



Assumptions for Fourier-based modelling of diurnal temperature variations in the top soil layer under Istebna spruce stands



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ABSTRACT

Soil temperature is a key factor which affects both soil-forming processes and the hydrological balance of water exchange between the atmosphere and the ground. The measured temperature waveforms in the top layer of forest soils demonstrate very characteristic diurnal variations. This paper presents a method of determining the amplitude of the diurnal temperature variation using the Fourier transform. Temperature measurements were carried out in the top layer of soil at a depth of approx. 0.08 m within 4 homogeneous, even-aged stands of different age-classes (from a 12-year-old thicket to a 117-year-old mature stand) and at 3 inter-forest meadows. The main aim of this paper was to relate all parameters in a simple empirical model of diurnal temperature variations in the top layer of soil under a stand to biometric features of stands. The parameters describing the model depend to a large extent on the soil exposure factor and the total biomass of above-ground tree parts. The soil exposure factor and the total biomass of a stand depend solely on the number of trees per hectare, the mean height of a stand, and the mean tree diameter measured at breast height (i.e. at a height of 130 cm), all of which are very easy to measure from the ground. The analyses also show that the amplitude values, particularly in an open field, also depend on the mass of organic matter accumulated in soil. The presented model was verified using measurement results in spruce stands of the Istebna ecotype (the Silesian Beskid Mts.).

The model and parametrisation proposed for spruce stands depends solely on easily measurable biometric features and should be readily adaptable to stands composed of other tree species, using appropriate coefficients that differentiate these stands from spruce stands. The necessary improvements to the presented empirical model will be possible after a series of measurements taken within various types of stands. A thorough understanding of the factors determining temperature variation in woodlands may considerably expand the knowledge of the water exchange balance within forest complexes, as well as the estimation of site productivity.

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1. Introduction

Proper approximation of soil temperature is a fundamental issue in climate monitoring and various hydrological and ecological applications. Besides wind velocity and solar radiation, soil temperature in forests is the main factor influencing the volume of water evaporating from inter-particle spaces in the soil. Evapotranspiration from soil is also a fundamental factor affecting water exchange between the atmosphere, stands, and the soil (Galicija et al., 1999; Bouchter et al., 2001). Variations in soil temperature (diurnal and seasonal) have an impact on various biological and

chemical processes, such as decomposition and mineralisation of soil organic matter or release of CO₂ (Paul et al., 2002). Soil temperature is determined by many factors, for example meteorological conditions (i.e. solar radiation, wind velocity, air temperature), site topography (aspect and tilt angles, the topographic relief of the surrounding terrain and the outline of adjacent stands), water content, biomass, and spatial arrangement of plants. Furthermore, in forest complexes, the structure of the canopy, understorey and flora at the litter level change during stand growth. Roots and stems supply water to leaves, carrying energy to higher parts of plants, thus affecting soil moisture and evaporation (Eagleson, 1970; Czarnowski, 1989). In addition, the canopy, understorey and the forest floor may reduce diurnal downward heat transfer from the atmosphere to the soil or nocturnal upward long-wave thermal radiation from the soil to the atmosphere.

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Due to technical and organisational constraints of field research, air or soil temperature can only be measured at a few carefully chosen points at different heights (depths). The ongoing development of measurement methods and the automated recording of results create greater opportunities for the gathering and processing of a large amount of data. The well-understood techniques previously used to verify and analyse data have become inadequate. Therefore, new efficient methods and numerical algorithms for solving the aforementioned tasks should be found and signal processing techniques are worth considering. An adequate theory would suggest several methods that should be capable of fulfilling the arising needs and expectations (Korohoda et al., 2001; Sypka, 2003; Elias et al., 2004; Paul et al., 2004; Weiss and Hays, 2005; Graham et al., 2010). Still, the problem of the proper choice of measurement points, essential for identification of theoretical models, and improvement of the methods of extrapolating the measurement results remains to be solved on a large spatial scale.

