brady (2017)

successive extension of phenological days with temperatures > 5 °C by 25 days could have a significant impact on forested and agricultural used ecosystems. 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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Data availability All data can be downloaded from a public-available portal hosted by the German Weather Service (https://cdc.dwd.de/portal/).

Materials availability Not applicable.

Code availability The R script will be made available upon request from the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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