Received: 26 January 2024 | Accepted: 1 July 2024
DOI: 10.1002/jpln.202400052

RESEARCH ARTICLE

Soil warming by electrical underground transmission lines impacts temporal dynamics of soil temperature and moisture

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This article has been edited by Horst Gerke.

Abstract

Background: The current transformation of the entire energy system leads to a large-scale expansion of extra-high-voltage underground transmission lines (UTL). Knowledge of the impact on soil temperature and soil moisture dynamics is fundamental for environmental evaluation.

Aims: We investigated the impact of an existing 320 kV underground cable in continuous operation on soil temperature and moisture dynamics.

Methods: A soil-monitoring programme was established at four study sites in Western Germany. Data were continuously recorded in soil up to 120 cm depth using soil sensors over a period of 1 year.

Results: Soil warming was in a range of 0.6 K in the topsoil, approx. 1–1.3 K in the rooting zone and 1.7 K in the subsoil at 120 cm depth and was restricted mainly to the immediate vicinity of the cable route. Likewise, the impact on soil moisture dynamics was on average in a range of −1.00 wt.-% in 0–60 cm depth and −2.45 wt. 2-% in the subsoil relative to control. Although at a calculated maximum load capacity of 100% in regular operation, soil warming might remain moderate, with 1.5 K in the topsoil, 2.3–3.1 K in the rooting zone and 4.1 K in the subsoil.

Conclusions: It is assumed that the reasons for the low-to-moderate influence of the UTL are to be found in the operational cable load (on average 65%), heat loss of cables (approx. 12 W m^{-1} per cable) and the quality of the imbedding material for the cables.

KEYWORDS
soil heat balance, soil moisture balance, soil warming, thermal capacity, thermal conduction, underground transmission lines

1 | INTRODUCTION

A new initiative of the European Council and the Parliament negotiators towards climate change mitigation envisages the share of renewable energy in the EU's overall energy consumption to 42.5% by 2030. Each member state will contribute to this common target (Council of the EU, 2023).

The energy transition from fossil fuel–generated power to more sustainable renewable energy brings about new requirements, among others, on the number as well as the performance of energy trans-

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mission lines, with extra-high-voltage transition lines >300 kV being of particular relevance for grid expansion. The energy industry in Germany is facing major challenges within the transition towards a climate-neutral energy system and a flourishing trade of electricity with other members of the EU. Beside the conventionally used overhead cables, underground electric transmission lines (UTLs) will ultimately play a vital role in the national power grid of Germany in the future. Hence, the EnLAG (2009) as the central instrument and its extensions, like the Federal Requirement Plan Act (2013), aim to enable the accelerated realisation of projects with high-voltage underground cables on the basis of research opportunities.

Related to that, electricity from renewable resources, for example wind power stations, will be increasingly and predominantly distributed by UTL in Germany, leading through soil typically in a depth of 1.8–2.0 m. In Germany, for example, it is expected that approx. 10,000 km of electricity grids will be installed until the year 2030 (Federal Ministry for Economic Affairs and Climate Action [FMEC], 2023), the majority as UTL.

During operation, UTLs emit heat into soil in relation to cable load, number, set-up and insulation of cables, the electric voltage of cables and soil properties being responsible for the thermal conductivity and thermal capacity of soil, such as, for example, soil texture, amount of soil organic matter, dry bulk density and soil moisture content and regime. As a result of the interaction of the above-mentioned soil properties, sandy soils, for example, will warm up more intensively than clayey soils. Furthermore, soils influenced by stagnant water or groundwater will heat up less than terrestrial soils without free moisture. According to Markert et al. (2016), differences in thermal conductivity of soils are small under low water contents but will increase at higher amounts in the order sand > loam > clay. On the other hand, peat soils show low thermal conductivity over a large range of water contents.

Naturally, under European climate conditions, soil temperature decreases with depth in line with respective temperature amplitudes. As such, soil temperature shows a strong diurnal, seasonal and vertical dynamic (Bachmann, 1997; Bonan, 2019).

Soil heat modifies several processes in soil directly and indirectly, which makes artificial soil warming a highly significant environmental impact factor. Solution and transformation reactions, especially nitrogen transformation, that is ammonification and nitrification, are temperature-dependent, and thus, soil warming may severely impact soil water and nutrient regimes. Moreover, soil temperature has a significant impact on plant growth, evapotranspiration and soil organisms. It has been shown that an increase in soil temperature of 10°C theoretically will promote growth and activity of soil microbes by factor 2 ($Q_{10} = 2$; van't Hoff's rule). On the opposite, soil faunal communities, for example soil macro-arthropods, are sensitive against high temperatures because of energy loss due to increased respiration activity at higher temperatures (Killham, 1994). According to results from Rykbost et al. (1975), soil warming resulted in higher yields of strawberries and spatula, whereas Patil et al. (2010) did not find any effect on grain yield and total biomass of winter wheat.

It is hypothesised that UTL operation will thereby lead to temperature anomalies within the soil profile in the way that soil temperature will increase from the topsoil to the subsoil. However, it is still an open question if this temperature anomaly occurs during the whole year or may be more profound in specific periods of the year (Guoju et al., 2012). Artificial soil warming and its effects have already been investigated in anthropogenic soils of waste or sewage sludge landfill sites, where organic matter decomposition led to heat emission into the cover soils in a range of 2–4°C (Blume, 2021).

Soil temperature and moisture are usually inversely related; however, as already mentioned, soil moisture content is significantly impacting heat dissipation in soil, and thus, moist soils will dissipate heat emission from UTL better than dry soils under the same boundary conditions (Blume et al., 2016). This may be traced back to the thermal conductivity of soil, which is strongly dependent on water content. This is caused by the high thermal capacity of water and by the increased number of contact points among the particles due to the water, leading to an easier transfer of heat between them. Thermal conductivity also depends strongly on soil depth, as the soil water content is commonly higher in deeper soil depths. On the opposite, soil warming due to heat emissions from UTL might as well impact soil water balance and water vapour dynamics (Bertermann et al., 2020). For example, heat emission may lead to water vapour effluent, which may condensate at some distance in areas of lower temperatures and may flow back to the heat source as liquid water (Wild, 2010). On the other hand, water vapour transport may also result in a drying out of warmer soil near the heat source and a wetting of cooler parts. It seems likely that a decrease in soil moisture due to soil warming during UTL operation may as well impact transformation processes in soil, nutrient supply, plant growth and the activity of soil organisms.

