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A method for standardised description of soil temperatures in terrestrial ecosystems

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Contents

Abstract

Regarding thermal behaviour, two opposite extremes occur in soils of terrestrial habitats: the zero-insolation soil (ZIS) without direct sunlight falling to soil surface and the full-insolation soil (FIS) with full exposition of soil surface to sunlight throughout the whole day. ZIS temperatures are mainly determined by the medium-term air temperature history and FIS temperatures by both medium-term air temperature history and sunshine intensity of the actual day. The paper shows the detailed derivation of a method enabling direct comparisons of allochronic and allotopic soil temperature measurements by correction against long-term meteorological and astronomical standards. The first target value, the overall corrected soil temperature (TSCO), can be understood as the maximum soil temperature that would be achieved when the air temperature history of the previous 15 days corresponds to the long-term seasonal mean of a given locality and when actual sunshine duration amounts 80 % of the seasonal mean of astronomically possible sunshine duration at the given latitude. Long-term meteorological standards were derived as an average of 1 May – 31 August of the last 30 years (1977 – 2006), measured in 134 German meteorological stations and one Polish station. A depth of 35 mm was defined as standard measuring depth of soil temperature. TSCO ranged between 7 °C and 36 °C over all habitats investigated between 47.42 – 54.10°N, 9.62 – 15.55°E and 5 – 1465 m a.s.l. The mean error of TSCO for a measuring site was only ±0.73 °C in ZIS habitats and ±1.97 °C in FIS habitats. This means a reduction to 30 and 34 % of the primary error respectively. The TSCO method is extended by consideration of relative local sunshine frequency which allows the calculation of an all-weather seasonal mean of maximum daily soil temperature (TSCM). A microhabitat-specific system of guiding values (TSCG) is proposed which allows the prediction of soil temperatures in dependency from microhabitat structure, geographic and astronomic parameters and inclination. Because of the high correlation of temperatures in topsoil, soil surface and lower field layer plants, the TSCO/TSCM method is recommended as a standard system not only for soil biology but also for investigations of any epigean group of organisms.

Keywords: habitat, microhabitat, meteorological standards, air-temperature history, astronomic parameters, insolation

Zusammenfassung

Eine Methode zur standardisierten Beschreibung von Bodentemperaturen in terrestrischen Ökosystemen – Bezüglich des thermischen Verhaltens terrestrischer Böden existieren zwei entgegengesetzte Extreme: der »zero-insolation soil« (ZIS), bei dem während des ganzen Tages keinerlei direktes Sonnenlicht die Bodenoberfläche erreicht, und der »full-insolation soil« (FIS), dessen Oberfläche während des ganzen Tages voll besonnt ist. ZIS-Temperaturen werden hauptsächlich durch die mittelfristige, 15-tägige Lufttemperaturgeschichte (TAS) bestimmt. FIS-Temperaturen werden hingegen sowohl durch TAS als auch durch die Sonnenscheinintensität des Messtages bestimmt. Die Arbeit zeigt die detaillierte Ableitung einer Methode, die durch Abgleich gegen meteorologische und astronomische Langzeitstandards direkte Vergleiche allochroner und allotoper Bodentemperaturmessungen erlaubt. Die erste Zielgröße, die »overall corrected soil temperature« (TSCO), kann aufgefasst werden als die maximale Bodentemperatur, die auftreten würde, wenn TAS dem langjährigen saisonalen Mittel und die Sonnenscheindauer 80 % des Saisonmittels der astronomisch möglichen Sonnenscheindauer des Untersuchungsortes entspricht. Die meteorologischen Langzeitstandards wurden als Mittelwerte der Periode 1. Mai bis 31. August der letzten 30 Jahre (1977 – 2006) durch Daten von 134 deutschen und einer polnischen Hauptstation berechnet. Als Standardmesstiefe für die Bodentemperatur wurde 35 mm definiert. Für alle zwischen 47,42 – 54,10°N, 9,62 – 15,55°E und 5 – 1465 m NN untersuchten Habitate variierte TSCO zwischen 7°C und 36°C. Der mittlere Fehler von TSCO betrug nur ±0,73°C in ZIS-Habitaten und ±1,97°C in FIS-Habitaten. Dies bedeutet eine Reduktion auf 30 bzw. 34 % der Abweichung der primären Messdaten. Eine Erweiterung der TSCO-Methode durch Berücksichtigung der mittleren saisonalen Sonnenscheindauer des Untersuchungsgebietes ermöglicht die Berechnung eines auf alle Wetterlagen bezogenen saisonalen Mittels der maximalen Bodentemperatur (TSCM). Ein mikrohabitatspezifisches Richtwert-System wurde entwickelt, welches die Vorhersage von Bodentemperaturen in Abhängigkeit von Mikrohabitatstruktur, geographischen und astronomischen Parametern sowie Richtung und Stärke der Hangneigung ermöglicht. Wegen der hohen Korrelation der Temperaturen in Oberboden, Bodenoberfläche und unterer Feldschicht ist das TSCO/TSCM-System nicht nur als Standardmethode für die Bodenbiologie sondern auch für Betrachtungen von epigäisch lebenden Organismengruppen zu empfehlen.

1. Introduction

Temperature is one of the most important ecological factors directing the distribution of organisms in soils of terrestrial ecosystems. Description of seasonal and daily temperature dynamics in relation to differing soil depths requires the presentation of a rather complex data system. Further complication is added by random climatic fluctuations, preventing a direct comparison of measurements over many years or decades, even if referring to exactly the same soil depth and the same season. For example, topsoil in a mountain spruce forest in the Iser Mountains at an altitude of 850 m achieved the same temperature in the hot summer of 2003 as in a structurally similar colline spruce forest at 250 m near Görlitz in the relatively cold summer of 1987. The typical long-term summer difference between these two *Picea abies*-stands is at least 3.8 °C.

These problems raise the question if measuring and descriptory standards can be defined to allow the demonstration of typical temperature differences between habitats independent from time, locality and short-term climatic fluctuation. This standard should aim to reflect just the deciding factor responsible for soil temperature differences in terrestrial ecosystems, which is direct input of solar radiation. The need for such a standard is independent from measuring technology – the problem is basically the same in a 12-month measuring series with automatic data loggers as it is in point measurements with simple thermometers.

The method recommended here is a further development of the prototype presented earlier (SEIFERT 1986). Its basic idea is to enable direct comparisons of allochronic and allotopic soil temperature measurements by calibration against long-term meteorological standards. The model aims to extract the main responsible factors and to simplify as much as the required error tolerance in the ecological context allows. Factors such as water saturation of the soil or wind velocity were not incorporated into the model. The observed range of calibrated maximum soil temperature (TSCO) was 7 to 36 °C in all habitats between 100 and 1500 m a.s.l. The fact that the mean error of a single spot measurement was only ±0.73 °C in soils with very weak temperature dynamics and 1.97 °C in extremely dynamic soils shows the practical value of the system. TSCO, defined as the daily maximum on a sunny day of the summer period at a depth of 35 mm, is a good indicator of soil temperature in general and would also allow predictions for different hypogean and epigean strata when basic knowledge on vertical temperature distribution exists. This paper aims to explain not only the principles of the method but also the theoretical and empirical background of its derivation.

2. Materials and methods

2.1. Spot measurement of soil temperature in natural habitats

Measurements of soil temperature were carried out in the German federal states Sachsen-Anhalt, Sachsen, Thüringen and Bayern and in the Polish parts of the Iser Mountains and Giant Mountains from 1980 to 2006. All investigations were restricted to the period from 1 May to 31 August. Any type of terrestrial habitat from 100 to 1500 m a.s.l., situated on variable geological underground, ranging from the wettest bogs to the most xerothermous sand dunes, from completely bare protosoils to thick humous soils in damp, dark woodland was investigated. Measurements focussed on the standard depth of 35 mm. They were carried out on 75 sunny days and measured 213 different microhabitat patches in 76 study areas. In habitats with heterogeneous microhabitat structure, up to 10 thermometers were used simultaneously.

From 1980 to 1990, only mercury thermometers were used, which were partially replaced by Pt100 resistance thermometers and thermoelements from 1989 on. All systems used, irrespective if mercury thermometers, resistance thermometers or thermoelements, if automatic or manual, showed a measuring error ≤ 0.2 °C within the temperature range from +10 to +45 °C when tested in a water bath. The best system for spot measurements in the ecological context finally proved to be a Testo type T thermoelement needle sensor of 60 mm length, 1.4 mm diameter and a t_{99} of only 2 seconds. Combined with a Testo 926 measuring unit, a single sensor allows measurement of dozens of different spots within a few minutes, including temperatures within microspaces such as hollow hazel nuts or narrow rock crevices. Furthermore, the minute size of the measuring tip and low thermal capacity of the whole sensor guarantee equality of insertion and reference depth, when this sensor is inserted into the substrate for more than 30 mm. Big deviations between insertion depth and reference depth do occur in mercury thermometers with large apical fillings. Provided that the vertical temperature gradient of soil along the mercury filling is linear, real measuring depth is equal with the mass centre of the apical mercury filling and always lower than the insertion depth of the thermometer. Since the height of the apical mercury filling varied from 10 to 40 mm depending upon the type and specimen of thermometer, the reference depth had to be defined and marked in each thermometer individually. Thermometers with large fillings had to be inserted as much as 55 mm to record the 35 mm level.

2.2. Meteorological background data

All meteorological background data to develop standards, to describe dependencies from latitude, longitude, altitude and solar radiation and to calibrate spot measurements were supplied by the Deutscher Wetterdienst (DWD, National Meteorological Service). Data sets on the Giant Mountains were supplied by the Department of Meteorology of the University of Wrocław. A total of 498 150 station days in the period from 1 May to 31 August of the years 1977 – 2006 from the following 135 meteorological stations was evaluated to define the air temperature standard and basal soil temperature:

Aachen, Angermünde, Arkona, Artern, Aue, Augsburg-Mühlhausen, Bad Hersfeld, Bad Kissingen, Bad Lippspringe, Bad Marienberg/Westerwald, Bad Salzuflen, Bamberg, Baruth, Bendorf, Berlin-Dahlem, Berlin-Schönefeld, Bocholt, Boizenburg, Boltenhagen, Braunlage/Harz, Braunschweig, Bremen-Airport, Bremerhaven, Brocken, Carlsfeld, Chemnitz, Cottbus, Cuxhaven, Diepholz, Doberlug-Kirchhain, Dresden, Düsseldorf, Emden, Erdinger Moos, Erfurt-Bindersleben, Essen, Feldberg/Schwarzwald, Fichtelberg, Frankfurt/Main, Freiburg, Freudenstadt, Fürstenzell, Gardelegen, Garmisch-Partenkirchen, Geisenheim, Gera-Leumnitz, Giessen, Görlitz, Göttingen, Goldberg, Greifswald, Grosser Arber, Grünow, Hahn/Hunsrück, Hamburg, Hannover, Harzgerode, Helgoland, Hof-Hohensaas, Hohenpeissenberg, Kahler Asten, Karlsruhe, Kassel, Kempten, Kiel-Holtenau, Kleiner Feldberg/Taunus, Klippeneck, Konstanz, Lahr, Leinefelde/Eichsfeld, Leipzig, Lichtenhain-Mittelndorf, Lindenberg, Lingen/Ems, List/Sylt, Lübeck-Blankensee, Lüchow, Lüdenscheid, Magdeburg, Mannheim, Manschnow, Marnitz, Meiningen, Menz, Michelstadt-Vielbrunn, Mühldorf, München-City, Münster-Osnabrück/Airport, Neubrandenburg, Neuhaus am Rennweg, Neuruppin, Norderney, Nürburg, Nürburg-Barweiler, Nürnberg, Oberstdorf, Öhringen, Oldenburg i. O., Oschatz, Osnabrück, Osterfeld, Plauen, Potsdam, Regensburg, Rostock-Warnemünde, Saarbrücken, Sankt Peter-Ording, Schleiz, Schleswig, Schmücke, Schwerin, Soltau, Sonneberg, Stötten, Straubing, Stuttgart-Airport, Stuttgart-Schnarrenberg, Szrenica/Giant Mountains (Poland), Trier (Petrisberg), Ueckermünde, Ulm, Ummendorf, Wasserkuppe, Weiden/Oberpfalz, Weinbiet/Pfälzer Wald, Weissenburg, Wendelstein, Wernigerode, Westermarkelsdorf, Wiesenburg, Wittenberg, Würzburg, Zinnwald-Georgenfeld, Zugspitze.

