A method for standardized description of soil temperatures in terrestrial ecosystems – data sources and theoretical background to develop the *CalibSoil* software program*

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* This is a further developed version of the methodological paper of Seifert & Pannier (2007). Some sections remained unchanged referring to old data bases while others were developed under inclusion of new data. This explains some disagreements in the number and distribution of reference data.

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 calibration against long-term meteorological and astronomical standards. The first target value, the calibrated maximum soil temperature (TSCmax), 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 this locality and when actual sunshine duration amounts 80 % of the seasonal mean of astronomically possible sunshine duration at the given latitude. A dynamic meteorological standard, following the long-term climate change, was defined by the data of the next meteorological station/s as average air temperature 1 May-31 August of the 10 years before the year of measurement. As standard measuring depth was defined 35 mm. TSCmax ranged between 8°C and 34°C over all habitats investigated between 46.5-54.10°N, 9.6-15.6°E and 5-2097 m a.s.l. The mean error of TSCmax 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 TSCmax method is extended by consideration of relative sunshine duration which allows the calculation of an all-weather seasonal mean of soil temperature (TSCmean). Because of the high correlation of temperatures in topsoil, soil surface and lower field layer plants, the TSCmax/TSCmean method is recommended as standard system not only for soil biology but also for investigations of any epi- and hypogaeic group of organisms.

Content

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, a topsoil in a mountain spruce forest in the Iser Mountains at an altitude of 850 m achieved the same temperature in the hot summer 2003 as in a structurally similar colline spruce forest at 250 m near Görlitz in the relatively cold summer 1987. The typical long-term summer difference between these two *Picea abies*-stands is 3.8 K at least.

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 tries 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 (TSCmax) was 8 to 34°C in all habitats between 5 and 2097 meters 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 thermodynamic soils shows the practical value of the system. TSCmax, defined as the daily maximum at 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 to different hypogaeic and epigaean 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. Material 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 meters 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 focused 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 heterogenous 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 posteriorly. 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. As best system for spot measurements in the ecological context finally proved 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 to measure 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). Data sets on the Giant mountains were supplied by the Department of Meteorology of the University of Wroclaw. A total of 498150 station days in the period 1 May to 31 August from the years 1977-2006 of 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, Duesseldorf, Emden, Erdinger Moos, Erfurt-Bindersleben, Essen, Feldberg/Schwarzwald, Fichtelberg, Frankfurt/Main, Freiburg, Freudenstadt, Fürstenzell, Gardelegen, Garmisch-Partenkirchen, Geisenheim, Gera-Leumnitz, Giessen, Goerlitz, Goettingen, Goldberg, Greifswald, Grosser Arber, Gruenow, 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, Luebeck-Blankensee, Luechow, Luedenscheid, Magdeburg, Mannheim, Manschnow, Marnitz, Meiningen, Menz, Michelstadt-Vielbrunn, Muehldorf, Muenchen-City, Muenster-Osnabrueck/Airport, Neubrandenburg, Neuhaus am Rennweg, Neuruppin, Norderney, Nuerburg, Nuerburg-Barweiler, Nuernberg, Oberstdorf, Oehringen, Oldenburg i.O., Oschatz, Osnabrück, Osterfeld, Plauen, Potsdam, Regensburg, Rostock-Warnemünde, Saarbrücken, Sankt Peter-Ording, Schleiz, Schleswig, Schmücke, Schwerin, Soltau, Sonneberg, Stoetten, Straubing, Stuttgart-Airport, Stuttgart-Schnarrenberg, Szrenica /Giant Mountain (Poland), Trier(Petrisberg), Ueckermünde, Ulm, Ummendorf, Wasserkuppe, Weiden/Oberpfalz, Weinbiet/Pfälzer Wald, Weissenburg, Wendelstein, Wernigerode, Westermarkelsdorf, Wiesenburg, Wittenberg, Wuerzburg, Zinnwald-Georgenfeld, Zugspitze.

2.3. The 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 calibration 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 near Görlitz at 14.93°E, 51.06°N (Landeskrone). No direct sunlight fell on the measuring spot to any hour of 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. The 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 in 50 mm depth was constantly recorded in 10-minute intervals for 5474 station days of any weather situation giving a total of 788256 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 m² patches of soil with completely bare surface and were fully sun-exposed from sunrise to sunset. The former measurements in depths of 20 mm, which would have allowed to interpolate on the situation at 35 mm depth, are currently no longer performed by the weather stations. However, there was found a very high correlation of maximum soil temperatures TS_{35} at 35 mm depth and TS_{50} in 50 mm depth 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

$$TS_{35} = 1.0287\ TS_{50} + 0.995\ (r = 0.999, n=19).$$

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 at standard radiation days during 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
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	Oehringen	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	Stoetten	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 Astronomic parameters

Astronomic parameters are calculated by the *CalibSoi* program based upon astronomic parameters and atmospheric extinction parameters of MEEUS(1992) and 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 or inclined 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 meters
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 15-day air temperature and from standard air temperature (10-year mean before the year of measurement): 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 **theoretically achievable 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 duration 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 in 2 m height.

TAA - “15-day air temperature history”: weighted average of TA of the day of soil temperature measurement and of the 14 previous days.

(TAS_{pred} - predicted standard air temperature for the years 1977-2006 given by a regression against LAT, LON and ALT using the data of 135 meteorological stations. Static reference, no longer used)

TAS_{real} - standard air temperature: mean of TA from 1 May to 31 August of the 10 years before the year of soil temperature measurement, defined by data of the next meteorological stations.
This is a dynamic standard for calibration which follows the climate change.

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: mean temperature achieved in zero insolation soils; as medium-term seasonal standard fully correlated with TAS, but in absolute terms 3.3°C lower and in value equal to TSCmin of full insolation soils at standard radiation days.

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

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

TSCmax - 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: TSCmax = TSCA *(1-INS) + TSCS * INS.