In contrast to farmland, forest soils are characterised by specific soil profiles and their top layer is composed of organic levels formed by dead needles, seeds, cones, pieces of bark, dry branches of trees, dead organic undergrowth remains, and material of animal and microbial origin. However, the majority of the organic matter comes from the stands (Kowaliński and Gonet, 1999; Dziadowiec et al., 2004). Accumulated in soil, the organic matter is in various states of decomposition and is constantly subject to further disintegration (Pepper and Josephson, 1996) by way of mineralisation, which consists of hydrolysis and oxidation of organic molecules in the initial phase, crushing by macro and mezofauna, and rotting due to microflora and microfauna in the microbiological phase (Dziadowiec et al., 2004). Humification of organic compounds occurs simultaneously, which in the deeper organic layers is the last stage of decomposition (Kowalik, 2001). All of the processes associated with the decomposition of organic matter are among the most important soil-forming factors and are dependent, among others, on hydrothermal conditions (Kowaliński and Gonet, 1999; Zawadzki, 1999). As a result of these changes the top layer of soil consists of ecto- and endohumus layers. It may be expected that temperature dynamics in the top layer of soil (to a depth of approx. 0.08 m) are affected both by the thickness and the physico-chemical properties of the ecto- and endohumus on the temperature sensor. An additional factor that may influence the thermal conditions of the top layer of soil is the exothermic mineralisation (rotting) that occurs under aerobic conditions (Puchalski and Prusinkiewicz, 1990; Kowaliński and Gonet, 1999).

This paper presents variations of temperature in the top layer of soil at a depth of approx. 0.08 m inside a densely forested mountain valley (49°35'N, 18°50'E) which covers an area of 1.68 km² (0.649 mi²). In such a small investigated area, varying temperature values may be only a result of topographic factors (aspect and slope angles, altitude) and the structure of the neighbouring tree stands, with negligible differences arising from the geographical position or climate. The aim of the study was to compare the amplitudes of diurnal variation of soil at a depth of approx. 0.08 m under spruce stands of different age classes and on an inter-forest meadow, as well as to attempt to describe this variation by empirical equations. An additional objective is the expression of relations that describe dependencies between the amplitudes of the diurnal temperature cycle in the top layer of soil by means of stand characteristics, as well as an attempt at ecological interpretation of the obtained coefficients of the model. It will be possible to use models which express general relationships in extrapolation of results from single measurements to large areas. Models which describe general relationships may be important in forest practice for predicting natural changes in stands due to stand development and the consequences of management measures (weeding and thinning). It should also be noted that the research object is an element of soil climate. For

that reason, the relationships described may also be useful for forest soil science, especially for processes related to organic matter decomposition and the circulation of elements in the forest ecosystem (Puchalski and Prusinkiewicz, 1990; Blum, 1999; Dziadowiec et al., 2004).

2. Sites, measurements and methods

In hydro-meteorological research, all measurements can be taken at only a few carefully chosen points, meaning the obtained results have to be extrapolated over a large spatial scale. Therefore, the investigated sites should be typical and have properties representative of all study regions.

2.1. Research sites

The research sites were located within the Dupniański Stream experimental catchment area (49°35'N, 18°50'E) in the Silesian Beskid Mountain Range (Poland). The experimental catchment was arranged by the Department of Forest Engineering at the University of Agriculture in Krakow. This small mountain catchment (average height: 680 m AMSL, total area: 1.68 km², maximum length: 2.09 km, maximum width: 1.47 km, circuit: 5.39 km, valley prominence: 404.4 m, geology: Istebna series sandstone) was 95% covered by a Norway spruce stand (*Picea abies* (L) Karst., *ecotype—the Istebna spruce*). The Istebna spruce is characterised by very fast growth up to a height of 50 m, productivity up to 1500 cubic meters per hectare, extraordinary stem quality, and high resistance to disease. Spruce stands in this region of the Silesian Beskid Mountains have been rated among the best seed forest stands in Europe (Giertych, 1996; Janson, 1996; Pacalaj et al., 2002; Małek and Gawęda, 2005; Liesebach et al., 2010). Seven research sites with automatic data recording were deliberately located inside the experimental basin area: 3 at inter-forest meadows (sites S5, M1 and M2); 4 within homogeneous, even-aged stands of different age classes, from a 12-year-old natural thicket (site S1) to a 117-year-old mature stand (site S4). The spatial arrangement of all research sites within the Dupniański Stream catchment is presented in Fig. 1. Table 1 presents selected characteristics of the experimental sites in the investigated area. The homogeneous, even-aged spruce stands on the research site consisted only of a canopy and stem layer; there was no forest vegetal cover in the vicinity of the selected measurement points. The biometric features of the investigated stands were measured *in-situ* on circular sites with an area of 10 ares around the measuring profiles. The diameters at breast height (i.e. 1.30 m above ground, *DBH*) were recorded with precision callipers. The heights of trees (*H*) in the experimental stands were determined trigonometrically using a Zeiss Dählta 010B tacheometer. The obtained data was used to calculate the mean diameter at breast height and the mean tree height by applying Lorey's formula, which gives slightly higher values than the traditional arithmetic average because of a correction to the basal area. Thereafter, the biomass of leaves (needles) and the volume of the stem and small-sized branch wood were estimated for the model mean tree by the method proposed by Suliński (1993, 2007). The empirical equations used in this procedure were identified using data included in yields tables (Schwappach, 1943) and in volumetric tables (Czuraj et al., 1966). The total biomass of fresh timber (stem and branches, [tonne per hectare]) was approximated by multiplying the model mean tree volume by the green spruce wood density of 0.75 [tonne per cubic meter] (Suliński, 1993, 2007), and the total number of trees per hectare (*N*). The total biomass of the stand was the sum of the total biomass of fresh timber and the total biomass of leaves. The results (standardised for 1 ha) are shown in Table 2. The detailed