In this contribution, we present the results of a monitoring programme on the impact of operational soil warming of an existing high-voltage UTL on spatiotemporal gradients in soil temperature and moisture within the soil profile up to 120 cm in the immediate vicinity of the cable during one year from June 2022 to May 2023.

2 | MATERIALS AND METHODS

2.1 | Underground electric transmission line ALEGrO and study sites

Soil temperature and moisture monitoring were carried out at four different study sites along an existing UTL, acronym ALEGrO (Aachen–Liège Electrical Grid Overlay). ALEGrO was planned and implemented by Amprion Ltd, one of the four transmission system operators in Germany. It is part of the Federal Requirement Plan Act of Germany. In cooperation with the Belgian transmission system operator "Elia," the cable line acts as a power link between both countries from Oberzier (near Aachen, Germany) to Lixhe (near Liège, Belgium) over a distance of 90 km. It was constructed between 2018 and 2020, finalised and has been in operation since November 2020. Accord-

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ing to Amprion Ltd (2020), ALEGrO was constructed as a symmetrical monopole with a voltage of ±320 kilovolts (kV) and transmits power of up to 1000 megawatts (MW). It uses direct-current (DC) transmission technology, which reduces the loss of energy caused by flow direction changes that occur when using alternating current (AC) technology. Two converter stations, one at each end, are needed to feed in the transmitted DC energy into the local AC power grids and vice versa. The two DC high-voltage cables are placed inside plastic protection pipes with a diameter of 240–300 mm. One of the cables has a positive voltage, the other a negative voltage. Copper is used as the conductor material. The insulation consists of cross-linked polyethylene and a semi-conductive outer conductive layer. Above the insulation, there is a screen made of individual wires and a continuous metal sheath made of aluminium. The pipes are imbedded in a thermally optimised liquid floor, a temporarily pourable filling material, which is mixed with low admixtures of cement as a binding agent. The cement accounts for less than 2 Vol.-% of the mixture. The protection pipes are located 1.8 m below the soil surface, with the distance between them being 0.75 m. During the whole year of investigation, UTL cable load ranged from approx. 45% to 80%, with an average of 65%. A seasonal dynamic of the cable load was not recognisable. Heat loss is estimated in a range of 11.5–12.8 W m^{-1} for each cable based on a 75% cable load. For comparative purposes with other case studies, we additionally calculated a maximum (100%) permissible cable capacity.

2.2 | Soil temperature and moisture monitoring programme

For the monitoring programme, the soil was investigated orthogonally to the cable line at four different study sites near Aachen, Germany. Soil in a distance of 4.5–5.5 m without UTL impact was used as a control at each study site, respectively. Soil monitoring was carried out at the following four locations (UTM coordinates of the four study sites in brackets): Weisweiler (E 311276.7923, N 5634895.201), Dürwiss (E 309051.9734, N 5634461.858), Haaren (E 301011.0493, N 5631394.64) and Brand (E 300848.2264, N 5627809.112). The study area is characterised by a mild, oceanic climate. The MAT (mean annual temperature) in the period under investigation was approx. 11°C, and the mean annual precipitation was approx. 793 mm. The multi-year averages are 10.3°C and 867 mm (German Weather Service, climate station Aachen-Orsbach, station ID 15000).

Figure 1 illustrates how temperature and moisture monitoring were conducted at each study site. In total, eight soil temperature sensors (ST2 Thermistor, delta T devices) each in a distance of 0.75 m were inserted into soil in a depth of 20, 60, 90 and 120 cm, together with four soil moisture sensors (WET150, delta T devices) in a depth of 20, 60 and 120 cm. The control sites differed from UTL sites in the way that only four temperature sensors instead of eight have been installed in the respective soil depths (Figure 1).

At all sites, the deepest installed sensors, both temperature and moisture, were approx. 60 cm above the two cables within the cable lines. Sensor measurements were continuously recorded each in 60 min intervals and stored on a data logger (DL2e and YDOC; delta T devices). Soil moisture was measured in Vol.-% and conferred into weight per cent by using the dry bulk density of each soil depth as correctives.

2.3 | Soils

At three out of four study sites, soils were under arable land use, one soil was managed as grassland. The parent material of each soil is derived from air-blown silt (loess), and thus soils showed less variation in soil physical properties with the exception that the soil water regime of the grassland soil at location Brand differed markedly. Arable soils at the study sites Weisweiler, Dürwiss and Haaren were characterised as Luvisols (partly with stagnic properties), whereas the soil type at grassland study site Brand was a Gleysol in slope position. All in all, soil textures, soil pore distribution and bulk density showed only small differences among the four soils and between UTL cable lines and the control sites, respectively. Soil pH values of the arable soils ranged from 6.7 to 7.7 at Weisweiler and Dürwiss study sites, whereas the pH was lower in a range of 6.3–4.6 at Haaren study site. At the grassland site Brand, pH values varied especially vertically in soil from 6.4 to 7.3. Amounts of total organic carbon (TOC) showed a typical vertical gradient in soil and were comparable between sites and between UTL cable lines and the respective control sites (Table S1).

The relation between thermal conductivity and soil moisture content is mainly determined by the matrix potential. As a consequence, both thermal conductivity and thermal capacity of studied soils did not severely differ among the four study sites because of the largely similar parent materials and soil textures. For example, at pF 1.8 (field capacity), the calculated thermal conductivity W_{LFK} ranged from 1.59 to 1.95 W m^{-1} K^{-1} (20 cm depth) and 1.65–1.97 W m^{-1} K^{-1} (120 cm depth) in UTL and 1.59–1.97 W m^{-1} K^{-1} as well as 1.74–2.01 W m^{-1} K^{-1} in control sites, respectively. The differences in the calculated volumetric thermal capacity (C_v) among study sites, soil depths and treatments (UTL vs. control) were as well very low at the various soil moisture conditions, dry soil, field capacity and water saturation (Tables S2 and S3).