2.3. Data set for the zero-insolation soil

In order to get fundamental information on the dependency of soil temperatures from climatic fluctuation and to find out the most appropriate correction function, data sets from habitats representing opposite extremes of temperature dynamics were evaluated. The lower extreme, the zero-insolation soil, was represented by a soil in a fully closed *Carpinus betulus-Acer pseudoplatanus* forest situated at 330 m in a trough at the north slope of a steep basaltic mountain (Landeskrone) near Görlitz at 14.93°E, 51.06°N. No direct sunlight fell on the measuring spot at any hour within the measuring period from 1 May to 31 August 2003, and the mean daily temperature amplitude for 123 season days was only 0.99 °C at a depth of 35 mm. Temperature recording was done here in 30-minute intervals with a HOBO Pro data logger equipped with a remote sensor.

2.4. Data sets for the full-insolation soils

Soil temperature data from the gardens of 54 meteorological stations of the DWD in the period from 1 May to 11 August 2003, recorded by Pt100 resistance thermometers belonging to the equipment of the stations were used. Soil temperature at 50 mm depth was constantly recorded in 10-minute intervals for 5474 station days with any weather situation giving a total of 788 256 evaluated measurements. The condition of a standard radiation day, with SUN > 8.9 hours, was given for 2593 station days. The evaluated stations and their basic data are given in Tab. 1. The measuring points were situated in horizontal, 4 m^2 patches of soil with completely bare surface and were fully sun-exposed from sunrise to sunset. The former measurements at depths of 20 mm, which would have allowed to interpolate the situation in 35 mm depth, are currently no longer performed by the weather stations. However, a very good correlation between maximum soil temperatures TS_{35} at 35 mm depth and TS_{50} at 50 mm depth was found during radiation days. According to test measurements in bare and fully sun-exposed sand and loess soils, TS_{35} can be derived from TS_{50} data in the range TS_{50} [9.0, 41.0] with a mean error of ±0.44 °C by the formula

$$TS35 = 1.0287\ TS_{50} + 0.995\ (r = 0.999,\ n = 19).$$

All DWD TS_{50} data were transformed by this function into TS_{35} data.

Tab. 1 Basic data of 54 DWD stations used to evaluate maximum daily soil temperatures on standard radiation days during the period from 1 May to 11 August 2003. Given are the number of days with a minimum of 9 sunshine hours and the mean of sunshine hours during these days.

No	Name	ALT [m]	LAT [°N]	LON [°E]	days SUN ≥ 9 mean	SUN [h]
3334	Manschnow	12	52.55	14.55	52	12.47
3052	Grünow	55	53.32	13.93	45	11.99
3349	Baruth	55	52.07	13.50	44	11.75
3040	Goldberg	58	53.60	12.10	48	11.58
3055	Menz	77	53.10	13.05	41	11.11
3342	Potsdam	81	52.38	13.07	49	12.51
3346	Lindenberg	98	52.22	14.12	50	12.16
3352	Wittenberg	105	51.88	12.65	44	11.70
2640	Frankfurt/Main	113	50.05	8.60	51	11.94
3368	Leipzig-Schkeuditz	141	51.43	12.23	50	12.36
3377	Oschatz	150	51.30	13.10	54	12.20
3173	Ummendorf	162	52.17	11.18	39	12.25
3350	Wiesenburg	187	52.12	12.47	46	12.34
3180	Wernigerode	234	51.85	10.77	46	12.00
3380	Görlitz	238	51.17	14.95	55	12.19
4064	Bamberg	243	49.88	10.92	51	11.58
3416	Osterfeld	246	51.08	11.93	50	12.65
2674	Würzburg	268	49.77	9.97	55	12.06
2311	Freiburg	269	48.00	7.85	54	12.06
2684	Öhringen	276	49.22	9.52	57	11.88
4406	Gera-Leumnitz	311	50.88	12.13	51	12.36
4200	Erfurt	323	50.98	10.97	49	12.49
4499	Regensburg	371	49.05	12.10	52	12.27
4426	Plauen	386	50.48	12.13	46	12.26
4422	Aue	391	50.60	12.72	41	11.71
3193	Harzgerode	404	51.65	11.13	45	12.16
4412	Chemnitz	418	50.80	12.87	45	12.65
2795	Konstanz	443	47.68	9.18	58	11.90
4190	Erdinger Moos	444	48.36	11.82	58	12.46
4236	Meiningen	450	50.57	10.38	48	12.10
2508	Michelstadt-Vielbrunn	453	49.72	9.10	56	11.79
4128	Augsburg	463	48.43	10.95	52	12.25
2020	Hahn	491	49.95	7.27	53	12.24
4234	Schleiz	501	50.57	11.80	49	12.25
4124	München	535	48.17	11.55	56	12.32
2249	Bad Marienberg	547	50.67	7.97	38	12.33
4027	Hof-Hohensaß	567	50.32	11.88	48	12.31
2730	Ulm	571	48.38	9.95	53	11.99
3984	Braunlage	607	51.73	10.60	42	11.89
4246	Sonneberg	626	50.38	11.18	51	12.35
4156	Garmisch-Partenkirchen	719	47.48	11.07	44	11.39
2728	Stötten	734	48.67	9.87	49	11.99
2751	Freudenstadt	797	48.45	8.42	47	11.81
2648	Kleiner Feldberg	805	50.22	8.45	39	12.01
4144	Oberstdorf	810	47.40	10.28	44	11.16
1594	Kahler Asten	839	51.18	8.48	38	12.29
4240	Neuhaus a. Rennweg	845	50.50	11.13	48	12.12
4414	Zinnwald-Georgenfeld	877	50.73	13.75	47	12.30
4435	Carlsfeld	897	50.43	12.62	41	11.76
2625	Wasserkuppe	921	50.50	9.57	45	12.50
4226	Schmücke	937	50.65	10.77	42	12.17
2758	Klippeneck	973	48.10	8.75	46	11.87
4161	Hohenpeißenberg	977	47.80	11.02	50	12.44
4428	Fichtelberg	1213	50.43	12.95	41	12.15

2.5. Astromomic parameters

Astronomic parameters were calculated under use of the Excel program Insolation3a, developed by Lutz Pannier based upon astronomic parameters and atmospheric extinction parameters (Meeus 1992, Sagot & Savoie 1992). The program calculates the daily duration of sunshine as well as the sum and maximum of daily solar energy input on plane surfaces in relation to date, geographical latitude, atmospheric extinction and surface inclination (slope and azimuth).

2.6. Explanation of acronyms

ALT – altitude; height above sea level in metres

AST – number of astronomically possible sunshine hours

AST80 – Standard sunshine value, defined as 80 % of astronomically possible sunshine hours and given as the daily mean for 123 season days (1 May – 31 August). At 51°N, AST80 is 12.27 h.

AZI – astronomical azimuth (direction) of a surface inclination (S = 0°, W = 90°, N = 180°, E = 270°) in decimal degrees

DEV – difference between the daily TSCA/TSCS values and the seasonal mean of TSCA/TSCS

DIF – difference of recent air temperature history and standard air temperature: DIF = TAA –TAS

HEH – average height of herb layer plants in cm

HEC – cover of herb layer plants scaled between 0 and 1 (corresponds to 0 and 100 %)

INC – slope of a surface inclination in decimal degrees

INS – insolation – The overall direct solar energy input to soil surface dependent from habitat structure, surface inclination (INC and AZI) and astronomical parameters. In fully shaded soils INS is 0 and in fully insolated (bare) soils 1.0. INS is the product of INSTR, INSHE and INSIN.

INSHE – amount of direct solar radiation penetrating the herb (field) layer

INSIN – inclination component of insolation of a habitat in dependency from astronomical parameters and surface parameters AZI and INC

INSTR – amount of direct solar radiation penetrating tree and bush canopies

LAT – geographical latitude in decimal degrees

LON – geographical longitude in decimal degrees

RSV – Relative sunshine value; value to estimate intensity of direct sunshine when SUN data are not available or misleading. The value of RSV is 1.0 at AST80.

SRU – Solar radiation unit: a value predicted by astronomical calculations considering date, AZI, INC, LAT, atmospheric extinction and atmospheric refraction. SRU has no physical unit but is directly proportional to energy input per unit area.

SRU$_5$ – the seasonal average of the 5-minute maximum value of SRU for a given surface

SRUM$_5$ – The seasonal average of the 5-minute maximum value of SRU of a S-inclined surface. At 51°N, this maximum value is achieved by a 30°S-inclined surface.

SUN – number of daily sunshine hours measured at meteorological stations

SUNR – Relative sunshine frequency defined as the quotient of the seasonal mean of SUN and maximum measurable sunshine hours. In Central Europe, the maximum of measurable sunshine hours is about 96 % of AST.

TA – mean daily air temperature at 2 m above ground

TAA – the recent air temperature history: weighted average of TA of the soil temperature measuring day and 14 the previous days

$\mathrm{TAS}_{\mathrm{pred}}$ – Predicted standard air temperature for the years 1977 – 2006 given by a regression against LAT, LON and ALT. Replacement value if $\mathrm{TAS}_{\mathrm{real}}$ is not available.

$\mathrm{TAS}_{\mathrm{real}}$ – real standard air temperature as mean of the years 1977 – 2006 directly given by data of 135 meteorological stations

TRC – canopy closure or cover of trees and bushes

TS – primary measuring value of maximum soil temperature at 35 mm depth

TSB – Basal soil temperature at 35 mm depth for a given locality achieved under zero-insolation conditions. TSB is fully correlated to TAS or $\mathrm{TAS}_{\mathrm{pred}}$ but estimated to be 0.5 °C lower.

TSCA – soil temperature at 35 mm depth only calibrated against the air temperature (calibration valid for the special case of zero-insolation soils with INS = 0)

TSCG – guiding value for TSCO valid for ALT = 300 m, LAT = 51°N, LON = 11°E and years 1977 – 2006

TSCM – The seasonal mean of calibrated maximum soil temperature at 35 mm depth under consideration of relative local sunshine frequency:

TSCM = (TSCA * (1 – INS) + TSCS * INS) * SUNR + TSB * (1 – SUNR). TSCM can be understood as the average of daily maximum temperatures for an average season.

TSCO – Overall calibrated maximum soil temperature at 35 mm depth considering both the TSCA and TSCS calibration. The weighting of TSCA and TSCS is dependent from insolation of the habitat: TSCO = TSCA * (1 – INS) + TSCS * INS.

TSCS – soil temperature at 35 mm depth calibrated against air temperature and sunshine intensity (calibration valid for the special case of full-insolation soils with INS = 1)

All temperatures are given in °C.

3. Derivation of the method

3.1. Theoretical and practical preconditions

Theoretical and practical fundamentals of the method were already outlined by Seifert (1986). Some changes in the reference systems have been performed since then and the basal preconditions in the actual context are explained here.

(a) The sun-induced maximum is the deciding parameter – According to temperature measurements of topsoils made by different authors from April to September in different terrestrial habitats of Central Europe (Lützke 1958, Lache 1976, Reichhoff 1977, Vogel 1981, Seifert 1986), the maxima are always decisive for daily and seasonal temperature differences between habitats. During sunny days, maximum soil temperatures are highest in habitats where solar radiation directly hits the soil surface and lowest when the thermally active layer is high above the soil – for instance in the upper canopy of a closed forest or in the upper layer of a high-grass meadow. In other words, for spots of equal geographic and astronomic frame conditions, the deciding factor causing soil temperature differences between habitats is the input of solar radiation causing the maxima while minima have almost no significance (Tab. 2). As a consequence, mean daily temperatures are determined by the maximum and are close to the mean of maximum and minimum. On the other hand, topsoil temperatures – maxima, minima and means – of all habitats tend to equalise during weather periods with a fully closed cloud cover. These facts clearly indicate that measurements must focus on maximum topsoil temperature during sunny days. This maximum should also allow predictions of average seasonal temperatures when the local relative sunshine duration is known.