TSCmean - calibrated mean soil temperature, -35 mm

TSCmin - calibrated minimum soil temperature, -35 mm

TSmax - maximum daily soil temperature, -35 mm

TSmean - mean daily soil temperature, -35 mm

TSmin - minimum daily soil temperature, -35 mm

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]

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 we explain here basal preconditions in the actual context.

(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 deciding 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-grassy 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 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.

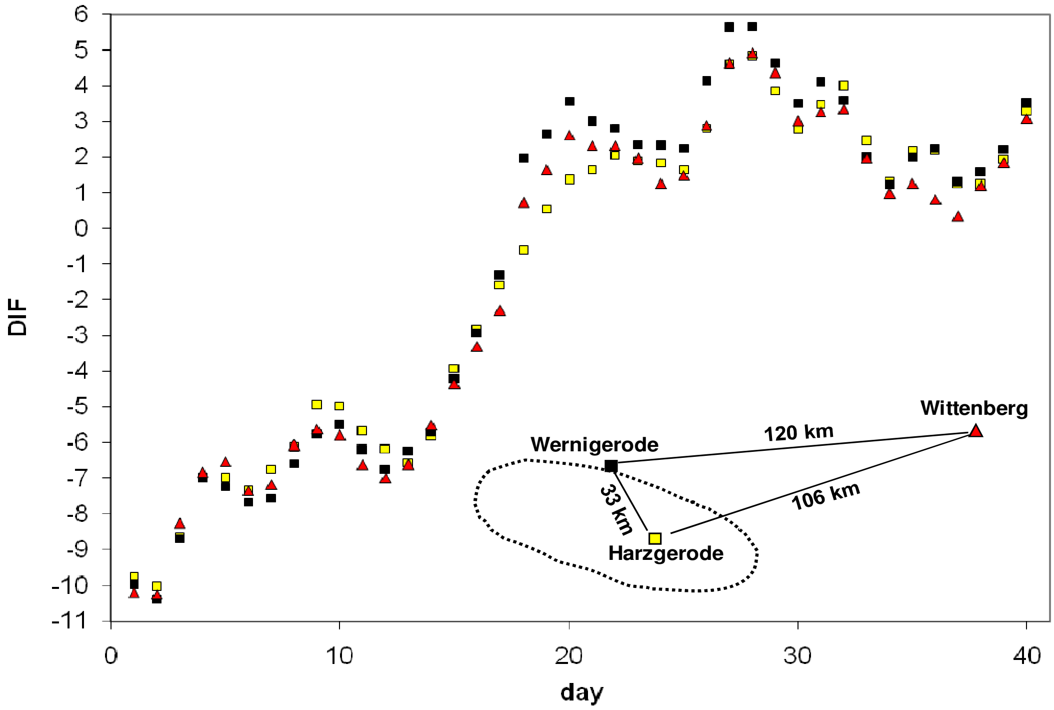
Tab. 2: Minimum, maximum and mean temperatures in soils of different habitats on the Landeskrone near Görlitz 21 June to 10 July 1983. Air temperature at the DWD station Görlitz: minimum 7.0°C, maximum 31.0 °C, overall mean 19.4°C (coldest daily mean 14.2°C, warmest 24.5°C). Under syntopic conditions, 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<0.001]. Hence maxima are also best indicators of mean temperature differences during radiation days. *****value outside the range of the minum-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) The 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 N 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 more than one station are used for a prediction, their data are inversely weighted to their distance from the study plot.

Fig.1. Deviation of the recent 15-day air temperature history from the long-term seasonal mean of air temperature 1 May – 31 August of thee meteorological stations in Sachsen-Anhalt.



(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 in 2 m height is well established (WATSON 1980, SEIFERT 1986, actual weather reports of Deutscher Wetterdienst and of Meteorologischer Dienst der DDR 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.

(e) 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 of significant early spring and autumn activity and breeding in some groups of organisms, this is doubtless 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 biologicaly more reasonable reference period actually appears to be 15 April - 31 August. We maintain the "historical" definition because other calibration references would not change the ranking of temperature values over all habitats.

(f) The most informative and most practicable measuring is performed in topsoil but not too near to soil surface.
Several arguments favour a selection of the standard measuring depth in topsoil. Measurements in only 10 mm depth show high errors because temperature change is very strong if misplacing the

thermometer 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 thermometer. Measurements in deeper soil layers frequently cause heavy 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 lower 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 epigaean 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 top soil and in deeper soil layers down to 50 cm is fully established by soil meteorology (e.g. Täglicher Wetterbericht des Meteorologischen Dienstes der DDR 1961-1990). Hence, the 35-mm level will also provide indirect information on the situation in deeper soil layers as it will be the case for temperatures in lower strata of the herb layer.

(g) 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 in 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 digging in) 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-minimum thermometers are much cheaper, more easy to handle and they can be quickly installed in another habitats of a locality. Apart from deviations occurring in E, SE, SW or W facing 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 p.m. Knowledge on 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. Describing the meteorological standards and calibration procedures

3.2.1 The standard air temperature TAS and the basal soil temperature TSB

The **standard air temperature TAS** is the deciding meteorological standard. It is defined as the mean air temperature at 2 m height of the next meteorological station/s in the period 1 May to 31 August of the ten years before the year of measuring. This is a period long enough to calculate a representative mean and short enough to follow medium-term climate dynamics.