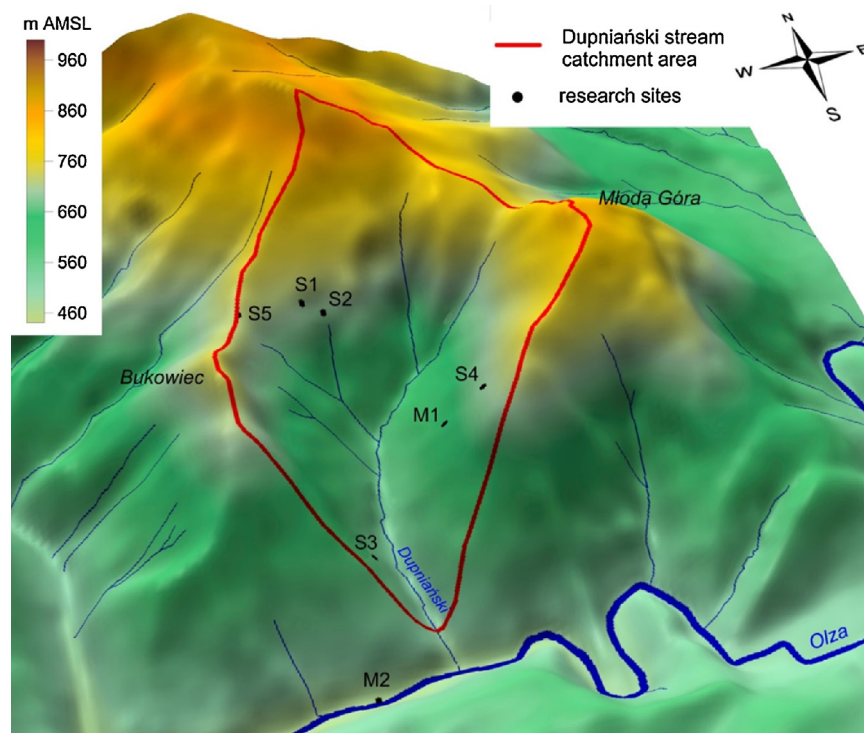


Fig. 1. Dupniański Stream drainage basin (49°35'N, 18°50'E, total area: 1.68 km²/0.648mi², average height: 690 m AMSL, valley prominence: 404.4m, 95% forested by *Istebna* ecotype Norway spruce) and spatial arrangement of 7 research sites with automatic data recording: 3 in inter-forest meadows (sites S5, M1 and M2); 4 within homogeneous, even-aged stands of different age classes, from a 12-year-old thicket to a 117-year-old mature stand (see also Tables 1 and 2).

Table 1

Selected characteristics of the research sites in the Dupniański Stream catchment with empirical features of soils on the investigated sites (M_0 measured in 1999).