Tab. 2 Minimum, maximum and mean temperatures in soils of different habitats on the Landeskrone near Görlitz from 21 June to 10 July 1983. Air temperature at the DWD station Görlitz: minimum 7.0 °C, maximum 31.0 °C, overall mean 19.4 °C (coldest daily mean 14.2 °C, warmest 24.5 °C). Under syntopic conditions, minima are most similar between thermally most differentiated habitats and not correlated with the mean ($r = -0.589$, n.s.) while maxima are strongly differentiated and highly correlated with the means (+0.991, $p < 0.0019$). Hence maxima are also best indicators of mean temperature differences during radiation days. *value outside the range of the minimum-maximum thermometers used in 1983 and later determined under comparable meteorological frame conditions with a Pt100 resistance thermometer.

	10 mm depth			35 mm depth		
	min.	**max.**	**mean**	**min.**	**max.**	**mean**
10°N-inclined *Fagus sylvatica* forest, 320 m	10.4	24.7	17.6	16.0	18.4	17.2
25°S-inclined *Tilia cordata* forest, 340 m	10.4	30.6	20.5	14.5	22.0	18.2
30°S-inclined *Prunus spinosa* shrub on basalt, 375 m	10.2	44.7	28.0	13.0	26.0	19.5
35°S-inclined bare soil over basalt, 370 m	10.0	58.7*	34.4	12.5	36.5	24.3

(b) Long-term (= standard) and recent temperature history of a studied locality must be estimated with data from the next meteorological station/s – When a soil temperature has been measured on a sunny day in a certain locality, the measured values have to be corrected up by calibration functions when the foregoing weather situation has been colder than the defined long-term standard and to be corrected down in the opposite case. Because almost always no data are available for exactly that locality, the deviation of its recent temperature history from the long-term standard must be estimated by data from the next weather station/s. The thesis that the transfer of a temperature history difference (see section 3.2.2.) from one locality to another is possible is supported even by the data of meteorological stations embedded in different climatic contexts: the station Wernigerode (LAT 51.85, LON 10.77, ALT 234) situated at the margin of the Harz Mountains to the North German Plain, the station Harzgerode (LAT 51.65, LON 11.15, ALT 403) situated within the Harz Mountains, which is an area almost entirely covered by woodland, and the station Wittenberg (LAT 51.89, LON 12.65, ALT 105) in the flood plain of the Elbe River. These stations are 33, 120, and 106 km apart but their temperature history differences calculated for 40 days in May to August 1980 show a mean linear correlation coefficient of 0.993 and a mean deviation of only 0.54 °C (Fig. 1). When data of different stations are used for a prediction, their data are proportionally considered – eventually under inverse weighting with their distance to the study site.

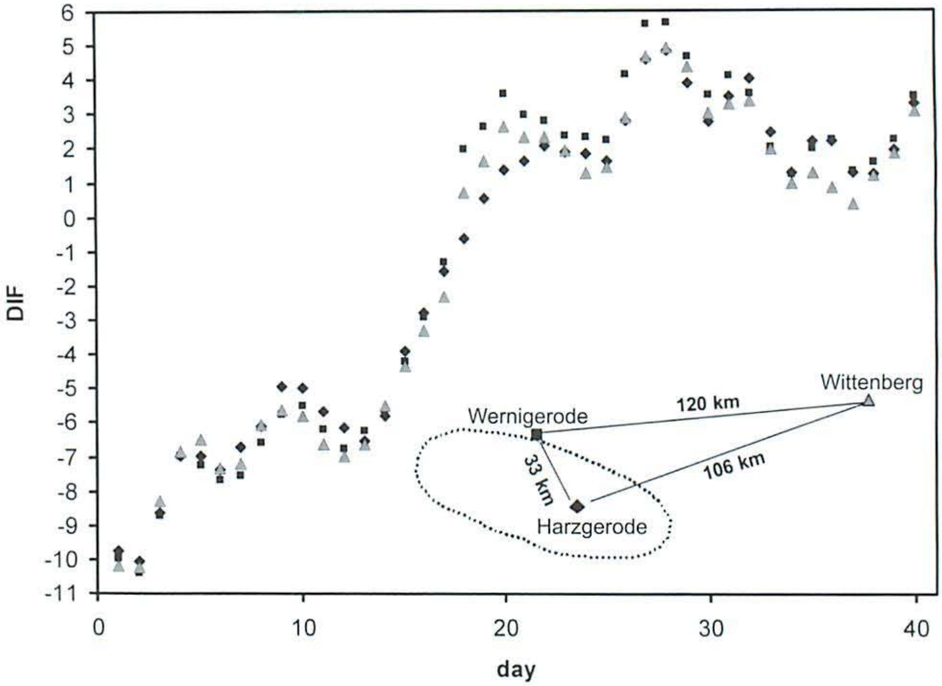

Fig. 1 Deviation DIF of the recent air temperature history (15 days) from the long-term seasonal standard of three meteorological stations in N Sachsen-Anhalt May to August 1980. Though embedded in different climatic contexts, the DIF data of the stations are highly correlated (r = 0.993) and show a mean deviation of only ±0.54 °C.

(c) Calibration of soil temperature measurements must be done against air temperature standards – A direct use of soil temperature data from weather stations for calibration of soil temperature measurements is not possible because only a portion of these stations record such data. The high correlation between soil temperature and air temperature at 2 m above ground is well established [Watson 1980, Seifert 1986, as well as current weather reports of the Deutscher Wetterdienst (National Meterological Service) and of the Meteorologischer Dienst der DDR (Meterological Service of the GDR) 1961 – 1990, see also data presented below]. Topsoil temperature dynamics clearly follows air temperature dynamics. As a consequence, the air temperature history recorded by any weather station is a good indicator for soil temperature history.

(d) The most appropriate reference period is May to August – The period between 1 May and 31 August was fixed as reference season for the following reasons. Despite significant early spring and autumn activity and breeding in some groups of organisms, this is doubtlessly the season of maximum activity and biomass production in the majority of plant and animal species in Central European terrestrial ecosystems. The fixation of this period was done under consideration of the climatic situation of the early 1980ies. In the time since then, global warming has led to an earlier onset of spring activity also in Central Europe. Thus, a more reasonable reference period appears to be 21 April to 20 August. We maintain the »historical« definition because it is not decisive if a defined temperature standard is 0.1 °C higher or lower. Nevertheless, we recommend performing temperature measurements preferentially between 21 April and 20 August.

(e) The most informative and most practicable measuring is performed in topsoil but not too near to the soil surface – Several arguments favour a selection of the standard measuring depth in topsoil. Measurements at only 10 mm depth show high errors because the temperature change is very strong if the thermometer is misplaced by a few millimetres, and random error sources such as surface irregularities in the natural habitats have a strong influence. Furthermore, special devices are needed to guarantee a stable stand of the thermometer. Measurements in deeper soil layers frequently cause serious mechanical problems when fragile thermometers must be inserted into hard or rocky soil; special thermometers with long measuring heads must be used and the measured differences between the habitats become lower. A measuring depth of 35 mm appears as a good compromise: random factors and small insertion errors have a lesser effect, mechanical problems are usually inconspicuous, the stability of the thermometer is usually given and the differentiation between habitats is still very clear. Furthermore, this moderate measuring depth seems biologically more »universal« because it is nearer to the high number of epigean or surface-dwelling organisms. For studies of spiders, carabid beetles or aculeate Hymenoptera it represents a really good choice. On the other hand, the strong correlation of temperatures in topsoil and in deeper soil layers down to 50 cm is fully established by soil meteorology (e.g. daily weather reports of the Meterological Service of the GDR 1961 – 1990). Hence, the 35 mm level will also provide indirect information on the situation in deeper soil layers as will also be the case for temperatures in lower strata of the herb layer.

(f) Within the context of required information, simple maximum thermometers with manual recording remain a good alternative to automatic systems – The best modern data loggers do almost anything what we need: equipped with a small-dimensioned external sensor they allow a precise positioning at the required measuring depth and accurate recording of data in 10-minute intervals over a period of several months and they work reliably – apart from disturbance caused by animals and humans. However, long-term installation of expensive data loggers in the field needs careful camouflage (usually burying) of the recording unit to prevent destruction or thieving and makes little sense when temporal spot measurements of the maximum daily soil temperature are required. Furthermore they become a financial problem when study areas with strongly deviating microhabitat temperatures need the installation of up to 10 measuring spots and when several such study areas have to be investigated. Simple maximum thermometers are much cheaper, easier to handle and they can be quickly installed in other habitats of a locality. Apart from deviations occurring in E-, SE-, SW- or W-exposed habitats, the temperature maximum is generally built up in full-insolation soils 40 – 130 minutes after sun passage of the meridian but in zero-insolation soils 5 to 7 hours PM. Knowledge of this maximum point and a good planning of measurements may allow, for instance, that the same 10 thermometers can be used to measure the maxima of a xerothermous Teucrio-Seslerietum (at 13.30 h local time), a semidry meadow (14.30 h), a fresh *Alopecurus* meadow (16.00 h) and a *Fagus* forest (17.30 h) at the same locality and day.

3.2. Description of the meteorological standards and calibration procedures

3.2.1. Standard air temperature and basal soil temperature

As meteorological standard for the reference region – i.e., the territory between 47 and 55°N, 6 and 16°E and 0 to 2960 m a.s.l. – was defined the mean air temperature at 2 m height observed from 1 May to 31 August within the years 1977 – 2006. 498 150 station days of 135 stations in this territory (one of them in Poland: Szrenica/Giant Mountains) were evaluated. The mean predicted standard air temperature TAS_{pred} in °C is defined for this period by a regression function against geographical latitude LAT and longitude LON in degrees (decimal format) and altitude ALT in metres:

$$TAS_{pred} = -0.694\ LAT + 0.078\ LON - 0.00661\ ALT + 52.20 \qquad [1]$$

The linear correlation coefficient between TAS_{pred} and the really observed values TAS_{real} was 0.991 ($n = 135$, $p < 0.00001$), the mean error of prediction was ±0.29 °C and its largest upper and lower deviation +0.87 °C (Oberstdorf) and –1.08 °C (München-City). Predictions for exposed mountain peaks and sea islands are slightly below and those for urban areas slightly above the real values. Introduction of urbanity gradients could further improve the predictions but this is not really important in our context, since calibration is almost always done with the TAS_{real} data of the next meteorological stations. TAS_{pred} data are only required in the rare case when no TAS_{real} data are available.

The temperature mean that a zero-insolation soil would achieve during a standard season is defined here as the basal soil temperature TSB. Neglecting the very rare cases of strong geothermal heat emission, a temperature increase above TSB is almost always of solar origin. TSB is fully correlated to TAS but in absolute value slightly lower because of heat loss by evaporation. We have fixed this value with $TSB = TAS - 0.5$ as own field data from soils not exposed to direct sunlight suggest (woodland sites with closed canopy, high-grass meadows etc.). This is not the absolute minimum as the zero-insolation soil at the Landeskrone shows. According to [1] TSB can be predicted by

$$TSB = -0.694\ LAT + 0.078\ LON - 0.00661\ ALT + 51.70 \qquad [2]$$

3.2.2. Calibration of soil temperature against air temperature

The influence of a previous weather situation on actual soil temperature will decrease with growing temporal distance – i.e., the mean air temperature 10 days before will have a lower weight than that of the previous day. Of practical importance is the question as to how many previous days must be considered in addition to the actual day and which function offers the best description of weighting factors. Different calculation schedules were tested in simulations with the data of the 54 full-insolation sites and the zero-insolation site. For all sites a retrograde consideration of 15 days was sufficient and the weighting factor W was described by an exponential function

$$W = 1 + 0.00005\ e^{(A * DAY)} \qquad [3]$$

where DAY = 1 for the date 14 days before the actual and DAY = 15 for the actual (soil temperature measuring) day. A weighted average of previous air temperature TAA is then calculated as

$$\mathrm{TAA} = \sum_{i=1}^{15} (W_i * \mathrm{TA}_i) \,/\, \sum_{i=1}^{15} W_i \qquad [4]$$

where TA_i is the mean daily air temperature for DAY i = 1 to 15. When TAA is lower than the standard air temperature TAS, measured soil temperature TS has to be corrected up and vice versa. Iterative simulations varying the exponential factor *A* were performed until correlation between TAA and TS, was highest. The full-insolation and zero-insolation soils differed in their temperature dynamics. As already stated by SEIFERT (1986), the air temperatures of the days very near to the soil temperature measurement have a higher weight in full-insolation soils, which is reflected by their higher factor *A*: 0.919 vs 0.795 in the zero-insolation soil (Fig. 2).