As **basal soil temperature TSB** is defined here the mean temperature a zero-insolation soil (ZIS) would achieve during a standard season. Neglecting the very rare cases of strong geothermal heat emission, a temperature increase above TSB is almost always of solar origin. TSB in ZIS is fully correlated with TAS but in absolute value significantly lower because of heat loss by soil evaporation and the rather slow heat absorption in spring and summer. This retarded temperature dynamics is explained by the fact that temperature exchange proceeds only between soil and air flown in from areas outside of the ZIS habitat and by the fact that soils of ZIS habitats are usually covered by an isolating litter layer. The significant reduction of TSB in ZIS habitats is indicated by the following data sets.

a) A perfect ZIS habitat was given by a fully closed *Carpinus betulus-Acer pseudoplatanus* forest situated at 330 m a.s.l. in a trough at the north slope of Landeskrone near Görlitz. No direct sunlight fell on the measuring spot to any hour of the year and the mean daily temperature amplitude for 123 season days was only 0.99°C at a depth of 35 mm (for details see Seifert & Pannier 2007). Correcting for an altitudinal temperature drop of 0.59°C relative to the DWD station Görlitz (240 m a.s.l.) and referring to the period 1 May to 31 August 2003, the mean daily soil temperature TSmean was **3.69** ± 0.86°C colder than the weighted average of previous air temperature TAA.

b) *Fagus sylvatica* forests with almost closed canopy are almost ideal ZIS habitats. The overall calibrated maximum soil temperature TSCmax in six 60-100 years old *Fagus* forests of ± 94% tree cover in Central Germany was 13.32°C when referred to 51°N, 11°E and 300 m a.s.l. (Seifert & Pannier 2007). Assuming a mean daily temperature amplitude of 1.14°C, the overall calibrated mean soil temperature TSCmean was 12.75°C. This a **-2.93°C** difference to the standard air temperature TAS - the reference of this calibration.

From these data it is reasonable assuming TSB to be 3.3 °C colder than TAS (or TSmean of ideal ZIS habitats being 3.3 °C colder than TAA). Most important in this context is that minimum soil temperatures TSmin of full-insolation soils (FIS) given in the gardens of meteorological stations, drop to a similar value at dawn of standard radiation days:

c) Using data of the DWD stations Würzburg, Plauen, Wernigerode, Baruth and Görlitz from May to August 2003, the average difference between TSmin and TAA was **-3.34** ± 1.73 °C at 246 station days with 12.06 ± 1.66 hours of sunshine (data in SRUI.dbf)

These data indicate the TSmin of FIS habitats at standard radiation days to be approximately equal to TSmean of ZIS habitats. The relation

TSmin of FIS habitats ≈ TSmean of ZIS habitats ≈ TSB ≈ TAS – 3.3°C

allows us to use TSB as standard value for calculation of calibrated mean soil temperature TSCmean for any habitat irrespective of its structure (see function [34] below).

Consequently, the standard basal soil temperature of the study plot TSB_{SP} is estimated by the standard air temperature data of the next meteorological station/s TAS_{Stat} under consideration of altitudinal differences with

$$TSB_{SP} = TAS_{Stat} - 3.3 + (ALT_{Stat} - ALT_{SP}) * 0.00661 \quad [2]$$

with ALT_{Stat} and ALT_{SP} being the altitude of the station and the investigation plot. If data of more than one station are used, the station data are weighted inversely proportional to their distance from the study plot.

If there are three stations and d_1, d_2 and d_3 are the distances of the meteorological stations to the study plot, the weighting factor of station 1 is

$$W_1 = 1/d_1 \ / \ (1/d_1+1/d_2+1/d_3) \qquad [2a]$$

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 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

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

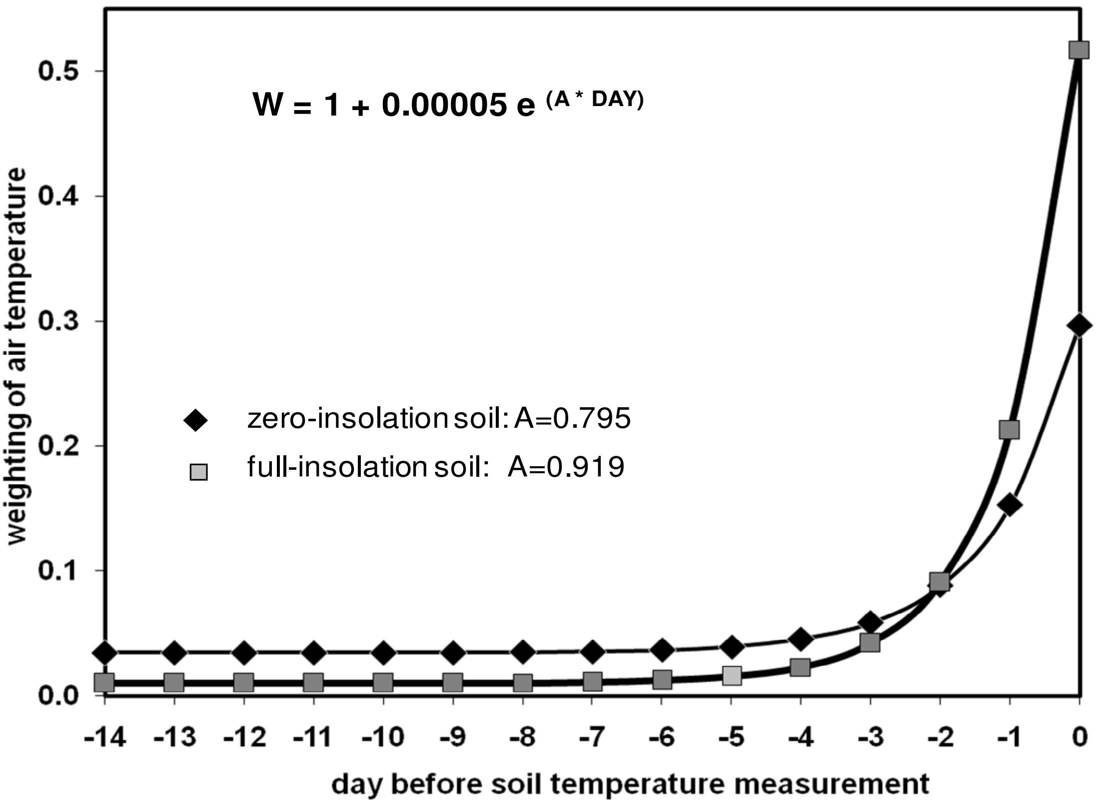
where TA_i is the mean daily air temperature for DAY i=1 to 15. When TAA is lower than the standard air temperature TAS, measured soil temperature TS has to be corrected up and vice versa. Iterative simulations varying the exponential factor ***A*** were performed until correlation between TAA and TS, was highest. The full-insolation and zero-insolation soils differed in their thermodynamic behaviour. 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].