Site	Latitude	Longitude	Z	δ	ε	M_0
S5	49°31'11"N	18°50'52.27"E	721.0	279	15	
M1	49°34'05.12"N	18°51'28.15"E	633.3	246	18	
M2	49°33'44.81"N	18°51'03.33"E	464.5	227	4	
S1	49°34'33.28"N	18°51'06.72"E	706.0	147	25	98.9
S2	49°34'33.05"N	18°51'12.54"E	698.2	189	23	93.6
S3	49°33'59.90"N	18°51'08.26"E	556.1	77	20	85.8
S4	49°34'13.79"N	18°51'33.74"E	691.3	279	18	104.2

Z—altitude [m AMSL]; δ —azimuth [°]; ε —tilt angle [°]; M_0 —a total mass of dry organic matter in the top layer of soil up to 0.08 m depth [t ha⁻¹].

equations used to estimate the biometric features of the stand are included in the Appendix A.

Furthermore, temperature variations in the top layer of soil may be dependent upon the screening effect caused by the plants (i.e. the tree stands) which covered the research sites. On the basis of Suliński's theory (Suliński, 1993), the soil exposure factor can be calculated as a product of the coefficient of solar radiation absorption and the coefficient of wind attenuation:

$$W_0 = \left(\frac{1}{100} \cdot \sum \left(\frac{DBH}{100} \right) \right)^2 \cdot \exp \left\{ -0.0972 \cdot R_c \cdot \left(1 - \frac{H_s}{H} \right) \right\} \quad (1)$$

where: W_0 denotes soil exposure factor; DBH is the average diameter at breast height [cm]; H represents the average tree stand height on the investigated site [m]; H_s is the height of the stem layer [m]; R_c represents the biomass density of the crown layer [t ha⁻¹ m⁻¹]. The above formula was constructed based on the premise that reduction of solar radiation in stands, the first term in Eq. (1), is proportional to the square of the sum of diameters at breast height (Suliński, 1993; based on works: Rieger and Rutkowski, 1969; Rauner, 1972; Fross, 1981; Czarnowski, 1989; Gabeyev, 1990). The additional factor in this term (1/100) standardises the square of the sum of DBH for 1 ha [m ha⁻¹]. The second term in Eq. (1) was empirically developed ($R^2 = 0.956$, $\sigma = 0.044$) on the basis of a series

of wind velocity measurements taken within the *Istebna* spruce stands in the investigated area (Sypka and Starzak, 2013). Biomass density in the crown layer was calculated as the ratio of estimated biomass to its height $R_c = M_c/H_c$ [tonne of fresh mass per 1 ha per 1 m].

On the research sites, soils under homogenous spruce stands were acid brown podzolic (FAO), while measurements of the temperature in the top layer of soil in the investigated profiles were taken in the endohumus (A, biological accumulation) under the ectohumus layer, which contained all of the following sublayers: (1) the litter—consisting of almost unchanged plant debris in the first phase of decomposition, with tissue structures preserved; (2) the fermentation sub-layer—consisting of considerably decomposed and discoloured material, the excrement of small soil fauna and formless humus; (3) the humification sub-layer—containing mainly formless humus and a considerable amount of mineral material admixture (Dziadowiec et al., 2004). Due to the ecological interpretation of the variation of temperature dynamics in the vicinity of temperature measurements, organic monoliths were sampled three times during the research. In the monoliths, the organic matter content was determined by burning at 700 °C (Kucza, 2007). The averaged results allowed for the calculation of the soil mass of organic matter per 1 ha of forest area. The total mass of dry organic

matter in the top layer of soil up to a depth of 0.08 m (standardised for 1 ha) is shown in Table 1. Due to the very slow changes of organic matter in the soil, the presented values may be recognised as roughly constant during the research.

2.2. Measurements

Extensive, large-scale research on the water exchange balance between the atmosphere, the stand, and the soil of Istebna spruce stands was carried out from 1997 to 2003 in the Dupniański Stream catchment area. Measurements were continuously taken from 22-11-1997 to 31-03-2000 and then in seasonal sessions (usually in May, July-August and September-October), with a one-year break in 2002 due to silvicultural practices (early thinning on site S1, accretion cutting on site S2 and selective cutting on sites S3 and S4) performed in the investigated area. Temperature measurements were automatically taken every 6 min using precision semiconductor sensors with resolution of 0.2 °C. Soil temperature was measured at 3 different depths in open areas (sites M1, M2 and S5) and at 4 depths at sites located within the stands (S1, S2, S3 and S4). A diagram of all measurements within the stands and at weather stations in the open field is shown in Fig. 2. Table 2 presents empirical data and calculated biometric features of the stands on the investigated sites.