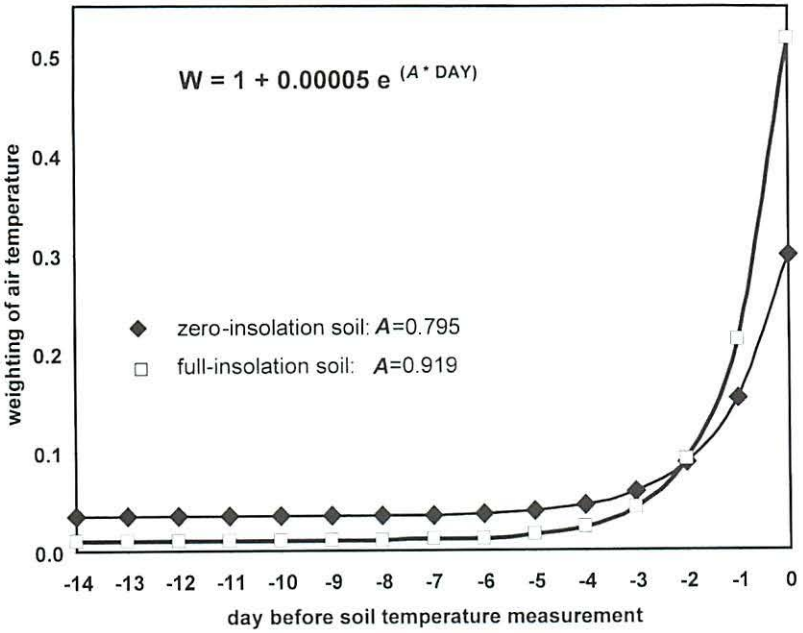

Fig. 2 Influence of recent air temperature history on actual soil temperature in zero-insolation and full-insolation soils as found by varying the exponential factor *A* until the variance of corrected soil temperatures reached a minimum. The more dynamic behaviour of full-insolation soils is expressed by the higher exponential factor.

The regression function of TS against TAA was in the zero-insolation site at the Landeskrone

$$\mathrm{TS} = 0.8446\ \mathrm{TAA} - 0.927\ (r = 0.954,\ n = 123,\ p < 0.00001) \qquad [5].$$

This high correlation is a clear indication for a close relationship between air and soil temperatures in zero-insolation soils, in which direct solar radiation is meaningless and can not produce accessory variance. Because of this rather clear and simple situation no further zero-insolation soils were evaluated. The mathematic treatment of full-insolation soils, in which actual sunshine intensity is most important, needs a much higher number of data sets and is given below.

In order to obtain air-temperature-calibrated soil temperatures, the following basic procedures were carried out for zero-insolation soils. Firstly, the difference DIF between the temperature history TAA and the standard air temperature TAS was calculated by

$$\mathrm{DIF} = \mathrm{TAA} - \mathrm{TAS}_{\mathrm{real}} \qquad [6].$$

An air-temperature-calibrated soil temperature is then calculated in a first step as interim value TSCAi by

$$\mathrm{TSCAi} = \mathrm{TS} - \mathrm{DIF} \qquad [7].$$

The error of this calculation, i.e. the deviation DEV between the daily TSCA values and the seasonal mean of TSCA (which is the best description of the standard) is then described as a function of DIF by

$$\mathrm{DEV} = -0.1554\ \mathrm{DIF} + 0.43\ (r = -0.507,\ n = 123) \qquad [8].$$

According to this function, up and down calibrations are too strong for lower and higher air temperatures. Consequently, the value of DEV has to be subtracted from TSCA. When only considering the slope of function [8] and neglecting its constant 0.43 (which theoretically should be zero), the final value of air-temperature-calibrated soil temperature TSCA is

$$\mathrm{TSCA} = \mathrm{TS} - \mathrm{DIF} - (-0.1554\ \mathrm{DIF}) \qquad [9]$$

or

$$\mathrm{TSCA} = \mathrm{TS} - 0.8446\ \mathrm{DIF} \qquad [10].$$

The slope of function [10], logically the same as in function [5], is clearly different from 1 and is an indication that functions [3] and [4] could not fully describe the retarded temperature dynamics of a zero-insolation soil covered by a layer of leaf litter. Consideration of a weather history longer than 15 days could be a possible solution. Results of this calibration procedure are given in section 4 (Tab. 7).

3.2.3. Standardisation of sunshine hours

The number of daily sunshine hours (SUN) is recorded in meteorological stations as the sum of time during which the intensity of direct radiation is at least 120 W/m². This Yes/No recording, saying Yes to both moderate and strong radiation, is surely not the best thinkable indicator for solar heating-up of solid substrates but it is the only sun parameter constantly recorded by all meteorological stations in the past and present. Hence, only this parameter and no absorption or global radiation data could be used as indicator for the intensity of solar radiation. A solution for future investigations could be direct measuring of solar energy input above the studied habitat and relating it to a standard.

The number of astronomically possible sunshine hours and the daily sum of solar radiation falling on a plane horizontal surface is dependent from geographical latitude and date. According to data provided by the Insolation3a program, the seasonal mean of astronomically possible sunshine hours AST for the period of 1 May to 31 August may be described as follows:

$$\mathrm{AST} = 0.004242\ \mathrm{LAT}^2 - 0.29606\ \mathrm{LAT} + 19.405 \qquad [11].$$

The solar component was standardised by the ratio of measured sunshine hours SUN and astronomically possible sunshine hours AST. A standard radiation AST80 is given when SUN amounts 80 % of AST which is defined in dependency from latitude as

$$\text{AST80} = 0.8\ (0.004242\ \text{LAT}^2 - 0.29606\ \text{LAT} + 19.405) \qquad [12]$$

or in equivalent transformation

$$\text{AST80} = 0.003394\ \text{LAT}^2 - 0.23685\ \text{LAT} + 15.524 \qquad [13].$$

At 51°N, the standard radiation day has 12.27 sunshine hours or a relative sunshine value RSV of 1.0 when RSV is defined as SUN/AST80.

Subjective estimates of sunshine intensity RSV are sometimes necessary when the SUN data of meteorological stations are misleading. This is the case (a) when very local weather situations are badly estimated by data from the next meteorological station, (b) when sunshine intensity was weak before noon but strong in the afternoon or (c) when atmospheric extinction was significant but the intensity of direct radiation was just above the 120 W/m^2 level.

The following rules of thumb may be applied in this case

clear air with 40 % clouds	: RSV = 0.75
strong atmospheric turbidity but cloudless	: RSV = 0.84
clear air with 30 % clouds	: RSV = 0.92
slight atmospheric turbidity but cloudless	: RSV = 1.00
clear air with 20 % clouds	: RSV = 1.05
clear air with 10 % clouds	: RSV = 1.10
clear and cloudless	: RSV = 1.20

RSV can then be transformed to SUN by

$$\text{SUN} = \text{RSV}\ (0.003394\ \text{LAT}^2 - 0.23685\ \text{LAT} + 15.524) \qquad [14].$$

3.2.4. Calibration of soil temperature against sunshine

The data of 54 DWD stations were used to estimate the influence of sunshine in full-insolation soils. The data sets were prepared in the following way. The seasonal mean of TSCA was calculated for each station separately and the difference between daily TSCA values and the seasonal mean was plotted against daily sunshine hours SUN. The resulting regression function was then adjusted for the condition that zero sunshine results in a zero soil temperature increase (Fig. 3). For SUN [0, 15.7] a highly significant function is found

$$\Delta\text{TS} = -0.0188\ \text{SUN}^2 + 0.8378\ \text{SUN}\ (n = 5774,\ r = 0.736,\ p < 0.0001) \qquad [15].$$

If restricting the data set only to radiation days with SUN > 8.9, the defined condition for habitat soil temperature measurements, a linear function gave the best fit

$$\Delta\text{TS} = 0.404\ \text{SUN} + 0.002\ (n = 2592,\ r = 0.330,\ p < 0.0001) \qquad [16].$$

The influence of sunshine during radiation days was also calculated by another approach in which the difference of primary soil temperature ΔTS of consecutive days was plotted against the corresponding difference of sunshine hours ΔSUN (Fig. 4). The consecutive day method provides the function

$$\Delta\text{TS} = 0.431\ \Delta\text{SUN} + 0.814\ (n = 2569,\ r = 0.555,\ p < 0.0001) \qquad [17].$$

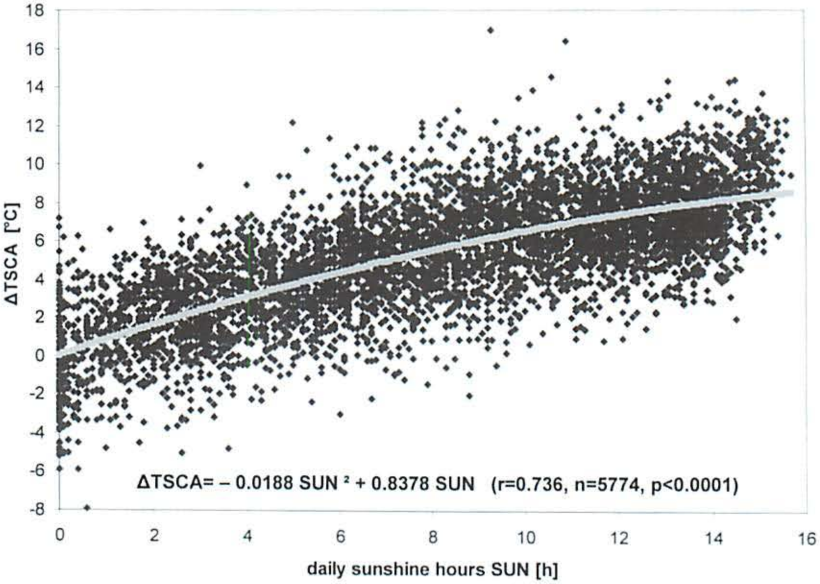

Fig. 3 Temperature increase ΔTSCA of air-temperature-corrected soil temperature above the seasonal mean as a function of daily sunshine duration SUN for any weather situation of May to August 2003 derived from data sets of 54 German stations.

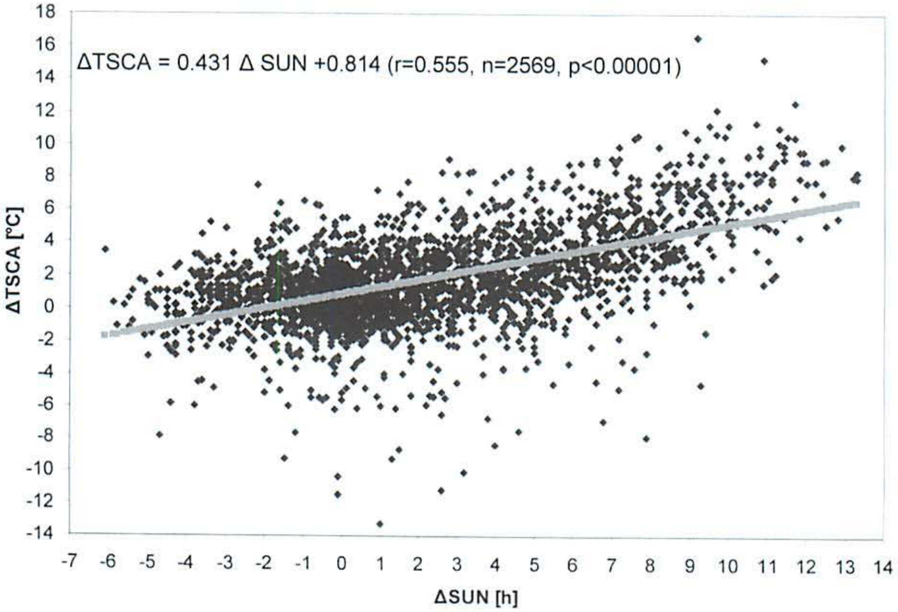

Fig. 4 Temperature change ΔTSCA of air-temperature-corrected soil temperature above the seasonal mean plotted against the change of sunshine duration ΔSUN of consecutive days from data sets of 54 German stations. Only data from radiation days with SUN ≥ 9 of May to August 2003 were used.