2.4 | Analytical methods

Representative soil samples were taken at each study site from each soil layer within the cable trench and the control. Methods for determining soil physical properties, such as soil texture, bulk density and pore size distribution, followed Hartge and Horn (1989). In brief, soil texture was determined with the sieve and sedimentation method, according to Köhn (1929). For the determination of the bulk density, soil sample rings were oven-dried at 105°C for 16 h. The pore volume as well as different pore size classes were measured on water-saturated samples placed on pressure plates at high

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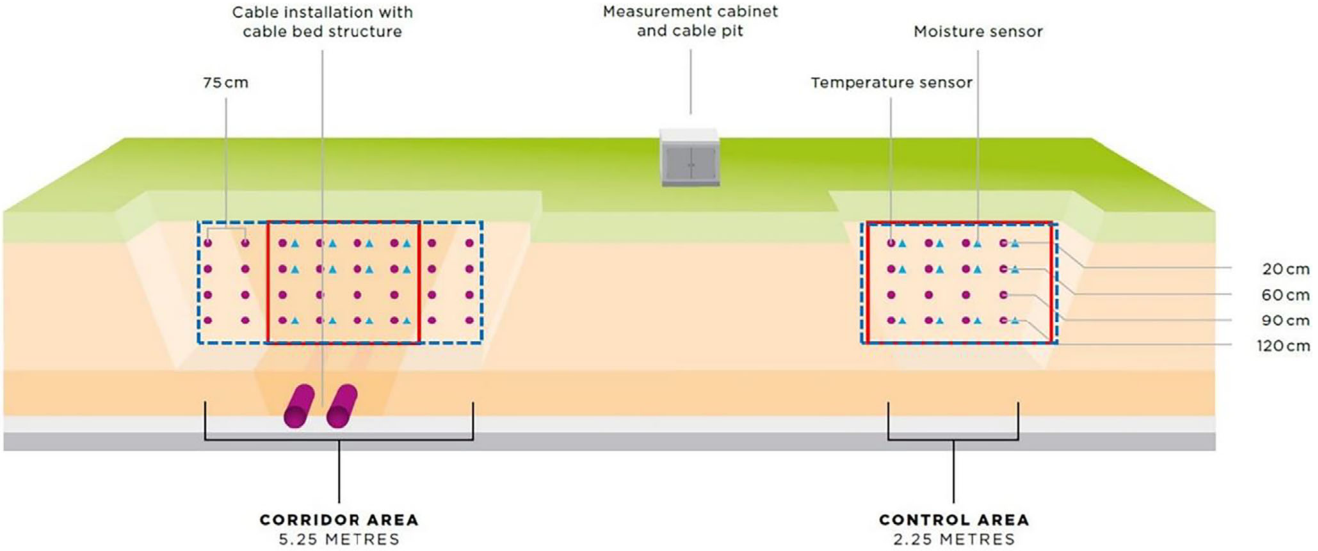

FIGURE 1 Cross-section illustration of soil temperature and moisture sensors (delta T devices) on the ALEGrO corridor at four (temperature) and three (moisture) soil depths. Note that sensors within the red mark were included in the statistical analyses, and those within the blue mark were considered for two-dimensional (2D) data presentations.

pressures of 60 hPa (pF 1.8), 300 hPa (pF 2.5) and 15,000 hPa (pF 4.2) in a pressure chamber, according to Richards and Fireman (1943).

Soil pH was determined using air-dried soil in a 0.01 M $CaCl_2$ solution. Samples were extracted in an end-to-end-shaker for 2 h. Measurement was done using a pH Cond 340i glass electrode (WTW Ltd). Amounts of total soil organic carbon (TOC) and total nitrogen (N_t) were quantified using an Elemental Analyser vario EL cube (Elementar Ltd).

2.5 | Statistical analysis

For the comparison of soil temperature and soil moisture dynamics of UTL and control sites, we calculated arithmetic means, standard deviation of means, median and the total range (min–max) for each study site and each soil depth. For the statistical comparison of soil temperature and soil moisture between UTL and control sites, a nonparametric Wilcoxon-test was used. For this analysis, only data from four soil temperature sensors above the cables (within the red-marked cable line trapeze in Figure 1) and all four soil moisture sensors have been considered.

For visualisation of the spatial (vertical, horizontal) expansion of soil temperature and soil moisture within the soil profile, we constructed two-dimensional (2D) illustrations. For these, all available sensor records were applied. Therefore, the arithmetic mean was calculated for each individual sensor from the hourly measured values of soil temperature and soil moisture for each month, which includes around 672–744 measured values, depending on the specific month. To visualise the spatial distribution of soil temperature and soil moisture, additional data were generated by linear interpolation between the sensor positions.

3 | RESULTS

For the comparison of spatiotemporal soil temperature and soil moisture dynamics, both in soils within the cable trenches and within the controls, and in order to envisage heat emission intensity and its spatial distribution as well as relations to soil moisture, 2D plots of sensor records have been conducted for a period of 1 year from June 1, 2022, to May 31, 2023, representing the seasonal variation under European climatic conditions (Figures 2 and 3).

3.1 | Spatiotemporal dynamics of soil temperature

Figure 2 illustrates the spatiotemporal temperature dynamics in the soil of the cable line and the control at the four soil depths by example of the representative study site Weisweiler during the year of investigation. The records from the ST2 sensors per depth have been pooled to a mean record per day and are presented as means per month each. The time course of the temperature differences between UTL and control for the various soil depths in the period from June 1, 2022, to May 31, 2023 for the representative study site Weisweiler can be found in Figure S1.

In early summer (i.e. June 2022), both soils of the cable line and the control showed homogenous high temperatures ranging from approx. 17 to 20°C from topsoil to subsoil. However, slightly increased temperatures above both cables within the cable line were also obvious (Figure 2). In the topsoil of the cable line, temperatures were as well slightly increased. This temperature profile lasted until August/September 2022. In autumn (i.e. October; Figure 2), the temperature regime was homogenous throughout the cable line and the control soils in the way that the temperatures had been reduced to a level between 12 and 15°C. Again, the temperatures were slightly