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

$$TS = 0.8446\ TAA - 0.927 \quad (r=0.954, n=123, p<0.00001] \quad [5].$$

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.

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 untill the variance of corrected soil temperatures reached a minimum. The more dynamic behaviour of full-insolation soils is expressed by the higher exponential factor.



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

$$DIF = TAA - TAS_{REAL} \qquad [6].$$

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

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

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 function of DIF by

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

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

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

or

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

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 thermodynamics 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 The standardization of sun shine 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 *CalibSoi* program, the seasonal ***daily*** mean of astronomically possible sunshine hours AST for the period of 1 May to 31 August may be described as follows:

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

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

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

or in equivalent transformation

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

At 51° N, the standard radiation day has AST80 of 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 a strong in the afternoon or (c) when atmospheric extinction was significant but the intensity of direct radiation was just above the 120 W/m² 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 air and cloudless: RSV = 1.20

RSV can then be transformed to SUN by

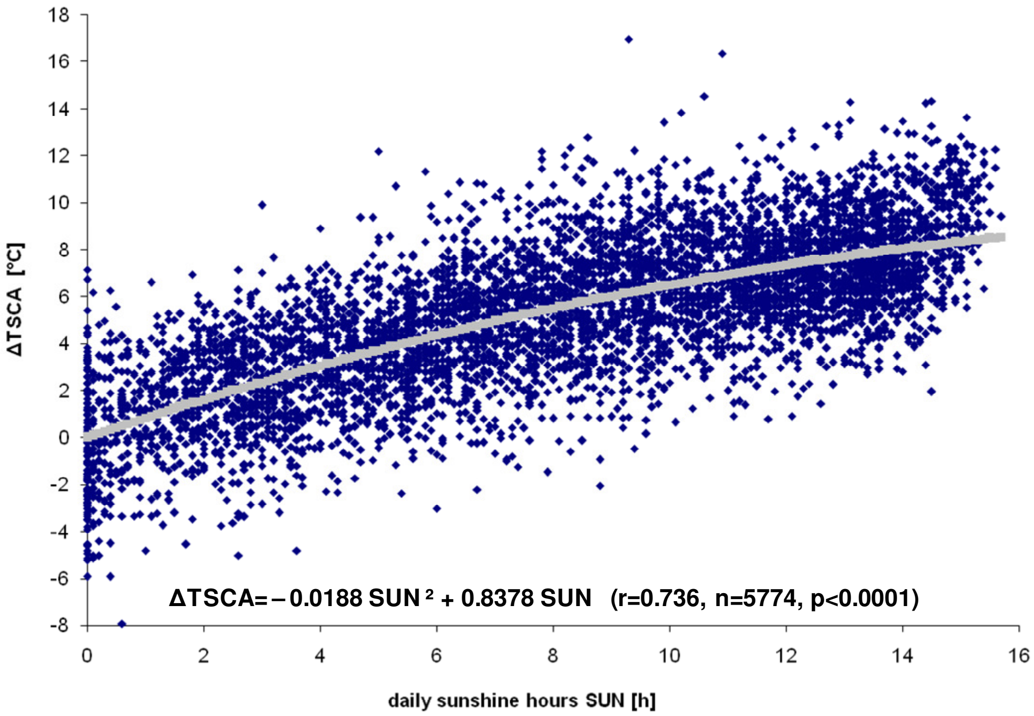
$$SUN = RSV\,(0.003394\,LAT^2 - 0.23685\,LAT + 15.524) \qquad [14].$$

3.2.4 The 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]h a highly significant function is found

$$dTS = -0.0188\,SUN^2 + 0.8378\,SUN \quad (n=5774,\ r=0.736,\ p<0.0001] \quad [15].$$

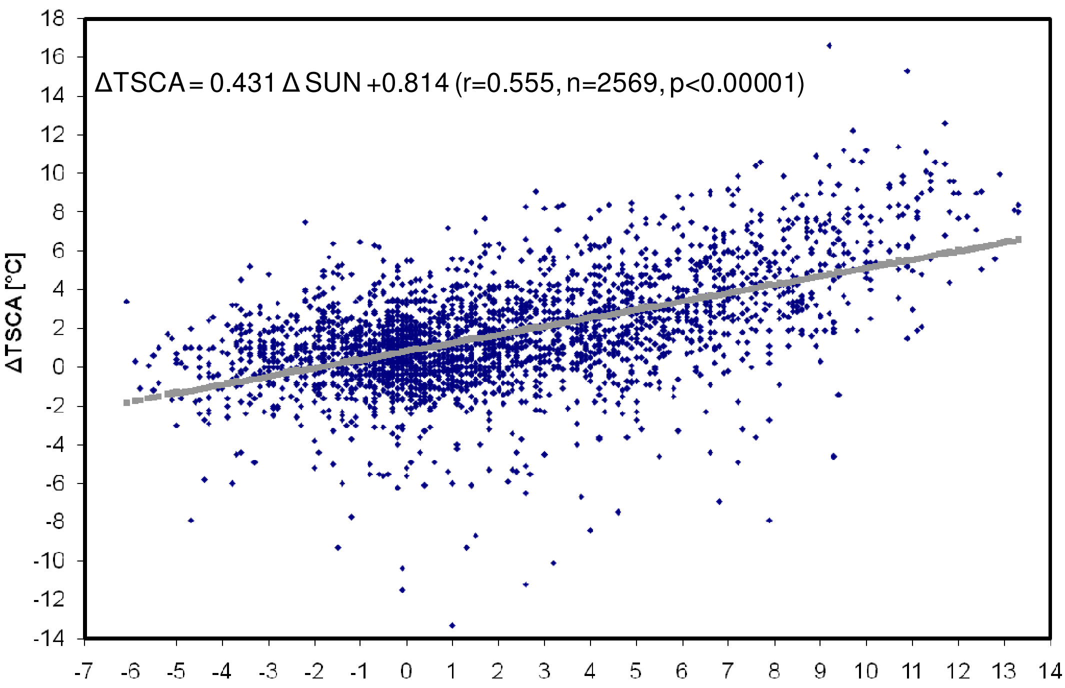
Fig. 3: Temperature increase dTSCA of air-temperature-corrected soil temperature above the seasonal mean as function of daily sunshine duration SUN for any weather situation of May to August 2003 derived from data sets of 54 German stations.