A third approach was iteratively varying the slope *b* of the function

$$\mathrm{TSCS} = \mathrm{TS} - \mathrm{DIF} - b\ (\mathrm{SUN} - \mathrm{AST80})$$

until the variance of TSCS data in the full data set is minimal. For SUN > 8.9 h, these testing calculations resulted in a slope of 0.413, which is intermediate between the predictions of the cumulative (0.404) and consecutive day method (0.431). We have substituted the optimum slope of iterative testing into the final calibration against sunshine with

$$\mathrm{TSCS} = \mathrm{TS} - \mathrm{DIF} - 0.413\ (\mathrm{SUN} - \mathrm{AST80}) \qquad [18].$$

This iterative testing also showed that, in difference to zero-insolation soils, minimum variance of TSCS is achieved without correction factor for DIF. Results of this calibration procedure are discussed in section 4 (Tab. 7).

3.2.5. Estimation of soil heating by solar radiation units

The Insolation3a program calculates the solar energy input falling on a surface expressed in solar radiation units (SRU) integrated for 5-minute intervals. The program considers slope and azimuth of surface inclination, astronomical data and atmospheric extinction. It predicts for horizontal surfaces that a locality at 47°N receives 93 % of the sunshine hours but 108 % of the daily energy input SRU_D compared to a locality at 55°N. The program furthermore predicts weakly differing daily energy input per unit area between horizontal and strongly south-inclined surfaces during May to August, but strong differences outside the reference season (Fig. 5). At 51°N, the SRU_D of a 40°S-exposed surface compared to a horizontal one increases by only 0.169 units (or 2.4 %) on 17 May but by 2211 units (or 64 %) on 15 March.

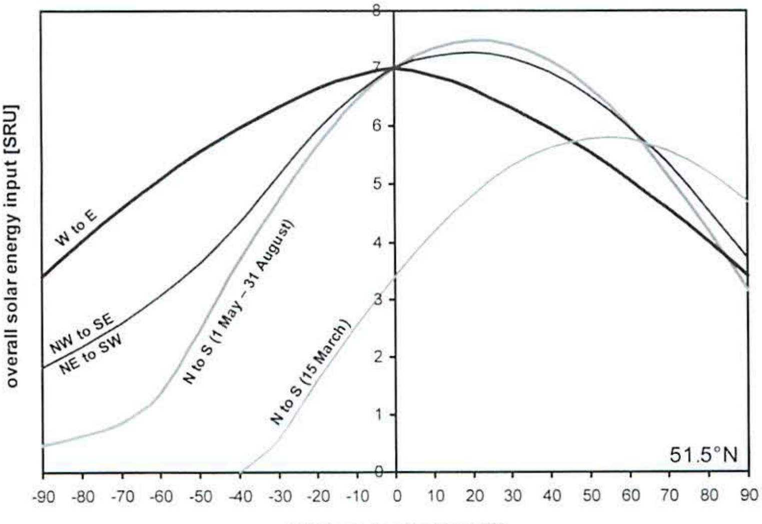

Fig. 5 Overall daily solar energy input expressed in solar radiation units SRU in dependency from slope and azimuth of differently inclined surfaces as predicted by the Insolation3a program for 51.5°N. Southern surface inclinations between 0 and 40° result in a most similar energy input during the period 1 May to 31 August but in most different values during early spring or autumn.

However, SRU_D must not necessarily be a good indicator of maximum soil temperatures. The few available data of syntopic and synchronous measurement of equally structured but differently inclined soil surfaces clearly suggest that solar heating of soil is closely correlated with the 5-minute maximum value SRU_{i5} ($r = 0.9987$, $n = 4$, $p < 0.01$) but not with the daily sum SRU_{iD} of the concrete measuring day ($r = 0.236$, n.s.) (Tab. 3). The insignificant correlation of SRU_{iD} in this small data set is explained by the fact that strongly S-inclined surfaces have clear solar energy deficits during morning and evening hours. These deficits, however, have a very low influence on maximum temperatures at noon.

Tab. 3 Synchronous and syntopic measurement of equally structured topsoils. INC – surface inclination, TS_{min} – minimum soil temperature in the early morning, TS – maximum soil temperature, $\Delta TS = TS - TS_{min}$, SUN – sunshine hours, SRU_{iD} – daily sum of solar radiation units, SRU_{i5} – 5-minute maximum of solar radiation units.

	INC	**TS_{min} [°C]**	**TS [°C]**	**SUN [h]**	**ΔTS/ SUN**	**SRU_{iD}**	**SRU_{i5} [10^{-5}]**
Quenstedt 6 July 1980 bare limestone protosoil	0°	17.1	32.7	11.4	1.368	7.541	7077
Quenstedt 6 July 1980 bare limestone protosoil	35°S	17.1	35.4	11.4	1.693	7.477	8053
Kaltwasser 19 July 2006 bare extremely dry sand	0°	23.59	43.58	14.8	1.351	7.244	6958
Kaltwasser 19 July 2006 bare extremely dry sand	35°S	25.89	50.74	14.8	1.679	7.394	8046

In order to increase the available data set, we have considered all available measuring data of bare soils taken at days with SUN > 8.9 h irrespective of the geological outcrop. The heterogeneous geological outcrop will cause some variation, but this factor is not really important (compare the guiding values in Tab. 6). In most of these data sets the real minimum temperatures at morning TS_{min} are unknown and we have substituted TS_{min} with the basal soil temperature TSB_i predicted for the concrete measuring day. Since TSB is highly correlated with air temperature TAS, the actual difference DIF of TAA from TAS can also be used to estimate the actual difference of basic soil temperature from TSB. When DIF2 is the difference of air temperature history for full-insolation soils, the actual basic soil temperature TSB_i is estimated by

$$TSB_i = TSB + DIF2 \qquad [19].$$

Most probably TSB_i is a little higher than TS_{min} which would lead to an underestimation of soil heating $\Delta T = TS - TSB_i$. When soil heating is calibrated against sunshine hours SUN to give a relative soil heating H with

$$H = \Delta TS / SUN \qquad [20]$$

and plotted against SRU_{i5} a significant linear function is calculated as

$$H = 0.00025618\ SRU_{i5} - 0.6830\ (r = 0.4423,\ n = 43,\ p < 0.01) \qquad [21].$$

The corresponding function for the data set of Tab. 3 is

$$H = 0.00031527\ SRU_{i5} - 0.8523\ (r = 0.9987,\ n = 4,\ p < 0.01) \qquad [22].$$

The smaller slope of function [21] is possibly explained by an overestimation of morning temperatures but we use this function for further considerations. Transforming function [21], a direct prediction of TS is possible

$$TS = (0.00025618\ SRUI_5 - 0.6830) * SUN + TSB_i \qquad [23].$$

For example, a »bare soil« with the parameters LAT 51°N, LON 11°E, ALT 300 m, date 17 May 2006, SUN 12.27 h and TSB_i 15.18 °C, is predicted to have a TS of 28.34 °C when horizontal but one of 32.05 °C when 35°S-inclined. Similarly, a horizontal bare soil with the same parameters but at 21 June and 31 August is predicted to have TS of 29.43 °C and 24.82 °C.

3.3. Estimation of soil insolation

3.3.1. Estimation of insolation by habitat parameters

The zero-insolation and full-insolation soils represent opposite extremes between which the temperature dynamics of all natural habitats will vary. Hence, a soil with intermediate insolation will have to be described by parameters intermediate between the TSCA and TSCS calibrations. The weight according to which the TSCA and TSCS parameters have to be considered depends upon the degree of insolation. Insolation, or its inverse expression extinction, is mainly influenced by vegetation structure and but also by inclination of soil surface. The estimation of insolation described below is only thought to serve as a weighting factor for the TSCA and TSCS calibrating functions. A direct prediction of soil temperatures from habitat structure (as originally intended) was not possible because the complicated structures would require consideration of many more parameters and availability of extensive measuring data to estimate these.

Effect of tree and bush canopies – The uppermost structural level in terrestrial habitats leading to extinction of solar radiation is the canopy layer of trees and bushes. In these two layers, extinction proceeds in Central European woodland biomes at heights between 45 and 1.5 m above the soil surface. Since both these upper and lower height levels are far enough from the soil surface, heat conduction of absorbed energy to the soil can be neglected. The influence of both tree and bush layer is thus fully comparable and consequently they can be considered to be the same factor. When canopy closure of the tree and bush layer is summarised to TRC and full canopy closure corresponds to TRC = 1.0, the solar insolation INSTR remaining after passage of this layer can be estimated by a quadratic function of geographical latitude LAT and TRC

$$INSTR = (0.0004031\ LAT^2 - 0.05178\ LAT + 0.4242) * TRC + 1 \qquad [24].$$

This formula has been derived from geometric considerations assuming homogeneously distributed trees with globular, equally-sized canopies and equal height and using the SRU_D data provided by the Insolation3a program. For 51°N, the formula predicts a zero insolation in the seasonal mean at TRC $\geq$ 0.86, which is in agreement with real observations in woodland. Zero insolation begins with TRC $\geq$ 0.89 at 47°N and with TRC $\geq$ 0.83 at 55°N.

Effect of the herb layer – The next structural level in terrestrial habitats extincting solar radiation is the herb layer. Mean height and density of the herb layer are the deciding factors but also growth forms of individual plants must be considered. Most difficult to assess are herb layers composed of plants with differing habitus. If an herbaceous plant has a long stalk with an umbrella-like arrangement of broad leaves at the top as in many shade plants of woodland, cover percentage alone is the deciding parameter but if the plant has a more globular or cylindric arrangement of leaves, calculations similar to tree-canopy function [24] may be appropriate. The more vertical and linear arrangement of grasses provides still another situation and distribution, grass stalks – i.e. if they are homogeneously distributed or concentrated in bults further complicate the picture. Hence, we cannot find a unique function describing this complex situation. Below we offer a significant formula describing extinction in grassland and apply this to the herb layer in general. The error of this simplification should practically be of low importance since grasses dominate in open land, but umbrella-like growth forms in shade habitats where extinction by tree canopies is already very strong.

Data from 18 fresh, horizontal grassland habitats with 100 % plant cover, investigated in Sachsen and Sachsen-Anhalt, provided empiric information on direct solar energy input in dependency from mean height of herb layer HEH (Fig. 6). TSCS is described in this data set

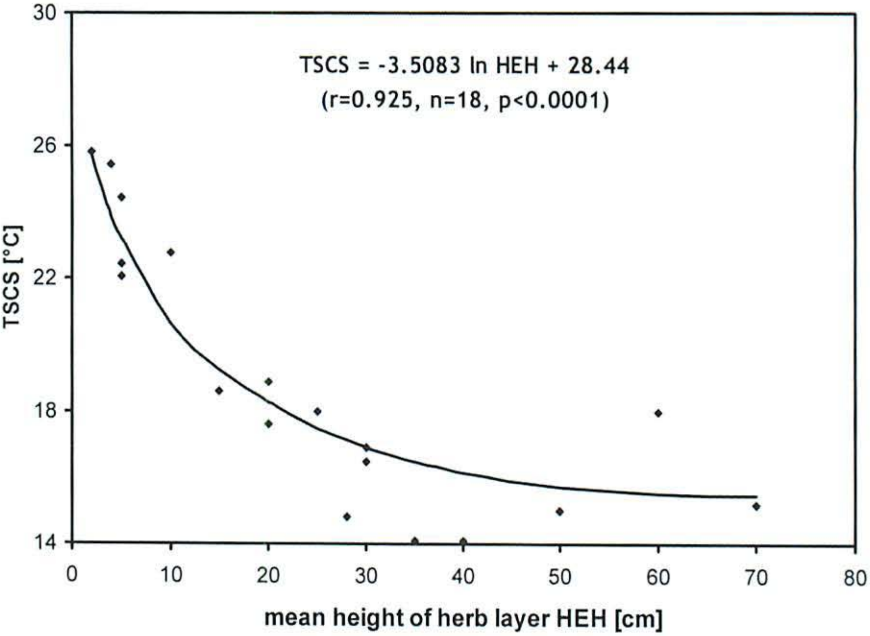

Fig. 6 Air-temperature and sunshine-corrected soil temperatures TSCS at 35 mm depth of fully closed grasslands of differing height as found at 51°N, 11°E and 300 m.

by a highly significant logarithmic function

$$TSCS = -3.5083 \ln(HEH) + 28.44 \quad (n = 18, r = 0.925, p < 0.0001) \qquad [25].$$

Minimum TSCS (with zero insolation) is obviously achieved at HEH of 70 cm or lower heights. If the TSCS at 70 cm of 13.53 °C is subtracted from function [25] and the result is divided by the difference of TSCS at 1 cm and 70 cm (= 14.9 °C), a good estimation for height-dependent insolation in dense grassland is provided

$$INSHEH = -0.235456 \ln(HEH) + 1 \quad (n = 18, r = 0.925, p < 0.0001) \qquad [26].$$

No data to estimate the influence of the herb cover HEC in combination with variable habitus and distribution of individual plants are available. Therefore only a simple estimation can be presented here. If height-dependent extinction EXTHEH in a grassy herb layer is

$$\mathrm{EXTHEH} = 1 - \mathrm{INSHEH} \quad [27]$$

and the overall extinction EXTOV resulting from density and mean height is

$$\mathrm{EXTOV} = \mathrm{EXTHEH} * \mathrm{HEC} \quad [28],$$

the resulting insolation of the soil permitted by the herb layer is

$$\mathrm{INSHE} = 1 - \mathrm{EXTOV} \quad [29].$$

Effect of the moss layer – The moss layer is closely attached to soil and usually a strong absorber of solar energy which is also conducted down to topsoil. In fact, soils under mosses and completely bare soils without mosses have similar TSCS data (Tab. 6). For these reasons, a solid (hard) and rather thin moss layer is considered in its thermal effects as a component of topsoil and measuring depth includes the thickness of moss layer.