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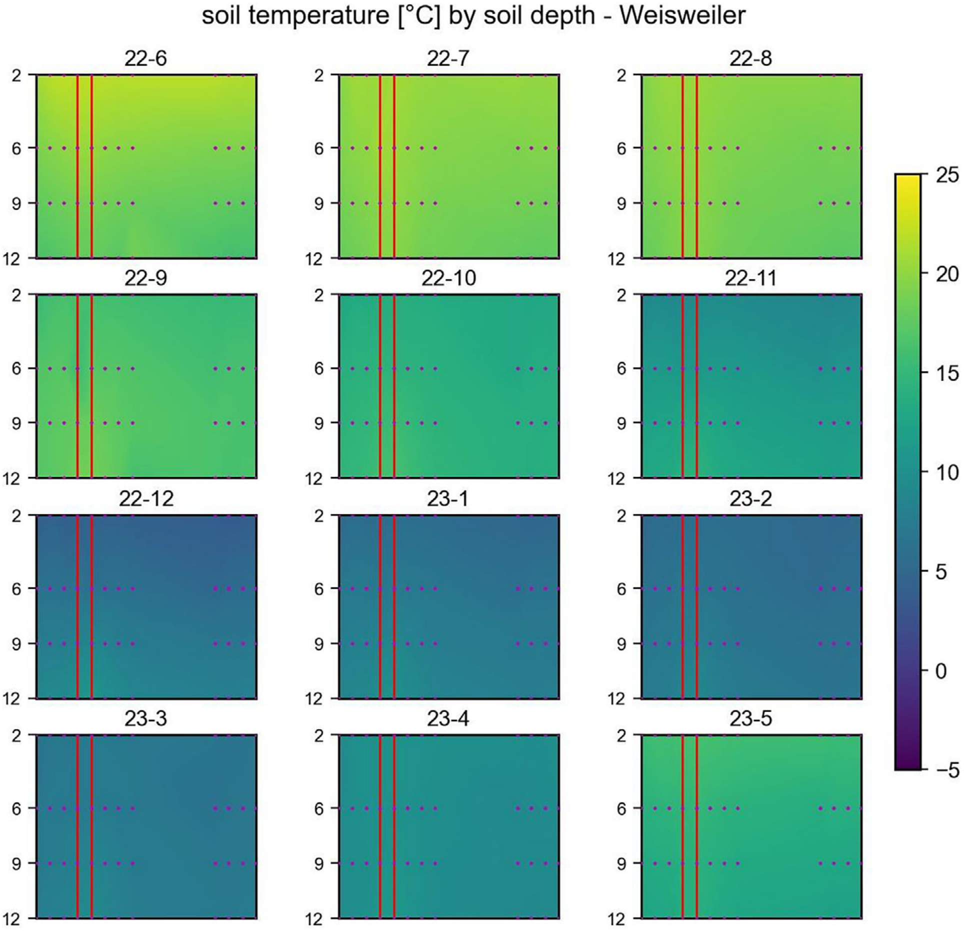

FIGURE 2 Two-dimensional (2D) presentation of soil temperature dynamics with soil depth (in dm, *y*-axis) from June 1, 2022, to May 31, 2023 (means per month) by example of Weisweiler study site. Soil temperatures of underground electric transmission lines (UTL) are depicted on the left part of the *x*-axis and of the control on the right. The two cables are indicated by red lines together with eight ML3-sensores (*x*) each at each depth on the left part of each 2D figure. Please note that the control in the right part of the figures consists of four ML3-sensores (*x*); mean of all temperature records of each soil depth per month.

higher in the subsoil in close proximity to the cables. From December 2022 until February 2023, a temperature inversion within the soil profiles appeared in the way that higher temperatures were recorded in the subsoil relative to the topsoil (Figure 2). Low temperatures below 10°C were documented within the whole soil profile, both in the cable line and the control (Figure 2). Slightly increased temperatures in the subsoil proximately above the two cables were recognisable. The spatial temperature dynamic in spring (Figure 2; i.e. April 2023) was comparable to the situation in June 2022; however, evidence showed slightly increased temperatures in both topsoils of UTL and control.

3.2 | Spatiotemporal dynamics of soil moisture

The spatiotemporal dynamics of soil moisture contents over the course of the year showed the differences between UTL and control sites more clearly relative to the soil temperatures (Figure 3). By example of study site Weisweiler, amounts of soil moisture continuously increased from the topsoil to the subsoil in the period of June to September 2022. In UTL, however, soil moisture content was quite lower compared to control sites. From mid-November 2022 onwards, the onset of precipitation caused a reversal of soil moisture conditions, showing lower amounts of soil moisture in UTL relative to the control sites (Figure 3).

All studied soils are characterised by a high water-holding capacity. As such, at the representative study site Weisweiler, soil moisture contents varied over the year. From minimum 5–16 wt.-% to maximum 28–38 wt,-% in control sites and from 6 to 11 (min.) and 26 to 34 (max.) wt.-% in UTL sites, all in all, during the year, a decrease in soil moisture content in the subsoil of UTL sites of relatively up to 12 wt.-% was recognisable.

3.3 | Differences in soil temperature and moisture between cable line and control

Mean increase in soil temperature of cable lines relative to the controls of all investigated study sites during the monitoring period of 1 year varied highly significantly in a range of 0.61 K (20 cm), 0.97 K (60 cm),

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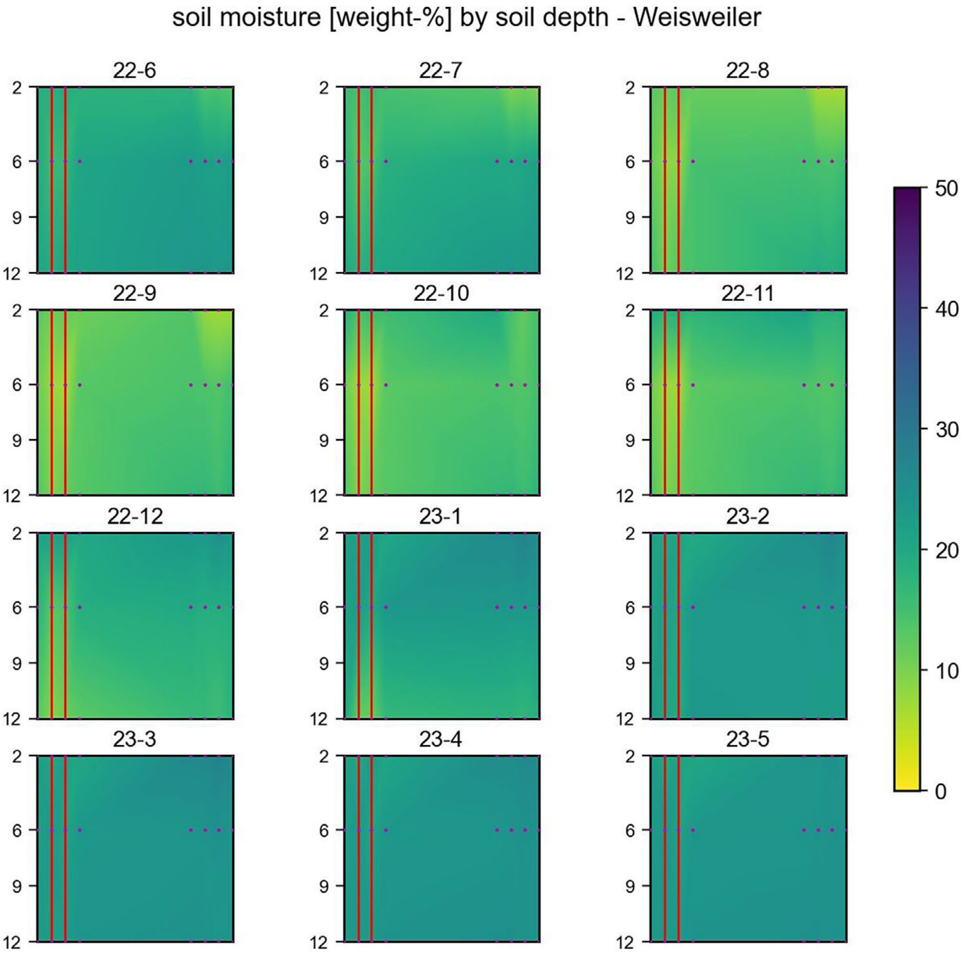