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

$$dTS = 0.404\,SUN + 0.002 \quad (n=2592,\ r=0.330,\ p<0.0001] \quad [16].$$

Fig. 4 Temperature change dTSCA of air-temperature-corrected soil temperature above the seasonal mean plotted against the change of sunshine duration dSUN 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.



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

dTS = 0.431 dSUN +0.814 (n=2569, r=0.555, p<0.0001] [17].

A third approach was iteratively varying the slope *b* of the function TSCS = TS - DIF - *b* (SUN-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

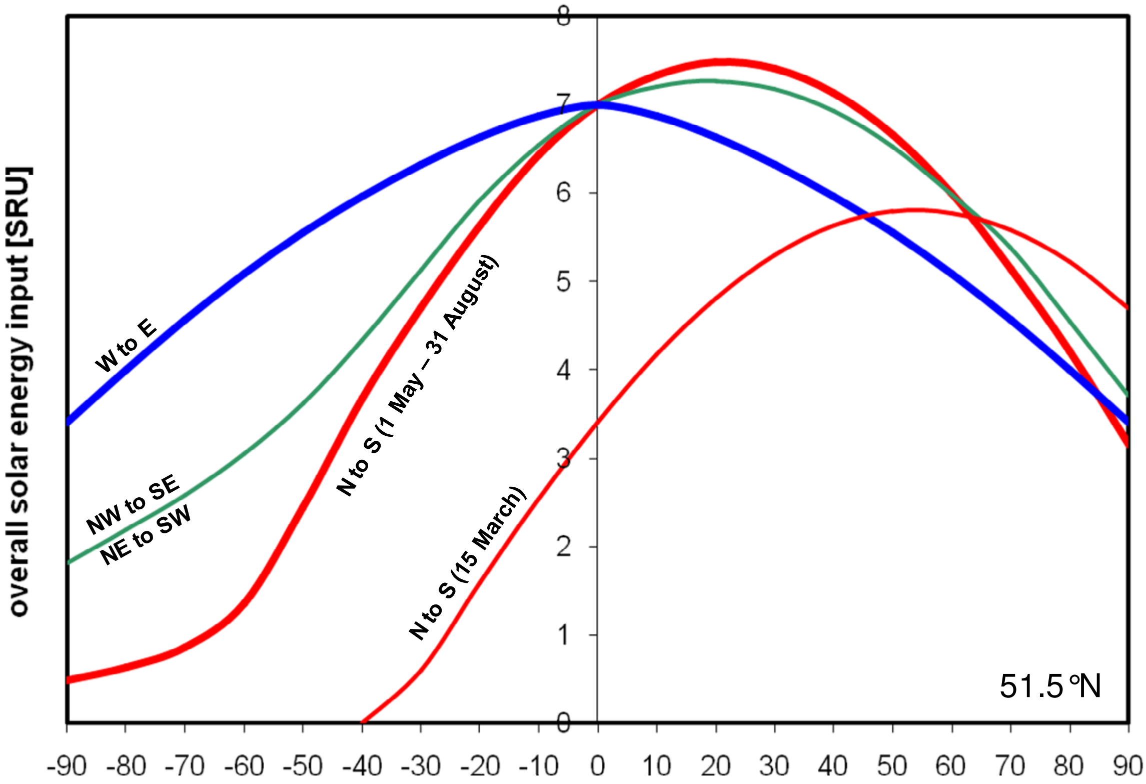
TSCS = TS - DIF - 0.413 (SUN-AST80) [18].

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 *CalibSoil* program calculates the solar energy input falling on a surface expressed in solar radiation units (SRU) integrated for 5-minute intervals. The program considers geographical latitude, elevation, slope and azimuth of surface inclination, astronomical data and atmospheric turbidity. With atmospheric turbidity setting 0.05, it predicts for a horizontal surface at 47°N and 0 m a.s.l. to receive 93 % of the sunshine hours and 108 % of the daily energy input SRU_D than 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-facing surface compared to a horizontal one increases by only 0.169 units (or 2.4 %) on 17 May but by 2.211 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 *CalibSoil* program for 51.5 °N and sea level. 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 as good indicator of overall energy input must not be the best variable for describing temperature dynamics. The following data show that that solar heating of soil from minimum to maximum is better described by the 5-minute maximum value SRU_5. If dTS is the difference between the maximum and the minimum of daily soil temperature and using data from the gardens of the meteorological stations Würzburg and Görlitz from May to August 2003, a highly significant description is provided by a divariate regression of daily sunshine hours SUN and SRU_5

$$dTS = 1.125\ SUN + 0.005142\ SRU_5 - 28.724 \quad (n=206,\ r=0.853) \qquad [19]$$

SUN contributes to this description with a partial correlation of 0.849 and SRU_5 with 0.372. An alternative description replacing SRU_5 with SRU_D achieved a less good fit of data (r=0.810) with a lower partial correlation of SRU_D (0.306).

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 12.38°C, is predicted by function [19] to have a TS of 32.69 °C when horizontal but one of 38.77 °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 34.49 °C and 26.93 °C.

Function [19] also provides good estimates for heating up in the example of artificial structures – i.e., a horizontal and 35° S-inclined surface of a fine sand heap (Tab.3).