Effect of surface inclination – The maximum thinkable daily insolation SRUM_5 is given in S-inclined surfaces. This value was calculated as mean for the measuring season and a given latitude with the Insolation3a program: the degree of inclination was varied in iterative testing until a maximum of the seasonal mean was achieved. The results can be approximated by the function

$$\mathrm{SRUM}_5 = -0.4957\ \mathrm{LAT}^2 + 29.8532\ \mathrm{LAT} + 7784.9 \quad [30]$$

With SRUM_5 being the standard to calibrate between 0 and 1, the inclination-dependent insolation INSIN of a habitat is then defined by

$$\mathrm{INSIN} = \mathrm{SRU}_5/\mathrm{SRUM}_5 \quad [31]$$

where SRU_5 is the seasonal mean for an explicitly given surface inclination and latitude computed by the Insolation3a program. At the present stage, there is no automatic program calculating the seasonal mean. However, its value can be calculated with sufficient accuracy as arithmetic mean of the data of 7, 17 and 27 May, 6, 16 and 26 June, 6, 16 and 26 July and 5, 15 and 25 August.

Overall structure-derived insolation – The overall insolation of a soil surface derived from habitat structure INSHA is the product of the insolation values remaining after passage of tree canopy and herb layer and of inclination-dependent insolation

$$\mathrm{INSHA} = \mathrm{INSTR} * \mathrm{INSHE} * \mathrm{INSIN} \quad [32].$$

3.3.2. Temperature-derived estimation of insolation

An alternative to estimation of soil insolation by habitat structure is its direct derivation from air temperature, soil temperature and solar radiation in a procedure similar to that given in section 3.2.5. Sunshine hours SUN, actual soil temperature TS, the deviations DIF1 and DIF2 of air temperature history TAA from standard air temperature TAS and standard basic soil temperature TSB are needed. Since soil temperature is highly correlated with air temperature, the differences DIF1 and DIF2 can be used to estimate the actual difference of the soil temperature from TSB. When DIF1 is the difference of air temperature history for zero-insolation soils and DIF2 that for full-insolation soils and when a prejudice on insolation is avoided, the actual basic soil temperature TSB_1 is estimated by

$TSB_I = TSB + (DIF1 + DIF2) / 2$ [33].

As the next step, the difference DEV of measured soil temperature TS from actual basic soil temperature TSB_i relativ to SUN is calculated by

$DEV = (TS - TSB_i) / SUN$ [34].

Plotting of structure-derived insolation INSHA against DEV results in a highly significant function with

$INSHA = 0.5339\ DEV + 0.196\ (n = 226, r = 0.868, p < 0.0001)$ [35].

This function is used to calculate a temperature-derived insolation INSTE. INSHA and INSTE are defined here to have values between 0 and 1 but for several data points the function predicts INSTE < 0 or > 1. Accordingly, all points with DEV < –0.371 are allocated to INSTE = 0 and those with DEV > 1.506 to INSTE = 1. The weak point of the structure-derived estimation of insolation is an insufficient reflexion of complicated habitat mosaic structures, and the weakness of the temperature-derived method lies in the possibility of measuring errors. Integration of both methods in a final insolation value

$INS = (INSHA + INSTE) / 2$ [36]

results in data which are in better agreement with subjective predictions than each method alone.

The weighting under which TSCA and TSCS contribute to overall calibrated maximum soil temperature TSCO of a given natural habitat is finally defined by

$TSCO = TSCA * (1 - INS) + TSCS * INS$ [37].

3.4. Consideration of local sunshine frequency

TSCO is a most important habitat parameter but it does not consider the local or regional sunshine frequency. The maximum of sunshine hours measured by the systems used in the meteorological stations is 96 % of AST. If relative sunshine frequency of a locality SUNR is defined as the quotient of the seasonal means of measured and maximum measurable sunshine hours

$SUNR = \sum_{i=1}^{123} SUN / \sum_{i=1}^{123} 0.96\ AST$ [38],

these data vary in the German stations between 0.369 (Brocken/Harz) and 0.552 (Kap Arkona/Rügen). TSCM, the seasonal mean of calibrated maximum soil temperatures under consideration of local sunshine frequency, is then according to functions [36] – [38]

$TSCM = TSCO * SUNR + TSB * (1 - SUNR)$ [39].

3.5. Prediction of habitat temperatures by a catalogue of guiding values for microhabitat spots

The method described above allows the use of single-day temperature measurements to estimate calibrated habitat temperatures. However, dependency from standard radiation days may cause serious problems with obtaining measurements in very cloudy summer seasons. In such cases, a prediction of habitat temperatures is an acceptable solution if certain conditions are given. The basis for such predictions is a catalogue of standard microhabitat and habitat temperatures that are referred to Central Europe at 51°N, 11°E, 300 m a.s.l., horizontal surfaces and the TAS of the years 1977 – 2006. The generation of such a catalogue of guiding values as mean values of measurements taken at geographically different sites needs knowledge on the dependency of TSCA and TSCS values from latitude, altitude and longitude. In Central Europe, these temperatures decrease with growing altitude, growing latitude and falling longitude.

Before generating guiding values, microhabitats or habitats must be ordered into groups of similar surface structure, substrate properties and overall insolation. Each group of similar microhabitat/habitat is treated as an entity and defined by average parameters. Such groups, for example, are on the microhabitat scale »bare limestone protosoil«, »bare sandy soil«, »closed moss crusts of the *Polytrichum piliferum* type in open habitats«. On the habitat scale exemplary groups are »old *Fagus sylvatica* forests with > 80 % canopy closure«, »40 – 70 cm high *Alopecurus pratensis* meadows« or »closed, 25 – 40 cm high *Calluna* heath«. In zero-insolation soils, TSCA approximates to TSB and is estimated by function [2]. In full-insolation soils the basic function was estimated by a highly significant trivariate regression from the TSCS data of the 54 DWD weather stations ($n = 54, r = 0.674, p < 0.0001$) with

$$TSCS_{pre} = -0.293\ LAT + 0.214\ LON - 0.00868\ ALT + 44.662 \qquad [40].$$

The guiding values TSCG were found in several steps. At first a microhabitat/habitat-specific temperature coefficient calibrated against zero-insolation conditions was calculated as

$$C(0) = TSCO\ /\ (-0.694\ LAT + 0.078\ LON - 0.00661\ ALT + 51.70) \qquad [41].$$

For full-insolation conditions and when the microhabitat spot is inclined, its thermal inclination component DIF_{in} is estimated by

$$DIF_{in} = 0.00025618 * AST80 * (SRU_5 - SRU_{5hor}) \qquad [42],$$

where SRU_{5hor} and SRU_5 are the seasonal means for a horizontal surface and the given spot respectively (see also function [21]). The horizontal reference value $TSCO_{hor}$ is then calculated as

$$TSCO_{hor} = TSCO - DIF_{in} \qquad [43].$$

If the spot is horizontal, $TSCO_{hor}$ is replaced with TSCO. The specific temperature coefficient calibrated against the full-insolation condition is then calculated with

$$C(1) = TSCO_{hor}\ /\ (-0.293\ LAT + 0.214\ LON - 0.00868\ ALT + 44.66) \qquad [44]$$

The arithmetic means of the C(0) and C(1) of all habitats belonging to the same group mC0 and mC1 were then used to calculate the guiding value TSCG referring to 51°N, 11°E, 300 m and horizontal surfaces with

$$TSCG = mC0 * (1 - INS) * 15.18 + mC1 * INS * 29.47 \qquad [45]$$

For a prediction which TSCS a given microhabitat/habitat would achieve at a given latitude, longitude, altitude and inclination, the removal of the inclination component of function [42] must be reversed. The inclination-right full-insolation soil temperature $TSCS_{inc}$ is then given by

$$TSCS_{inc} = TSCS_{pre} + DIF_{in} \qquad [46].$$

The overall predicted soil temperature $TSCO_{pred}$ is then

$$TSCO_{pred} = mC0 * (1 - INS) * TSB + INS * (mC1 * TSCS_{pre} + DIF_{in}) \qquad [47].$$

The results of this calculation process are given by two examples. The example for full-insolation soils refers to a group of structurally similar patches completely covered by a solid and 1.5 – 2.5 cm thick crust of dark moss (in growth form comparable to *Polytrichum piliferum* and *Ceratodon purpureus*) and the example for low-insolation soils to the group 60 to 125 years old *Picea abies* forests (Tabs 4 and 5). The mean deviation between TSCO and $TSCO_{pred}$ is 1.00 °C in the moss crust group and 0.70 °C in the spruce forest group. Considering a mean measuring error of ±1.97 °C within the full-insolation soils (according to DWD data) and a mean measuring error of ±0.73 °C within the zero-insolation soil, the predictions for some habitat spots are probably more realistic than single-day direct measurements (Lausche and Zscheiplitz in the moss crust group, Central Upper Lusatia in the spruce forest group).

Tab. 4 Soil temperature at 35 mm depth under the surface of solid moss patches similar to the *Polytrichum piliferum* and *Ceratodon purpureus* growth type. The number of measuring days is given in brackets.

Site	**year**	**LAT [°N]**	**LON [°E]**	**ALT [m]**	**TS [°C]**	**TSCO [°C]**	**$TSCO_{pred}$ [°C]**
Daubitz, sand (n = 2)	1981 2004	51.41	14.88	140	35.35	34.23	32.78
Zscheiplitz limestone (n = 1)	2006	51.22	11.73	190	35.51	30.44	32.19
Meisdorf, greywacke (n = 1)	1980	51.68	11.27	260	28.60	33.37	33.27
Königshain, granite (n = 1)	1988	51.17	14.83	305	33.40	30.22	31.25
Lausche, phonolite (n = 1)	2003	50.85	14.64	775	33.30	28.16	26.67
Giant Mountains, granite (n = 4)	2004 2006	50.78	15.55	1490	21.04	19.53	19.72

Tab. 5 Soil temperature within 60 to 125 years old *Picea abies* forests at 35 mm depth as weighted average of all microhabitat spots. The number of measuring days is given in brackets.

Site	**year**	**LAT [°N]**	**LON [°E]**	**ALT [m]**	**TS [°C]**	**TSCO [°C]**	**$TSCO_{pred}$ [°C]**
Central Upper Lusatia (n = 1)	2003	51.21	14.86	203	15.7	14.03	15.67
Iser Mountains (n = 1)	2002	50.87	15.33	907	14.5	12.21	11.67
Bavarian Forest, site 1.3 (n = 1)	2002	48.96	13.38	885	16.16	13.33	12.71
Bavarian Forest, site 3.1 (n = 1)	2002	48.88	13.63	810	16.20	14.11	13.34
Bavarian Forest, site 3.2 (n = 2)	2002	48.93	13.35	810	16.52	13.42	13.49
Bavarian Forest, site 3.3 (n = 3)	2002	48.88	13.63	750	16.87	14.33	13.76

Tab. 6 presents habitat-specific guiding values that allow some interesting generalisations. Open soil patches without vegetation show similar temperatures rather independent from soil substrate and geological outcrop. Soils under thin and dense moss or lichen crusts heat up slightly stronger than average bare soils. *Sphagnum* pads in open and wet peat bogs reach surprisingly high temperatures comparable to those under plant pads in xerothermous grassland or rocky areas. Soil temperatures in forests are closely correlated to the mean tree cover and herb cover and are lowest in *Fagus sylvatica* forests and moist to wet *Alnus glutinosa* fenwoods when referred to 51°N, 11°E and 300 m – it is clear that these two forest types cannot reach the low temperatures of montane *Picea abies* forests when local temperatures over the whole geographical gradient are considered.