FIGURE 3 Two-dimensional (2D) presentation of soil moisture dynamics with soil depth (in dm, *y*-axis) from June 1, 2022, to May 31, 2023 (means per month) by example of Weisweiler study site. Soil temperatures of underground electric transmission lines (UTL) are depicted on the left part of the *x*-axis and of the control on the right. The two cables are indicated by red lines together with four WET 150 -sensors (*x*) each at each depth on the left part of each 2D figure. Mean of all moisture records of each soil depth per month.

TABLE 1 Statistical comparison of soil heat balance (°C) in underground electric transmission lines (UTL) and control sites.

Depth	Cable line					Control							
(cm)	Mean (°C)	S.D.	Min.	Max.	Median	Mean (°C)	S.D.	Min.	Max.	Median	*p*-Value	(K)	MPC (K)
20	12.89	6.26	0.55	28.15	12.67	12.28	6.11	0.34	28.64	12.11	1.0071E – 44	0.61	1.46
60	13.20	5.21	3.63	23.53	13.47	12.23	5.05	3.04	22.21	12.36	4.1572E – 174	0.97	2.34
90	13.46	4.52	6.48	22.00	13.47	12.17	4.46	4.89	20.46	12.13	0.000E + 00	1.29	3.10
120	13.82	3.93	7.56	20.99	13.68	12.13	3.94	6.18	19.45	12.15	0.000E + 00	1.69	4.06

Note: Mean (± S.D.), amplitude (min–max), and median of all four study sites, differentiated by soil depth (K = temperature difference of cable line minus control; non-parametric Wilcoxon-test; ***$p < 0.001$); MPC = calculated increase in soil temperature (K) at maximum (100%) permissible cable capacity by factor 2.4 (square of average load 65%).

1.29 K (90 cm) and 1.69 K (120 cm depth; Table 1). The temperature amplitudes within the year of monitoring ranged on average from 6.18 to 19.45°C in the subsoil of control sites and from 7.56 to 20.99°C in the subsoil of UTL sites, respectively, indicating a slight soil warming in the subsoil of UTL sites. The differences in the maximum temperatures between cable lines and the respective control sites were very low and ranged from −0.5 K (20 cm), 1.3 K (60 cm), 1.5 K (90 cm) and 1.5 K in 120 cm depth.

The differences in soil temperatures within the four study sites, on the one hand, and between UTL and control sites, on the other, were

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TABLE 2 Statistical comparison of soil heat balance (°C) in underground electric transmission lines (UTL) and control sites at the four study sites (Weisweiler, Dürwiss, Haaren and Brand).

Depth (cm)	Location	Cable line Mean (°C)	S.D.	Min.	Max.	Median	Control Mean (°C)	S.D.	Min.	Max.	Median	*p*-Value	(K)	MPC (K)
20	Weisweiler	12.73	6.37	0.55	28.04	12.70	12.29	6.37	0.34	28.64	12.18	2.4E – 07	0.44	1.06
	Dürwiss	13.53	6.64	1.94	28.15	12.94	12.96	6.60	1.71	27.37	12.45	6.1E – 11	0.57	1.37
	Haaren	12.52	5.97	1.63	26.01	12.34	11.78	5.67	1.34	24.50	11.77	1.1E – 20	0.74	1.78
	Brand	12.77	5.98	2.14	23.78	12.76	12.09	5.67	2.40	22.82	12.11	6.1E – 22	0.68	1.63
60	Weisweiler	13.03	5.36	3.63	22.76	13.52	12.24	5.30	3.04	22.00	12.64	2.2E – 36	0.80	1.92
	Dürwiss	13.90	5.57	5.15	23.53	13.81	12.94	5.53	4.55	22.21	12.86	4.9E – 51	0.96	2.30
	Haaren	12.79	4.94	4.72	20.55	13.11	11.70	4.62	4.17	19.23	12.12	3.5E – 70	1.09	2.62
	Brand	13.10	4.87	5.50	21.02	13.64	12.05	4.59	4.44	19.03	12.28	9.6E – 68	1.05	2.52
90	Weisweiler	13.44	4.62	6.48	20.66	13.78	12.18	4.67	4.89	19.63	12.47	2.2E – 108	1.26	3.02
	Dürwiss	14.17	4.90	7.33	22.00	14.19	12.87	4.92	6.02	20.46	12.88	7.6E – 108	1.30	3.12
	Haaren	12.96	4.37	6.52	19.53	13.29	11.60	4.05	5.49	17.25	12.07	4.3E – 117	1.36	3.26
	Brand	13.28	4.05	6.75	19.62	13.12	12.03	4.05	5.76	18.06	11.97	2.6E – 113	1.25	3.00
120	Weisweiler	13.93	3.99	8.18	19.55	13.85	12.19	4.10	6.26	18.16	12.43	2.2E – 207	1.74	4.18
	Dürwiss	14.50	4.27	8.43	20.99	14.15	12.78	4.35	6.68	19.45	12.63	1.3E – 197	1.72	4.13
	Haaren	13.27	3.81	7.56	18.79	13.22	11.59	3.54	6.18	16.39	11.85	3.1E – 203	1.69	4.06
	Brand	13.57	3.48	7.66	18.91	13.31	11.96	3.61	6.49	17.30	11.72	1.0E – 208	1.62	3.89