Fig. 3 presents the measured temperature waveforms in the top layer of soil on different research sites. In the waveforms presented, a very characteristic diurnal variation may be distinguished. However, the range and dynamics of diurnal variation differs for different levels and profiles of measurement. The minimum air temperature value is observed in the early morning before dawn, whereas the occurrence of its maximum value strongly depends on meteorological conditions in the catchment area and on the season. Rapid temperature changes occur only in the air in open areas. Fast temperature variation does not occur at all in the ground due to the high thermal inertia of soil compared to air. In deeper soil layers, only long-term or seasonal variations can be observed. In most of the soils in that region, the depth of suppression of the diurnal wavelength amounts to approx. 0.20 m, whereas the amplitude of annual temperature changes is absent at depths of about 10 m. Below 10 m the temperature is constant and equal to the mean annual temperature of the atmospheric air, i.e. about 10 °C (Kowalik, 2001). Depending on the season, the relation between temperature values at different levels of the measurement profile also changes. In the summer period, higher temperatures occur at higher levels, whereas in the winter period the opposite is true; the highest temperatures are observed in the lowest soil layers of the measurement profile. In transitional periods, i.e. in spring and autumn, the temperatures at different ground levels are equal.

2.3. Methods

Under the assumptions that the Sun is the only source of energy for the soil and there is only one-dimensional (downward) heat flow (the secondary long-wave radiation is omitted), the observed variations in the top layer of soil (Fig. 3) resulted from different conditions of heat transfer on the research sites. Such divergences arose from various biometric features of stands on the research site (reduction of solar radiation, wind velocity) and terrain topography (aspect and tilt angles of the plots). The heat transfer equation (Mills, 1999; Rohsenow et al., 1998) under unsteady state conditions (the heating and cooling process based on solar radiation changeability) may be analytically solved in only in a few cases which refer to relatively simple shapes with uncomplicated boundary conditions. Therefore, the similarities or differences in the measured temperature waveforms on different sites may be captured by using objective and meticulous numerical methods and

certain algorithms of signal processing which are based on discrete time and coordinates. Furthermore, the observed temperature changeability caused by the two rotary movements of the Earth around its axis (diurnal variation) and around the Sun (seasonal variation) presupposes that methods of frequency-based analysis should be applied.

The Fourier transform, defined as a discrete sequence in the frequency domain, is the best known and most frequently applied method in engineering science (Oppenheim and Schaffer, 1989; Poularikas, 1996):

$$XT[m] = \sum_{n=0}^{N-1} T[n] \cdot e^{-j \cdot 2\pi \frac{m}{N} n} \quad (2)$$

where, $T[n]$ is a discrete sequence of measured temperature values; N represents the length of the signal (the number of sequence samples); n and m denote indexes, $n, m = 0 \dots N-1$; j is an imaginary unit, $j = \sqrt{-1}$. The support of the complex kernel of the transform (2), $e^{-j \cdot 2\pi \frac{m}{N} n} = \cos\left(2\pi \frac{m}{N} n\right) + j \cdot \sin\left(2\pi \frac{m}{N} n\right)$, is not bounded, hence the standard Fourier analysis is adequate for the treatment of stationary processes. The Fourier spectrum loses information about the time localisation of a given frequency component and yields average results. Yet, the Fourier transform data, XT , enables approximation of the measured series with the use of a linear combination of harmonic basis series (sinusoids of specific parameters, such as amplitude, frequency and delay):

$$T^{app}[n] = \frac{|XT[0]|}{N} + \frac{2}{N} \sum_{k=1}^K |XT[k]| \cdot \cos\left(2\pi \frac{k}{N} n + \angle(XT[k])\right) \quad (3)$$

where: N denotes the number of samples; K is the number of harmonics used in approximation, $K < (N-1)/2$; $||$ represents the absolute value of the complex number, and \angle is the phase angle of the complex number. The frequency values, f_k , for which the frequency domain complex coefficients $XT[k]$ may be calculated, are defined by $f_k = k / (N \cdot T_s)$, where: N denotes the number of samples (in the presented example $N=240$); T_s is the distance in time between measurements ($T_s=6$ min); k is index $k=0 \dots K-1$. The approximated amplitude of diurnal variation (the fundamental harmonic of the twenty-four-hour period, 1 nychthemeron) may be calculated by the following formula:

$$AT = 2 \cdot \frac{|XT[1]|}{240} \quad (4)$$

Division of the measured temperature data in the 24-h period ($N=240$) roughly fulfilled the requirements of the steady condition of downward heat transfer. After a series of experiments, the best conformity among calculated amplitudes of the diurnal variation and the measured data was obtained by removing the linear trend from the data before computing the Fourier transform. This procedure reduced errors caused by low frequency components (long-term or seasonal temperature variations).