Tab. 6 Examples for microhabitat-specific guiding values TSCG referring to 51°N, 11°E, 300 m, standard air temperature conditions and horizontal surfaces.

microhabitat/habitat type	n	INS	TSCG [°C]
rock crevice in granite and basalt /open sun-exposed rock	4	0.87	33.61
bare sand /open sand area	9	0.89	31.12
moss of *Polytrichum strictum* growth type or lichen crusts on sand, basalt, granite, greywacke, limestone	13	0.78	30.60
bare limestone protosoil /xerothermous grassland	9	0.93	29.48
bare soil on basalt, phonolite, greywacke, brown soil /xerothermous grassland	12	0.89	29.35
Pads of *Thymus*, *Teucrium* and *Potentilla* on limestone; 3 cm high, 10 cm diameter/xerothermous grassland	3	0.90	25.87
Sphagnum pads in open peat bog	8	0.71	25.48
below *Hieracium pilosella* plant /open sandy area; basalt	4	0.81	25.37
Carex humilis bult, diameter ±24 cm, height ±11 cm, /xerothermous limestone grassland	2	0.67	23.68
Sesleria bult, diameter ±24 cm, height ±13 cm, /xerothermous limestone grassland	2	0.65	22.98
Cynanchum vincetoxicum stand on basalt; mean height 40 cm, cover 80 % /open sun-exposed rock	2	0.52	19.95
different *Pinus sylvestris* woods; age 60 – 100, ±55 % tree cover, ±32 % herb cover of 18 cm mean height	8	0.26	17.79
dense *Sambucus* or *Ligustrum* shrub; 98 % cover	2	0.10	15.49
Picea abies forests; age 60 – 125 years; ±81 % tree cover, ±14 % herb cover of 28 cm mean height	9	0.10	14.89
dense *Erica* bult, 30 cm high; in wet *Erica* heathland of 88 % herb cover	2	0.17	14.86
Tilia-Acer-Carpinus-Ulmus woodlands; tree cover 86 %, herb cover 62 %	5	0.08	14.46
fresh, ±80 cm high *Alopecurus* meadows; 100 % herb cover	2	0.07	14.10
primary *Alnus* fenwoods; ±80 % tree cover, ±80 % herb cover of 40 cm mean height	2	0.06	13.34
60 – 100 years old *Fagus* forest; tree cover ±94 %, herb cover 8 % and 10 cm mean height	6	0.05	13.32

4. Discussion

4.1. Results of calibration procedures and the influence of factors not considered

Final results of calibration procedures are given in Tab. 7. In the zero-insolation soil, standard deviation was reduced in air-temperature-calibrated soil temperature TSCA to ±0.73 °C or 30.0 % of the primary, uncalibrated values. This corresponds to 2.6 % of the total range of calibrated soil temperatures observed in all habitats in Germany between 0 and 1500 m a.s.l. [7, 35.5] °C. In the full-insolation soils, standard deviation of sunshine-calibrated soil temperature TSCS was reduced to ±1.97 °C or 34 % of the primary, uncalibrated values for any weather situation which corresponds to 6.7 % of the total range.

The error of the TSCO values could possibly be minimised when wind velocity and soil moisture are considered. High wind velocity and soil moisture are expected to reduce soil temperatures particularly in open habitats with full-insolation soils. The influence of wind velocity was clearly demonstrated – both under the conditions of standard radiation days as well as for any weather situation (Fig. 7). Wind velocity was 3.18 ±1.42 [0.08, 12.18] m/s on 2589 standard radiation days in 54 DWD stations. When the difference ΔT between daily value and the station mean of TSCO was described as a function of the difference ΔW between the daily value and station mean of wind velocity, the best description is offered by a quadratic function with

$$\Delta T = -0.0565\ \Delta W^2 - 0.2858\ \Delta W + 0.092\ (n = 2589,\ r = 0.259,\ p < 0.0001) \qquad [48].$$

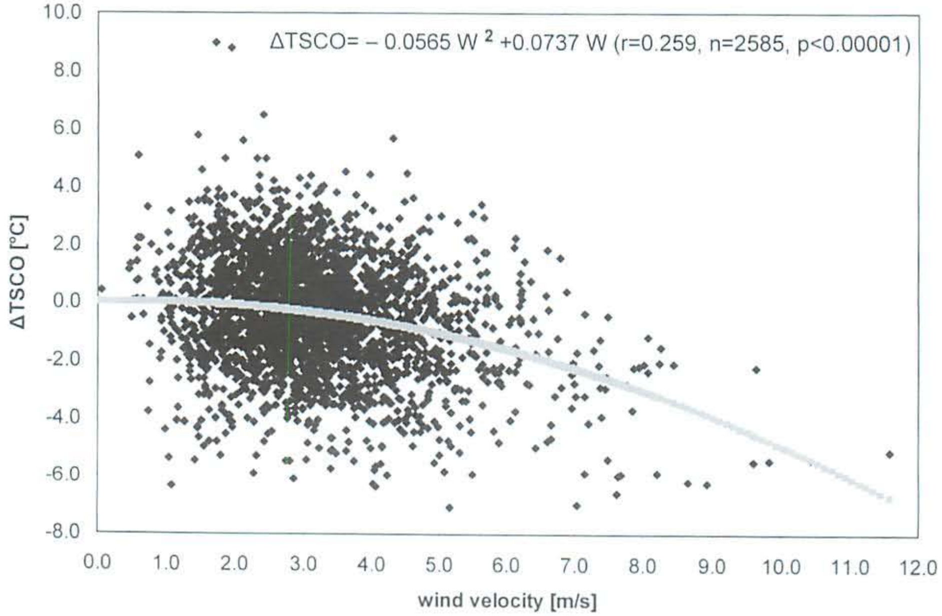

Fig. 7 Wind-induced decrease of air-temperature/sunshine-corrected soil temperature TSCO during radiation days with a minimum of 9 sunshine hours.

Tab. 7 Data of one zero-insolation soil 1 May to 31 August 2003 and of 54 full-insolation soils 1 May to 11 August 2003. Given are air temperature in 2 m height (TA) and uncalibrated primary soil temperature (TS) for any weather situation and n station days and sunshine-calibrated maximum soil temperature TSCS for i days with SUN > 8.9 h.

		TA		TS		TSCO		
	n	mean	SD	mean	SD	mean	SD	i
zero-insolation soil:								
Görlitz-Landeskrone-N	123	18.51	3.64	14.62	2.43	12.80	0.73	n.c.
full-insolation soils:								
Aue	103	17.76	3.88	25.59	5.80	30.24	1.98	41
Augsburg	103	18.32	3.95	31.13	6.20	31.42	1.99	52
Bad Marienberg	88	16.25	4.99	26.12	6.57	26.73	2.08	38
Bamberg	103	19.40	4.24	28.83	4.87	27.94	1.85	51
Baruth	103	18.34	3.55	34.36	5.99	34.88	2.75	44
Braunlage	102	15.30	4.45	20.68	4.76	19.47	1.66	42
Carlsfeld	99	14.63	4.23	27.18	5.84	27.76	2.02	41
Chemnitz	103	18.00	4.10	28.64	5.94	28.54	1.68	45
Erdinger Moos	100	19.45	4.14	30.84	6.47	29.17	2.20	58
Erfurt-Bindersleben	102	17.94	4.22	29.12	5.66	28.88	1.55	49
Fichtelberg	100	12.63	4.47	25.55	6.44	25.78	2.44	41
Frankfurt/Main	101	20.49	4.55	33.14	6.76	32.98	2.18	51
Freiburg	103	21.96	4.84	32.32	7.16	31.64	1.75	54
Freudenstadt	103	16.99	5.01	29.31	6.02	28.26	2.19	47
Garmisch-Partenkirchen	102	17.53	3.96	30.75	5.22	30.21	1.84	44
Gera-Leumnitz	103	18.24	4.11	26.57	4.97	25.78	1.30	51
Goldberg	103	17.74	3.78	28.36	5.74	29.39	1.93	48
Görlitz	103	18.40	3.70	32.72	6.20	33.62	1.65	55
Grünow	96	17.81	3.66	29.83	5.63	30.42	2.17	45
Hahn	103	17.33	4.74	26.63	5.22	25.83	1.51	53
Harzgerode	103	16.35	4.05	25.82	5.01	25.49	1.65	45
Hof-Hohensaß	103	17.13	4.26	25.35	6.01	25.03	1.85	48
Hohenpeißenberg	103	17.15	4.95	22.35	4.21	19.11	1.56	50
KahlerAsten	103	14.27	4.85	25.22	6.71	25.77	3.33	37
Kleiner Feldberg	86	15.42	5.24	24.55	5.84	24.31	2.05	39
Klippeneck	97	17.00	5.03	24.52	5.40	22.45	1.53	46
Konstanz	103	20.31	4.51	28.74	5.22	26.93	0.96	58
Leipzig-Schkeuditz	102	19.07	3.97	30.22	5.36	29.74	1.91	50
Lindenberg	103	18.83	3.77	29.78	5.35	30.25	1.53	50
Manschnow	103	18.33	3.41	29.94	4.85	30.15	2.26	52
Meiningen	103	17.84	4.57	28.73	6.71	28.44	1.67	48
Menz	101	18.01	3.68	31.66	5.46	32.92	1.66	41
Michelstadt-Vielbrunn	103	18.45	4.76	29.56	6.29	29.09	1.80	56
München	103	20.04	4.42	27.46	4.78	25.67	1.12	56
Neuhaus a.Rennweg	101	15.21	4.89	28.05	6.86	28.25	2.85	48
Oberstdorf	103	16.52	4.02	25.88	5.05	25.46	1.17	44
Öhringen	103	19.93	4.50	32.89	6.98	32.58	1.65	57
Oschatz	103	19.00	3.79	30.37	5.88	30.11	1.90	54
Osterfeld	100	18.51	4.04	30.20	5.63	30.06	2.41	50
Plauen	103	17.78	3.94	32.17	6.48	32.66	2.89	46
Potsdam	100	19.02	3.94	32.44	5.20	31.97	1.55	49
Regensburg	103	19.76	4.21	27.44	4.31	25.33	1.25	52
Schleiz	99	17.74	4.16	27.53	5.55	26.92	1.98	49
Schmücke	101	14.40	4.88	20.75	5.16	19.52	1.96	42
Sonneberg	103	17.12	4.80	26.60	5.80	25.53	1.86	51
Stötten	103	17.85	5.01	28.94	7.25	28.23	3.10	49
Ulm	103	18.76	4.49	24.80	3.74	22.51	1.50	53
Ummendorf	89	18.01	4.13	31.38	6.36	32.33	2.44	39
Wasserkuppe	103	14.98	4.99	25.49	5.98	24.62	3.03	45
Wernigerode	103	18.16	4.01	32.61	5.57	32.95	2.51	46
Wiesenburg	103	17.98	4.23	29.21	5.97	30.25	1.91	46
Wittenberg	103	19.18	4.08	30.43	5.43	30.29	1.63	44
Würzburg	103	19.96	4.56	37.06	8.24	37.38	3.04	55
Zinnwald-Georgenfeld	103	14.39	3.99	28.09	6.59	29.40	2.06	47
total mean		**17.72**	**4.31**	**28.59**	**5.79**	**27.75**	**1.97**	

Transforming this function to directly assess the influence of wind velocity, the temperature decrease ΔT below the situation in a windless day is described as a function of wind velocity W by

$$\Delta T = -0.0565\ W^2 + 0.0737\ W - 0.0009\ (n = 2589,\ r = 0.259,\ p < 0.0001) \qquad [49].$$

Compared to calm weather, wind velocities of 5 m/s would decrease TSCS by only 1.0 °C but one of 10 m/s by as much as 4.9 °C. When subtracting the values of this function from TSCO data of the 54 DWD stations for 2589 radiation days, TSCO is reduced from ±1.97 °C to ±1.90 °C. This moderate effect of correction against wind is mainly explained by the low average wind velocity during radiation days. Despite the significant influence of wind velocity on the maximum soil temperature, this factor was not introduced into the calibration system because of severe practical problems. Natural habitats have no standardised position – they may be situated in surface depressions such as troughs or river valleys, at the food of a slope, behind or in front of a wood verge, within dense woodland or at the top of a slope or on a mountain. Hence, there are extreme deviations from overall wind velocity measured by meteorological stations. The position of these stations is chosen, as far as orography allows, on a plane surface area in sufficient distance from structures that could affect measurements of wind, temperature and sunshine. We have so far no system to compensate for this complicated orographic and vegetational factor when measuring in natural habitats. A way of solving this problem could be to estimate for each habitat spot the average seasonal wind speed. This consideration must include the average regional wind velocity within the spectrum of observed wind directions and must assess how the wind is screened off by orographic or vegetation structures in the environment of the habitat spot. Then, an actual measurement of wind velocity at the spot of soil temperature measurement must be related to the seasonal background.