Note: Mean (± S.D.), amplitude (min–max), and median of all four study sites, differentiated by soil depth (K = temperature difference of cable line minus control; non-parametric Wilcoxon-test; ***$p < 0.001$); MPC = calculated increase in soil temperature (K) at maximum (100%) permissible cable capacity by factor 2.4 (square of average load 65%).

similar to the overall mean differences, indicating a low variation in the impact of various soil types among the study sites (Table 2). The variation in soil temperature at the various soil depths among study sites was on average low but more profound in the topsoils (Table 2). Interestingly, increase in soil temperature varied in a range of 0.26–0.29 K in the deeper horizons among sites, whereas the variation was approx. 0.7 K up to 60 cm depth. Remarkably, study site Brand, which is characterised by a Gleysol in slope position, was not conspicuous in this context (Table 2).

On the total average of all study sites and 1 year of monitoring, amounts of soil moisture in UTL sites decreased by 1.00 wt.-% in 20 cm depth, 1.02 wt.-% in 60 cm depth and 2.45 wt.-% in 120 cm depth relative to the control sites (Table 2). This corresponds to a relative deviation in soil moisture in the topsoil (20 cm depth) and main rhizosphere (60 cm) of 5.3% and in the subsoil at 120 cm depth of 11.8%. In the control soils, water content in the subsoil ranged during the year from 16.44 to 28.3 wt.-%, whereas in UTL sites, the amplitude was greater in a range from 11.39 to 33.85 wt.-%, respectively (Table 3).

By comparing soil moisture dynamics and the impact on UTL on soil moisture at the four study sites, it became evident that soil moisture content markedly decreased in Brand UTL site relative to its control (Table 4). The differences were −1.14 (20 cm), −2.76 (60 cm) and −2.91 (120 cm) wt.-%, and thus, soil water loss likely due to the operation of UTL was more distinct at this study site, which is impacted in the subsoil by groundwater.

4 | DISCUSSION

The dynamic management of underground electric power transmission lines has become a topic of great interest at present. Knowledge about the soil temperature and moisture dynamics affected by the operation of buried high-voltage cables is fundamental for environmental and soil ecological evaluation. Thus, a soil monitoring programme was conducted to continuously monitor soil temperature and moisture within the soil profile of 1.2 m depth during the operation of an existing extra-high-voltage UTL (ALEGrO). To our knowledge, this is the first monitoring of this kind in Europe and probably worldwide. Evidence from 1-year soil monitoring revealed that soil warming due to the operation of high-voltage underground cables was moderate and was on average in a range of 0.6 K in the topsoil, approx. 1–1.3 K in the rooting zone and 1.7 K in the subsoil up to 120 cm depth relative to control (see Table 1).

Apart from studies concerning the ampacity of buried cables (Georgiev et al., 2020; Jörgens & Clemens, 2021), a limited number of published information exists concerning soil warming due to the operation of high-voltage cables in soil (Kroener et al., 2017). First preliminary results received from various field experiments or from modelling projects in Germany (Table 5) revealed that soil warming is highly variable and increases with increasing soil depth, and this is in accordance with our results. Overall, these results confirm an operational temperature anomaly in the affected soils within the soil profile.

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TABLE 3 Statistical comparison of soil moisture (wt.-%) in cable line and control sites.

	Cable line					Control						
Depth (cm)	Mean (weight-%)	S.D.	Min.	Max.	Median	Mean (weight-%)	S.D.	Min.	Max.	Median	*p*-Value	Difference (weight-%)
20	19.04	6.04	5.76	34.04	19.21	20.03	7.36	4.82	37.52	21.26	2.743E – 93	−1.00
60	19.10	4.55	9.40	26.06	20.63	20.13	4.83	11.25	29.00	21.72	9.236E – 245	−1.02
120	20.83	6.39	11.39	33.85	20.67	23.28	3.07	16.44	28.30	23.74	0.000E + 00	−2.45

Note: Mean (± S.D.), amplitude (min–max), and median of all four study sites, differentiated by soil depth (difference = underground electric transmission lines (UTL) vs. control; non-parametric Wilcoxon-test; ***$p < 0.001$).

TABLE 4 Statistical comparison of soil moisture (wt.-%) in underground electric transmission lines (UTL) and control sites at the four study sites (Weisweiler, Dürwiss, Haaren and Brand).

		Cable line					Control						
Depth [cm]	Location	Mean (weight-%)	S.D.	Min.	Max.	Median	Mean (weight-%)	S.D.	Min.	Max.	Median	*p*-Value	Difference (weight-%)
20	Weisweiler	18.16	3.52	11.30	25.77	19.84	19.04	7.13	7.47	30.30	21.87	8.2E – 71	−0.88
	Dürwiss	16.43	3.69	8.77	23.59	17.78	18.25	4.67	9.07	25.51	19.34	8.5E – 224	−1.81
	Haaren	18.68	7.26	5.76	30.74	18.58	18.85	7.45	4.82	30.94	19.10	7.8E – 03	−0.16
	Brand	22.86	6.69	10.83	34.04	25.64	24.00	8.19	9.49	37.52	26.65	1.8E – 66	−1.14
60	Weisweiler	16.58	5.42	9.40	23.33	18.04	19.77	4.36	13.73	26.16	22.02	0.0E + 00	−3.19
	Dürwiss	18.17	3.24	13.20	21.96	19.45	18.12	4.27	11.58	23.92	20.09	1.3E – 35	0.06
	Haaren	22.01	3.39	16.19	26.03	24.42	20.22	5.40	11.25	27.75	22.02	7.0E – 06	1.79
	Brand	19.63	3.97	13.32	26.06	19.15	22.39	4.19	15.51	29.00	23.95	0.0E + 00	−2.76
120	Weisweiler	17.15	4.92	11.39	23.83	18.02	20.53	3.52	16.44	25.11	21.84	0.0E + 00	−3.39
	Dürwiss	22.71	2.26	19.51	25.21	24.20	23.50	2.49	20.08	27.45	24.95	0.0E + 00	−0.79
	Haaren	21.65	3.25	17.53	25.51	23.68	24.38	2.02	21.60	26.99	25.32	0.0E + 00	−2.73
	Brand	21.80	10.24	11.65	33.85	14.83	24.71	2.07	22.09	28.30	24.64	8.6E – 48	−2.91

Note: Mean (± S.D.), amplitude (min–max), and median of all four study sites, differentiated by soil depth (difference = UTL vs. control; non-parametric Wilcoxon-test; ***$p < 0.001$).