Tab. 3: Synchronous and syntopic measurement of equally structured top soils. INC - surface inclination, TS_{min} - minimum soil temperature in early morning, TS_{max} - maximum soil temperature, dTS = TS_{max} - 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}	TS_{max}	dTS (observed)	dTS (predicted)	SUN	SRU_{iD}	SRU_{i5} [10^{-5}]
Kaltwasser 19 July 2006 bare extremely dry sand	0°	18.52	43.58	25.06	23.70	14.8	7.180	6958
Kaltwasser 19 July 2006 bare extremely dry sand	35°S	20.85	50.74	29.89	29.29	14.8	7.319	8046

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 thermodynamic behaviour 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 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 much more parameters and availability of extensive measuring data to estimate these.

The 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 meters above soil surface. Since both this upper and lower height level are far enough from soil surface, heat conduction of absorbed energy to soil can be neglected. The influence of both tree and bush layer is thus fully comparable and consequently they can be considered as same factor. When canopy closure of tree and bush layer is summarized 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

$$INSTR = (0.0004031\ LAT^2 - 0.05178\ LAT + 0.4242) * TRC + 1 \quad [20].$$

This formula has been derived from geometric considerations assuming homogenously distributed trees with globular, equally-sized canopies and equal height and using the SRU_D data provided by the *CalibSoil* program. For 51°N, the formula predicts a zero insolation in the seasonal mean at

TRC>=0.86 which is in agreement with real observations in woodland. Zero insolation begins with TRC>=0.89 at 47°N and with TRC>=0.83 at 55°N.

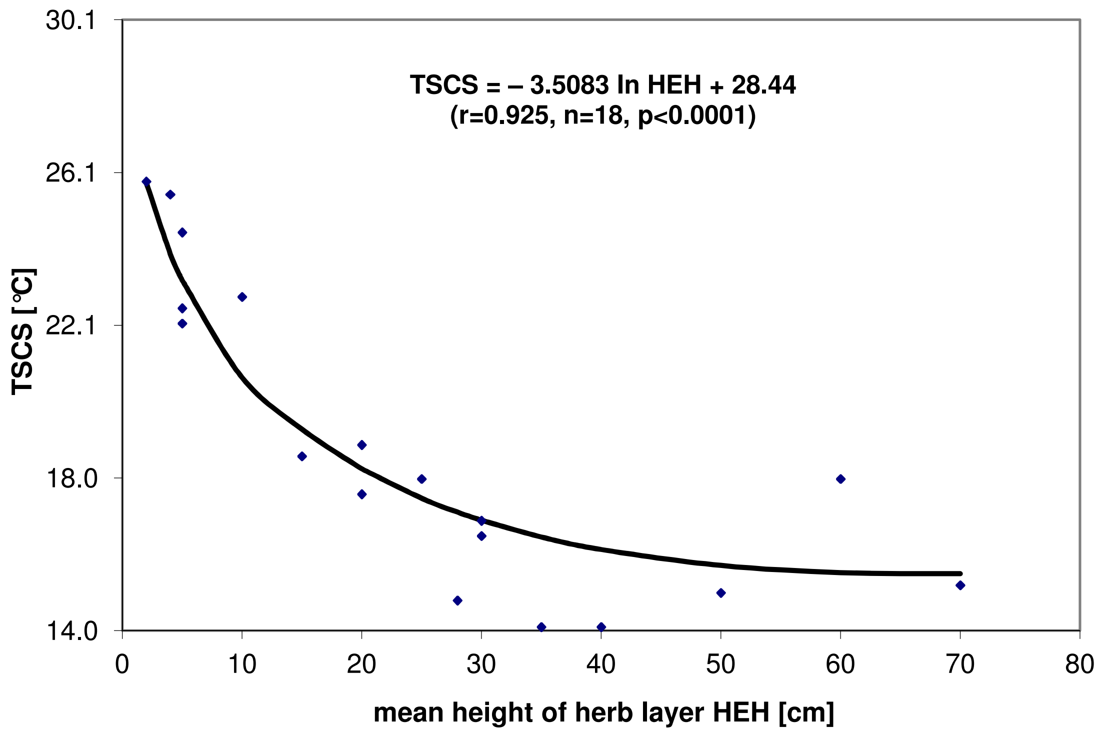
The effect of herb layer

The next structural level in terrestrial habitats extincting solar radiation is the herb layer. Mean height and density of 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 a 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 cylindrical 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 homogenously distributed or concentrated in bults further complicate the picture. Hence, we can not 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 have 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 by a highly significant logarithmic function

TSCS = -3.5083 LN (HEH) + 28.44 (n=18, r=0.925, p<0.0001] [21].

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



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 by the function

INSHEH = -0.235456 LN (HEH) + 1 (n=18, r=0.925, p<0.0001] [22].

We have no data to estimate the influence of herb cover HEC in combination with variable habitus and distribution of individual plants. We can only present here a simple estimation. If height-dependent extinction EXTHEH in a grassy herb layer is

EXTHEH = 1 - INSHEH [23]

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

EXTOV = EXTHEH * HEC, [24]

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

INSHE = 1 - EXTOV [25].

The effect of 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.

The 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 *CalibSoil* program: the degree of inclination was varied in iterative testing until a maximum of the seasonal mean was achieved. For latitudes between 45°N-57°N and an atmospheric turbidity of 0.05, the results can be approximated by the function

$$SRUM_5 = -0.4970\ LAT^2 + 29.7499\ LAT + 7789.2 \qquad [26a]$$

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

$$INSIN = SRU_5 / SRUM_5 \qquad [27]$$

where SRU_5 is the seasonal mean for an explicitly given surface inclination and latitude computed by the *CalibSoil* program.

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

INSHA = INSTR * INSHE * INSIN [28].