The influence of previous rainfall on soil temperature is most extreme in open sandy soils but usually weak in soils of zero-insolation habitats irrespective of their water retention capacity. Maximum soil temperatures of a bare, fully sun-exposed sandy river bank near Görlitz were measured on 1 June 2003. The following TSCO was measured in sand patches of otherwise completely similar structure: 22.82 °C at 19 cm above the water table with completely wet sand at the measuring depth of 35 mm, 32.42 °C at 38 cm above the water table with moist sand at measuring depth and 37.39 °C at 55 cm above the water table and completely dry sand at measuring depth. This enormous moisture-dependent temperature variation of sandy soils is accompanied by another extreme – the rapid loss of this effect during dry and warm weather in sandy soils not exposed to ground water. Bare clay soils in similar situation would probably show a similar dependency of temperature from moisture, but the much higher water retention of this material will strongly retard the loss of this effect during xerothermous periods. Soils immediately above the water table will show yet another behaviour. As a consequence there is a very differentiated dynamics of drying out from soil to soil, which complicates assessing the effects of precipitation history. There is no system to correct against this factor.

4.2. Prospects: Applicability in the context of global warming and within other countries

According to Jones & Moberg (2003) and Smith & Reynolds (2005) average global temperature over land and ocean has risen 0.07 °C/10 years from 1901 to 2000 but

0.13 °C/10 years from 1965 – 2005. Long-term trends in Germany above land are significantly correlated to the global situation but show a much stronger increase during the last 40 years: average annual air temperature rose 0.06 °C/10 years from 1901 to 2000 but as much as 0.40 °C/10 years in the period 1965 – 2005 (MÜLLER-WESTERMEIER 2002, data after 2001 from DWD data service). This obviously much accelerated global warming will inevitably have effects on the future applicability of the TSCO/TSCM system. To keep this system realistic, meteorological standard data must be adjusted to climatic development after reasonably short intervals. At the moment a 20-year interval seems sufficient. The TSCO/TSCM system presented here is calibrated with the average climatic situation of the years 1977 – 2006 instead with data of the CLINO reference period 1961 – 1990.

The TSCO/TSCM system developed for the territory of Germany is most probably also applicable unchanged or with minor changes to adjacent countries. To ensure its function, at least the predictions for air temperature standards should be adjusted or checked countrywise. It would be most valuable if some alpine countries could provide further data to check the altitudinal gradient of maximum soil temperature presented here. It is also possible that better mathematical solutions for estimating air-temperature history or influence of sunshine could be developed. A software program guiding through the procedures necessary to calculate TSCO/TSCM data is in preparation. The authors currently use dBASE and Excel programs. Offers for cooperation of programming specialists and mathematicians to transform these to systems more widely used are welcome.

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7. Appendix – synopsis of equations

$\mathrm{TAS_{pred}} = -0.694\ \mathrm{LAT} + 0.078\ \mathrm{LON} - 0.00661\ \mathrm{ALT} + 52.20$ [1]

$\mathrm{TSB} = -0.694\ \mathrm{LAT} + 0.078\ \mathrm{LON} - 0.00661\ \mathrm{ALT} + 51.70$ [2]

$\mathrm{W} = 1 + 0.00005\ \mathrm{e}^{(A\ *\ \mathrm{DAY})}$ [3]

$\mathrm{TAA} = \sum_{i=1}^{15} (\mathrm{W_i} * \mathrm{TA_i}) / \sum_{i=1}^{15} \mathrm{W_i}$ [4]

$\mathrm{TS} = 0.8446\ \mathrm{TAA} - 0.927\ (r = 0.954,\ n = 123,\ p < 0.00001)$ *[5]*

$\mathrm{DIF} = \mathrm{TAA} - \mathrm{TAS_{real}}$ [6]

$\mathrm{TSCAi} = \mathrm{TS} - \mathrm{DIF}$ [7]

$\mathrm{DEV} = -0.1554\ \mathrm{DIF} + 0.43\ (r = -0.507,\ n = 123)$ [8]

$\mathrm{TSCA} = \mathrm{TS} - \mathrm{DIF} - (-0.1554\ \mathrm{DIF})$ [9]

$\mathrm{TSCA} = \mathrm{TS} - 0.8446\ \mathrm{DIF}$ [10]

$\mathrm{AST} = 0.004242\ \mathrm{LAT}^2 - 0.29606\ \mathrm{LAT} + 19.405$ [11]

$\mathrm{AST80} = 0.8\ (0.004242\ \mathrm{LAT}^2 - 0.29606\ \mathrm{LAT} + 19.405)$ [12]

$\mathrm{AST80} = 0.003394\ \mathrm{LAT}^2 - 0.23685\ \mathrm{LAT} + 15.524$ [13]

$\mathrm{SUN} = \mathrm{RSV}\ (0.003394\ \mathrm{LAT}^2 - 0.23685\ \mathrm{LAT} + 15.524)$ [14]

$\Delta\mathrm{TS} = -0.0188\ \mathrm{SUN}^2 + 0.8378\ \mathrm{SUN}\ (n = 5774,\ r = 0.736,\ p < 0.0001)$ [15]

$\Delta\mathrm{TS} = 0.404\ \mathrm{SUN} + 0.002\ (n = 2592,\ r = 0.330,\ p < 0.0001)$ [16]

$\Delta\mathrm{TS} = 0.431\ \Delta\mathrm{SUN} + 0.814\ (n = 2569,\ r = 0.555,\ p < 0.0001)$ [17]

$\mathrm{TSCS} = \mathrm{TS} - \mathrm{DIF} - 0.413\ (\mathrm{SUN} - \mathrm{AST80})$ [18]

$\mathrm{TSB_i} = \mathrm{TSB} + \mathrm{DIF2}$ [19]

$\mathrm{H} = \Delta\mathrm{TS} / \mathrm{SUN}$ [20]

$\mathrm{H} = 0.00025618\ \mathrm{SRU_{i5}} - 0.6830\ (r = 0.4423,\ n = 43,\ p < 0.01)$ [21]

$\mathrm{H} = 0.00031527\ \mathrm{SRU_{i5}} - 0.8523\ (r = 0.9987,\ n = 4,\ p < 0.01)$ [22]

$$\mathrm{TS} = (0.00025618\ \mathrm{SRUI}_5 - 0.6830) * \mathrm{SUN} + \mathrm{TSB}_i \qquad [23]$$

$$\mathrm{INSTR} = (0.0004031\ \mathrm{LAT}^2 - 0.05178\ \mathrm{LAT} + 0.4242) * \mathrm{TRC} + 1 \qquad [24]$$

$$\mathrm{TSCS} = -3.5083\ \ln(\mathrm{HEH}) + 28.44\ (n = 18,\ r = 0.925,\ p < 0.0001) \qquad [25]$$

$$\mathrm{INSHEH} = -0.235456\ \ln(\mathrm{HEH}) + 1\ (n = 18,\ r = 0.925,\ p < 0.0001) \qquad [26]$$

$$\mathrm{EXTHEH} = 1 - \mathrm{INSHEH} \qquad [27]$$

$$\mathrm{EXTOV} = \mathrm{EXTHEH} * \mathrm{HEC} \qquad [28]$$

$$\mathrm{INSHE} = 1 - \mathrm{EXTOV} \qquad [29]$$

$$\mathrm{SRUM}_5 = -0.4957\ \mathrm{LAT}^2 + 29.8532\ \mathrm{LAT} + 7784.9 \qquad [30]$$

$$\mathrm{INSIN} = \mathrm{SRU}_5/\mathrm{SRUM}_5 \qquad [31]$$

$$\mathrm{INSHA} = \mathrm{INSTR} * \mathrm{INSHE} * \mathrm{INSIN} \qquad [32]$$

$$\mathrm{TSB}_I = \mathrm{TSB} + (\mathrm{DIF1} + \mathrm{DIF2}) / 2 \qquad [33]$$

$$\mathrm{DEV} = (\mathrm{TS} - \mathrm{TSB}_i) / \mathrm{SUN} \qquad [34]$$

$$\mathrm{INSHA} = 0.5339\ \mathrm{DEV} + 0.196\ (n = 226,\ r = 0.868,\ p < 0.0001) \qquad [35]$$

$$\mathrm{INS} = (\mathrm{INSHA} + \mathrm{INSTE}) / 2 \qquad [36]$$

$$\mathrm{TSCO} = \mathrm{TSCA} * (1 - \mathrm{INS}) + \mathrm{TSCS} * \mathrm{INS} \qquad [37]$$

$$\mathrm{SUNR} = \sum_{i=1}^{123} \mathrm{SUN} \Big/ \sum_{i=1}^{123} 0.96\ \mathrm{AST} \qquad [38]$$

$$\mathrm{TSCM} = \mathrm{TSCO} * \mathrm{SUNR} + \mathrm{TSB} * (1 - \mathrm{SUNR}) \qquad [39]$$

$$\mathrm{TSCS}_{\mathrm{pre}} = -0.293\ \mathrm{LAT} + 0.214\ \mathrm{LON} - 0.00868\ \mathrm{ALT} + 44.662 \qquad [40]$$

$$C(0) = \mathrm{TSCO} / (-0.694\ \mathrm{LAT} + 0.078\ \mathrm{LON} - 0.00661\ \mathrm{ALT} + 51.70) \qquad [41]$$

$$\mathrm{DIF}_{\mathrm{in}} = 0.00025618 * \mathrm{AST80} * (\mathrm{SRU}_5 - \mathrm{SRU}_{5\mathrm{hor}}) \qquad [42]$$

$$\mathrm{TSCO}_{\mathrm{hor}} = \mathrm{TSCO} - \mathrm{DIF}_{\mathrm{in}} \qquad [43]$$

$$C(1) = \mathrm{TSCO}_{\mathrm{hor}} / (-0.293\ \mathrm{LAT} + 0.214\ \mathrm{LON} - 0.00868\ \mathrm{ALT} + 44.66) \qquad [44]$$

$$\mathrm{TSCG} = \mathrm{mC0} * (1 - \mathrm{INS}) * 15.18 + \mathrm{mC1} * \mathrm{INS} * 29.47 \qquad [45]$$

$$\mathrm{TSCS}_{\mathrm{inc}} = \mathrm{TSCS}_{\mathrm{pre}} + \mathrm{DIF}_{\mathrm{in}} \qquad [46]$$

$$\mathrm{TSCO}_{\mathrm{pred}} = \mathrm{mC0} * (1 - \mathrm{INS}) * \mathrm{TSB} + \mathrm{INS} * (\mathrm{mC1} * \mathrm{TSCS}_{\mathrm{pre}} + \mathrm{DIF}_{\mathrm{in}}) \qquad [47]$$

$$\Delta T = -0.0565\ \Delta W^2 - 0.2858\ \Delta W + 0.092\ (n = 2589,\ r = 0.259,\ p < 0.0001) \qquad [48]$$

$$\Delta T = -0.0565\ W^2 + 0.0737\ W - 0.0009\ (n = 2589,\ r = 0.259,\ p < 0.0001) \qquad [49]$$

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