According to the available data, soil warming ranged from (min–max) <1 to 3.2 K in 0–10 cm depth, <1–6 K (20 cm depth), <4–10 K (60–90 cm depth) and 3–13.3 K in 100–120 cm depth (Table 5), indicating that the results from the ALEGrO monitoring programme are to be located in its lower range. The same is true, for example, for modelled data of the A-Nord UTL, which will be a main UTL throughout the North of Germany in near future. Some studies indicated relatively high soil heating, for example a case study in the city of Berlin (Trinks, 2010), or by using waste heat from power plants in hot water pipes (Reinken, 1975; Reinken et al., 1978). In case studies with experimental UTL heating and base load operation of cables (e.g. project TenneT; Ahl et al., 2023; see Table 5), it was found that soil warming was higher relative to the results from the ALEGrO-UTL operating with a similar cable load scenario. Under simulated long-term maximum permissible capacity operation with a heat loss per cable of 43 W m^{-1} soil warming was 4.5 K (30 cm), 6.2 K (60 cm), 8.1 K (90 cm) and 10.7 K in 120 cm depth (Ahl et al., 2023), and thus, soil warming was even more profound than the calculated heating at 100% permissible cable capacity scenario in the case of the ALEGrO-UTL. There is circumstantial evidence that the divergence might be attributed, especially to the technical performance of the case study and probably to differences in the imbedding material, whereas soils and soil properties are largely identical. It should also be noted that the individual projects differed in terms of individual test parameters, such as the number of cables, the distance between the cables and the current flow (AC vs. DC).

However, a precise and comparable evaluation of the results is necessary in order to derive their relevance to realistic conditions. For example, the comparable high ranges of soil heating, for example, above 5 K, cannot be generally transferred to recent or future UTL projects due to significant restrictions (see also Table 5): Soil depth of UTL was partly far away from practical relevance, and the electric voltage of cables (110 kV) or cable loads was too low and unstable. A comparison of soil warming by hot water pipes of 30–38°C in 75 cm depth with UTL is as well restricted because the water pipes were less insulated, and accordingly, heat loss from those hot water pipes was very high. When comparing the results from the ALEGrO-monitoring with, for example, field case studies with an experimental heating of empty cable tubes, differences in the experimental configuration and the composition of

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TABLE 5 Compilation of selected underground transmission line (UTL) projects/case studies with measured or modelled impacts on soil temperature dynamics.

			Expected deviation of Temperature (K) per depth (cm)				
UTL Project	**UTL type**	**Soil type**	**0–10**	**20 (30)**	**50 (60)**	**100 (120)**	**Source**
Case study Osterath[1]	110 KV	Anthrosol	2.5–3.2	4.2–5.2	k.A.	<3.0	Trüby (2018)
Monitoring Raesfeld[2]	380 KV	Plaggenesch, recult.	<1.6	k.A.	k.A.	4.0–7.0[3]	Trüby (2020)
East Coast UTL (TenneT)[4]	380 KV	Sandy soil Loamy soil Peat above Sand	1.2–1.6 1.2–1.6 0.4–0.6	2.3–3.0 2.3–2.9 2.7–3.3	4.0–5.1 4.6–5.9 <7–7.2	7.2–9.2 8.1–10.4 10.6–13.3	Stammen u. Dong (2020), and Wessolek u. Kersebaum (2020)
Agrotherm	Waste heat power plant	Alluvial soil	4.0	4.0–6.0	10.0	12.2	Reinken (1975) and Reinken et al. (1978)
Case study Berlin	110 KV	Anthropogenic soil	n.s.	n.s.	2.0	3.0	Trinks (2010) and Wessolek et al. (2016)
A-Nord[5]	380 KV	Various soils	n.s.	0.62	1.14	3.16	Delta-h (2022)
TenneT case study[6]	380 KV	Luvisol/Fluvisol (Loess)	n.s.	2.2	3.2	5.3	Ahl et al. (2023)
ALEGrO[7]	320 KV	Luvisols, Gleysol	n.s.	0.61	0.97	1.69	This study
Variation in temperature increase (K)			**<1–3.2**	**<1–6.0**	**<4–10.0**	**<3–13.3**	

Note: temperature increase due to UTL operation in Kelvin (K) for various soil depths.
Abbreviation: n.s., not specified.
[1] Field experiment, measured.
[2] Average load 26%; max. load 41% during 3.5 year.
[3] Calculated to 100% cable load; ref. Trüby (2020).
[4] Modeled.
[5] Modeled; data respond to a worst-case scenario with a cable load of 79% (NEP+).
[6] Base-load operation, heat loss per cable 13 W m^{-1}.
[7] Data from field monitoring; cable load on a yearly average of 65%.

the imbedding materials have to be considered. Precise information in this context is needed, and thus, this underlines the significance of soil temperature and moisture monitoring under realistic scenarios concerning electric voltage, cable load, cable depth, cable line construction and the composition of the imbedding material.

In order to compare the results from the ALEGrO-monitoring programme with other UTL case studies and for a careful generalisation of the impact of UTL operation on soil heat and moisture dynamics in the top and subsoil, some determining variables are essential, such as heat loss, cable load, number of cables, distance between cables, cable material, installation depth, soil properties and usage of imbedding material and its composition. Moreover, for the comparison of generated sensor data, their location within the cable line and the vertical distance to the cables are of significant relevance. In the present investigation, the heat loss of both ALEGrO cables can be estimated as 11.5 W m^{-1} (ref. to estimated 75% cable load). In the event of a short-term utilisation of 100% permissible cable capacity, heat loss per cable would increase to 21 W m^{-1} (pers. comm. Amprion Ltd.), indicating that the heat emission of the ALEGrO cables is very low due to the good insulation of the cables and optimised heat dissipation in the cable surrounding. In some case experiments, the permissible cable capacity was experimentally set to 100%. Thus, for a better comparison with those studies, we additionally calculated a 100% permissible cable capacity of the ALEGrO cables by using the factor 2.4 because the cable load is squared in the heat loss of the cables and correlates with the current intensity (see Tables 1 and 2). As a result, the calculated soil warming increased on average up to 1.5 K (20 cm depth), 2.3 K (60 cm depth), 3.1 K (90 cm depth) and 4.1 K (120 cm depth).