3.3.2. Temperature-derived estimation of insolation

An alternative to estimation of soil insolation by habitat structure is its direct derivation in a procedure similar to that given in section 3.2.5. The deviations DIF1 and DIF2 of 15 previous days air temperature history TAA from standard air temperature TAS, sunshine hours SUN, maximum soil temperature TSmax and the basal soil temperature TSB_i of the measuring day are needed. Since soil temperature is highly correlated with air temperature, the differences DIF1 and DIF2 can be used to estimate also the difference between actual basic soil temperature TSB_i from standard basic soil temperature TSB. As TSB of ZIS habitats can be considered equal to TSmin of FIS habitats at radiation days (section 3.2.1), the insolation of a soil is proportional to the difference TSmax – TSB_i. When DIF1 is the difference of air temperature history from standard air temperature for ZIS habitats and DIF2 that for FIS habitats and when a prejudice on insolation is avoided, the actual basic soil temperature TSB_I is estimated by

$TSB_I = TSB_{SP} + (DIF1+DIF2)/2$ [29a].

If, for instance, three weather stations are the reference, the contributions of these are weighted inversely proportional to their distances from the study site with W1 to W3 being the weighting factors according to function [2a] :
$DIF1_{Stat1}*W1 + DIF1_{Stat2}*W2 + DIF1_{Stat3}*W3$
$DIF2_{Stat1}*W1 + DIF2_{Stat2}*W2 + DIF2_{Stat3}*W3$

The heating up dTBSi of a concrete measuring point at a concrete day is given by the difference

$dTSi = TSmax - TSB_i$ [29a].

Within the system of 247 measuring spots, the average dependency of dTSi from SUN can be described as

dTSi= 1.01532 SUNi -2.61828 (r=0.264, n=247, p<0.0001) [30].

The residuals RES of dTSi are given by dTSi-dTS.

RES= dTSi – (1.01532 SUN – 2.61828) [30b]

Habitats with above-average / below-average insolation have positive / negative residuals.

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

INSHA = 0.04059 RES +0.49302 (n=247, r= 0.850, p<0.0001] [31].

This function with is used to calculate a temperature-derived insolation INSTE with

$$INSTE = 0.04059\ RES + 0.49302 \qquad [31b].$$

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 RES < -12.146 are allocated to INSTE=0 and those with RES > 12.490 to INSTE =1.

The weakness of the structure-derived estimation of insolation is insufficient reflection of complicated habitat mosaic structures and the weakness of temperature-derived method measuring errors. Integration of both methods in a final insolation value

$$INS = (INSHA+INSTE)/2 \qquad [32]$$

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 TSCmax of a given natural habitat is finally defined by

$$TSCmax = TSCA * (1-INS) + TSCS * INS \qquad [33].$$

If there is more than one meteorological reference station considered, the weighting factors of the TSCmax of each station are calculated according to function [2a].

3.4 Mean seasonal soil temperatures and consideration of relative sunshine duration

TSCmax (=TSCO) is undoubtedly a most important habitat parameter for soil organisms as it most strongly indicates differences between habitats and because it is also an indicator of possible heat stress. However, overall growth rates, brood development and mean metabolism should more strongly depend from mean soil temperatures of the whole season. Mean soil temperatures can be predicted when the local or regional relative sunshine duration is considered. The maximum of sunshine hours measured by the systems used in the meteorological stations is 96% of AST. If relative sunshine duration of a locality SUNR is defined as the quotient of the seasonal means of measured and maximum measurable sunshine hours

$$SUNR = \sum_{i=1}^{123} SUN / \sum_{i=1}^{123} 0.96\ AST \qquad [34],$$

these data vary in the German stations between 0.369 (Brocken/Harz) and 0.552 (Kap Arkona/Rügen). **TSCmean**, the seasonal mean of calibrated soil temperatures under consideration of SUNRy, is then according to functions [31]-[33]

$$TSCmean = (TSCmax + TSB_{SP})/2 * SUNR + TSB_{SP} * (1-SUNR) \qquad [35].$$

If there is more than one meteorological reference station considered, the weighting factors of the TSCmean of each station are calculated according to function [2a].

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 radiation days may cause serious problems to get 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 in 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 exemplaric 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

$$TSCS_{pre} = -0.293\ LAT + 0.214\ LON - 0.00868\ ALT + 44.662 \qquad [36].$$

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

$$C(0) = TSCmax/(-0.694\ LAT + 0.078\ LON - 0.00661\ ALT + 48.9) \qquad [37].$$

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

$$DIF_{in} = 0.0005142 * AST80 * (SRU_5 - SRU_{5hor}) \qquad [38],$$

where SRU_{5hor} and SRU_5 are the seasonal means for a horizontal surface and the given spot respectively (see also function [19]). The horizontal reference value $TSCmax_{hor}$ is then calculated as

$$TSCmax_{hor} = TSCmax - DIF_{in} \qquad [39].$$

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

$C(1) = TSCmax_{hor} / (-0.293\ LAT + 0.214\ LON - 0.00868\ ALT + 44.66)$ [40]

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

$TSCG = mC0 * (1-INS) * 15.18 + mC1 * INS * 29.47$ [41]

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 [39] must be reversed. The inclination-right full-insolation soil temperature $TSCS_{inc}$ is then given by

$TSCS_{inc} = TSCS_{pre} + DIF_{in}$ [42].

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

$TSCmax_{pred} = mC0 * (1-INS) * TSB + INS * (mC1 * TSCS_{pre} + DIF_{in})$ [43].

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 TSCmax and $TSCmax_{pred}$ 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 a depth of 35 mm 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**	**LON**	**ALT**	**TS**	**TSCmax**	**$TSCmax_{pred}$**
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	LON	ALT	TS	TSCmax	$TSCmax_{pred}$
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 which allow some interesting generalizations. 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 with 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 can not 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 1977-2006 and horizontal surfaces.

microabitat / 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* heath land of 88 % herb cover	2	0.17	14.86
Tila-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.