In sum, compared to other case experiments, the monitored soil warming of the present ALEGrO project is comparably moderate, even when it would be operated with 100% permissible cable capacity. This might be traced back particularly to the following reasons: differences in cable loads, soil properties and imbedding materials and thus to differences in heat loss of the cables. For example, the distance between the ALEGrO cables is comparable low with 0.75 m, whereas it is 1.6 m in the TenneT field experiment. In the case of the ALEGrO monitoring programme, it was not possible to install the sensors deeper in soil than 120 cm depth mainly for safety reasons. Thus, the deepest sensors were set approx. 60 cm above the cables. This is important, as in some field experiments, temperature sensors are in close proximity of the cables. However, the monitored soil profile from the plough layer up to the subsoil in 120 cm depth is significant from an agricultural perspective and representative, for example, for the cultivation of arable crops.

The effect of UTL operation on soil moisture dynamics is nearly unresearched. Malmedal et al. (2016) found that there is a relationship between the time it takes soil to dry around the cables and the diameter of underground cables. However, in their experiment, no imbedding

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material around cables was considered. Eslami et al. (2016) emphasised that during a heating period of 180 days, the moisture flow in soil was mainly caused by vapour transport under temperature gradients. This was significantly affected by hydrothermal properties of the surrounding soil. According to Brakelmann (1984), a capillary flow of water is no longer guaranteed if the soil water content falls below a critical value.

Based on the results from the 1-year ALEGrO monitoring of soil moisture, the impact of underground cable operation was on average very low in the top 60 cm of soils (±1.00 wt.-%). This is in accordance with results from previous experimental approaches on that question (Ahl et al., 2023; Verschaffel-Drefke et al., 2021) and might be related to the moderate soil warming within these soil layers. In the subsoil in 120 cm depth, soil water loss accounted on average for 2.45 (max. 2.91) wt.-%. Against the background of the soil moisture dynamics during the whole year of all investigated sites, which ranged from 5 to approx. 40 wt.-%, this decrease may be evaluated as well very low. A slightly lower water content merely indicates that the WET150 sensors have recorded less free soil water and not that there has been a loss of water in the soil. The warming has partly converted soil water into water vapour, which will then condense in cooler areas. Another possible reason for the slight decline in soil water content measured could be increased plant uptake. In contrast, differences in individual soil properties relevant for thermal conductivity and thermal capacity, such as SOM, soil texture or bulk density, between UTL and control do not appear to be relevant (see Tables S1–S3).

The soil at the study site Brand is characterised by groundwater dynamics; however, this is restricted to the subsoil due to its slope position. Because groundwater impact is known to dissipate heat well and thus lower soil warming, we calculated mean soil warming without taking this study site into account (results not presented). The results indicated that the impact of study site Brand was not significantly modulating the overall mean of all study sites.

From a soil ecological and agricultural perspective, soil temperature and moisture dynamics within the topsoil, the rooting zone and the subsoil up to 1.2 m depth are of significant relevance. However, in a previous study on the operational influence of the ALEGrO-UTL on agricultural yields, no significant difference between UTL and control sites was found (Feldwisch et al., 2023). For example, the grain yields of wheat varied between 74.0 ± 14 and 90.1 ± 11.3 dt ha^{-1}. The vitality of the plants (measured as infrared reflectance) and the photosynthetic potential (measured as chlorophyll content) also did not differ significantly.

Moreover, it is hypothesised that soil warming will result in a stimulation of soil microbes and microbial and enzyme activities, with the limiting factor being the loss of soil moisture. Soil faunal assemblages might react more sensitive due to potential energy loss at higher temperatures. The impact of underground cables on soil moisture might be of specific relevance for soil fauna, for example earthworms, as well. However, mean decrease in soil water might not limit behaviour and activity of soil faunal assemblages due to the minor impact of cable operation on soil moisture dynamics. The impact of soil warming during the operation of the ALEGrO-UTL on soil organisms is currently under investigation.

5 | CONCLUSIONS

During operation, extra-high-voltage underground transmission lines emit heat, leading to soil warming, especially in the subsoil and thus to a temperature anomaly within the soil profile. The extent of soil warming depends mainly on the heat loss of the cables, cable load and soil properties being responsible for thermal heat conductivity and thermal capacity. A special attention deserves the cable route construction and melioration, and the composition and physical performance of the imbedding material in which cables are laid.

A first and 1-year monitoring of soil temperature and soil moisture dynamics under practical operation scenario revealed that soil warming was low to moderate in UTL relative to control sites, and this corresponded with a likewise very low impact on soil moisture. It cannot be concluded from the available results whether increased drought stress occurs in crop plants in UTL soil under certain environmental conditions, such as coarse-textured soils and extreme weather conditions. The monitoring period is still too short, and the investigated loess soils show a high water storage capacity. It is therefore recommended that comparable soil temperature and soil moisture monitoring is implemented for other soil conditions in UTL operations.

In prospect of the imminent grid expansion of extra-high-voltage transmission lines, it appears possible to minimise the environmental impact of underground cable operation. This is important in order to achieve public acceptance of underground cables and reduce public concerns.

ACKNOWLEDGMENTS

We like to thank *Dr. S. Schweighoefer* and *Mr. van Oepen* (UP Umweltanalytische Produkte Ltd, Ibbenbüren, Germany) for the technical advice and help with the installation of sensors and loggers on the test sites. We would like to thank the technicians *Elvira Sieberger* and *Petra Ziegler* from the *Department of Soil Science* at the *University of Trier* for their support with the laboratory analyses.

Open access funding enabled and organized by Projekt DEAL.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Emmerling, C., Hoffmann, C., Herzog, M., Schieber, B., Stöckhert, F., Koschel, S., Kurtenacker, M., & Trüby, P. (2024). Soil warming by electrical underground transmission lines impacts temporal dynamics of soil temperature and moisture. *Journal of Plant Nutrition and Soil Science*, 1–11. https://doi.org/10.1002/jpln.202400052

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