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		TSCS		
	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

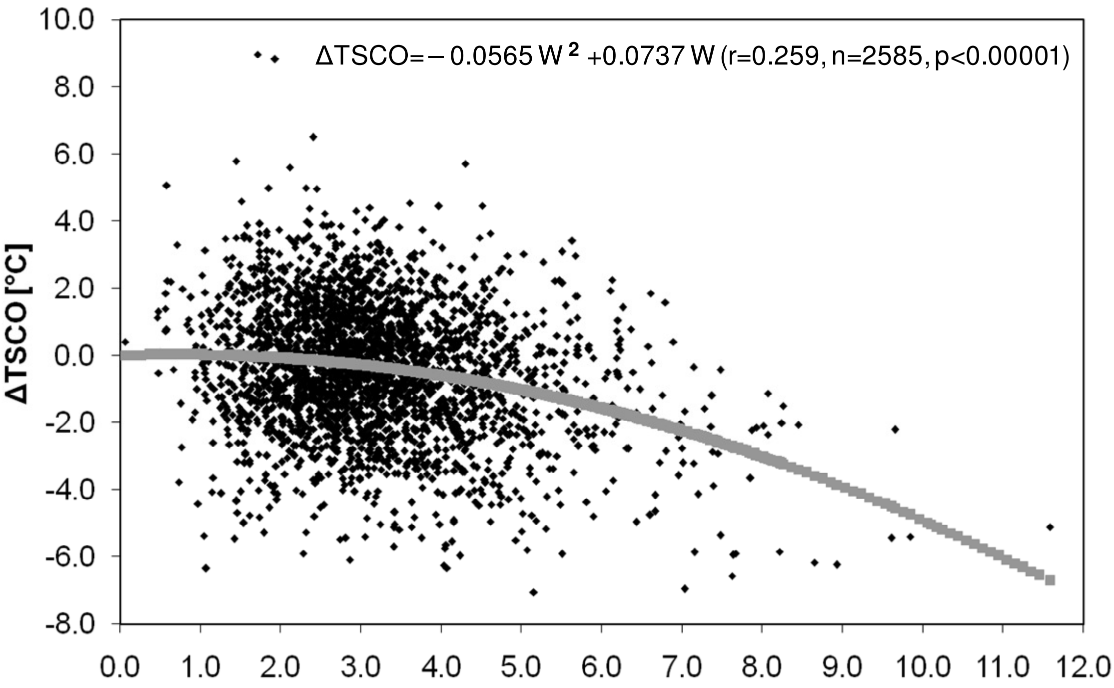
Augsburg	103	18.32	3.95	31.13	6.20	31.42	1.99	52
Bad Marienberg	88	16.25	4.99	26.12	6.57	26.73	2.08	38
Bamberg	103	19.40	4.24	28.83	4.87	27.94	1.85	51
Baruth	103	18.34	3.55	34.36	5.99	34.88	2.75	44
Braunlage	102	15.30	4.45	20.68	4.76	19.47	1.66	42
Carlsfeld	99	14.63	4.23	27.18	5.84	27.76	2.02	41
Chemnitz	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
Oehringen	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
Stoetten	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
Würzburg	103	19.96	4.56	37.06	8.24	37.38	3.04	55
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
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**	

The error of the TSCmax values could possibly be minimized when wind velocity and soil moisture are considered. High wind velocity and soil moisture are expected to reduce soil temperatures in particular 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 dT between daily value and the station mean of TSCmax was described as function of the difference dW between the daily value and station mean of wind velocity, the best description is offered by a quadratic function with

$$dT = -0.0565\ dW^2 - 0.2858\ dW + 0.092\ (n=2589, r=0.259, p<0.0001] \qquad [44].$$

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



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

$$dT = -0.0565\ W^2 + 0.0737\ W - 0.0009\ \ (n=2589, r=0.259, p<0.0001] \qquad [45].$$

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 TSCmax data of the 54 DWD stations for 2589 radiation days, the error of TSCmax is reduced from ± 1.97 °C to ± 1.90 °C. This only moderate effect of correction against wind is largely explained by the low average wind velocity during radiation days. Despite the significant influence of wind velocity on maximum soil temperature we did not introduce this factor into the calibration system because of severe practical problems. Natural habitats have no standardized position - they may be situated in surface depressions such as throughs or river valleys, at the food of a slope, behind or in front of a wood edge, 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 estimating for each habitat spot 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 with the seasonal background.

The influence of previous rain fall 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 1 June 2003. The following TSCmax was measured in sand patches of otherwise completely similar structure: 22.82 °C at 19 cm above the water table with completely wet sand in the measuring depth of 35 mm, 32.42 °C at 38 cm above water table with moist sand in measuring depth and 37.39 °C at 55 cm above water table and completely dry sand in 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 still 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. We have no system to correct against this factor.

4.3. References

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Appendix
Background of „Calculate Insolation“

Note: The Altitude Effect (AE) on solar radiation estimated by the *CalibSoil* software refers to total irradiance in the wavelength range between 300 and 3000 nm for clear sky conditions from April to September (northern hemisphere). This April-September average is ± 10% / 1000 m. The significantly larger annual mean of ± 13% / 1000 m is caused by a high AE in winter (Blumthaler et al. 1997).

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relative optical air mass $\mathbf{m_r}$ (for sea level)
$m_r = 1 / (\sin(\beta) + 1.5*\beta^{-0.72}) \approx 1/ \sin(\beta)$
($m_r = 1$ for 90° solar height)

absolute optical air mass $\mathbf{m_a}$ (includes ALT)
$m_a = m_r * p/ p_0$

p_0 air pressure at sea level (we use in our calculation a relative value of 1.0; the absolute value is 1013.25 hPa),
p air pressure at study site.

International altitude function [“Internationale Höhenformel”]:

$p = (1013.25-(0.0065*ALT/288.15))^{5.255}$

or as relative value

$p = (1-(0.0065*ALT/288.15))^{5.255}$ [annual mean, ± 13% /1000 m]

$= (1-(2.256* 10^{-5}*ALT))^{5.255}$ [annual mean, ± 13% /1000 m]

$p = (1-(1.8* 10^{-5}*ALT))^{5.255}$ [April to September, ± 10% /1000 m]

Tr Transmission trough atmosphere (for sea level)
h_{insol} solar angle relative to surface; resulting from solar height and slope of the study plot
t length of time interval

$SRU = (Tr * \sin (h_{insol}) * t) * p_0/p$