The main advantage of an approximation based on harmonic series (3) is the direct comparison of the calculated amplitudes and phases (delays) of temperature waveforms measured on various sites. Fig. 4 displays waveforms of temperature variation in the top layer of soil, recorded on the 31st of March 1999; a sunny spring day. In the presented case, amplitudes of diurnal variation (AT) on the sites located in inter-forest meadows M1 and S5 were equal to 4.6 °C and 2.9 °C, respectively. The difference was 1.7 °C and the maximum temperature occurred on site S5 about 1 h later than on site M1. These phenomena may have been caused by the various aspect and tilt angles of the investigated plots (Fig. 1, Table 1) as well as from obstructions caused by the topographic relief of adjoining mountains and surrounding tree stands (Sypka et al., 2015). The more harmonics are taken into account, the more precise the

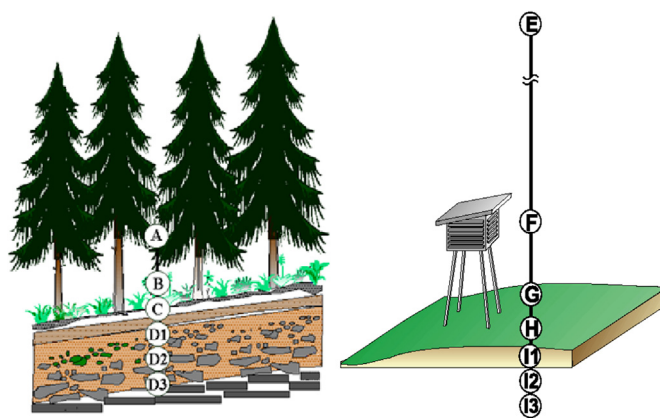


Fig. 2. A diagram of measurements within tree stand (left, sites S1, S2, S3 and S4—see Fig. 1) and at weather stations in the open field (right, sites M1, M2 and S5—see Fig. 1). A—at a height of 2 m above ground: wind speed, humidity deficit, total solar radiation intensity; B—at a height of 0.2 m above ground: wind speed, humidity deficit, total solar radiation intensity, rainfall; C—a surface run-off; D1–D4—soil temperature; E—at a height of 9 m above ground: wind speed, wind direction (one station is located higher than the others, on an inter-forest meadow—S5), total solar radiation intensity; F—a measurement in the Stevenson Screen at a height of 2 m above ground: humidity deficit; air pressure; G—rainfall at a height of 1 m above ground; H—at a height of 0.2 m above ground: wind speed, humidity deficit; total solar radiation intensity (site S5 only); I1–I3—soil temperature; surface run-off at ground level (not marked).

Table 2
Empirical data and calculated biometric features of the stands on the investigated sites (data collected in 1999).

Site	A	N	DBH	H	H _s	H _c	M _t	M _c	R _c	W _o
S1	12	20350	2.8	3.5		3.5	53.6	53.6	20.89	7.32
S2	25	2611	11.7	12.6	4.8	7.8	221.3	136.9	17.62	3.24
S3	92	382	39.7	37.9	14.5	23.4	668.4	303.6	12.98	1.05
S4	117	414	42.1	36.6	17.1	19.5	788.8	314.9	16.15	1.31

A—age [years]; N—number of trees per 1 ha; DBH—average diameter at breast height [cm]; H—average tree stand height [m]; H_s—the height of the layer of stems [m]; H_c—the height of the layer of tree crowns [m]; M_t—total mass of all trees with leaves [t/ha of fresh mass of over ground parts of plants]; M_c—mass of the tree crown layer [t of fresh mass ha⁻¹]; R_c—biomass density of the tree crown layer [t ha⁻¹ m⁻¹]; W_o—soil exposure factor.

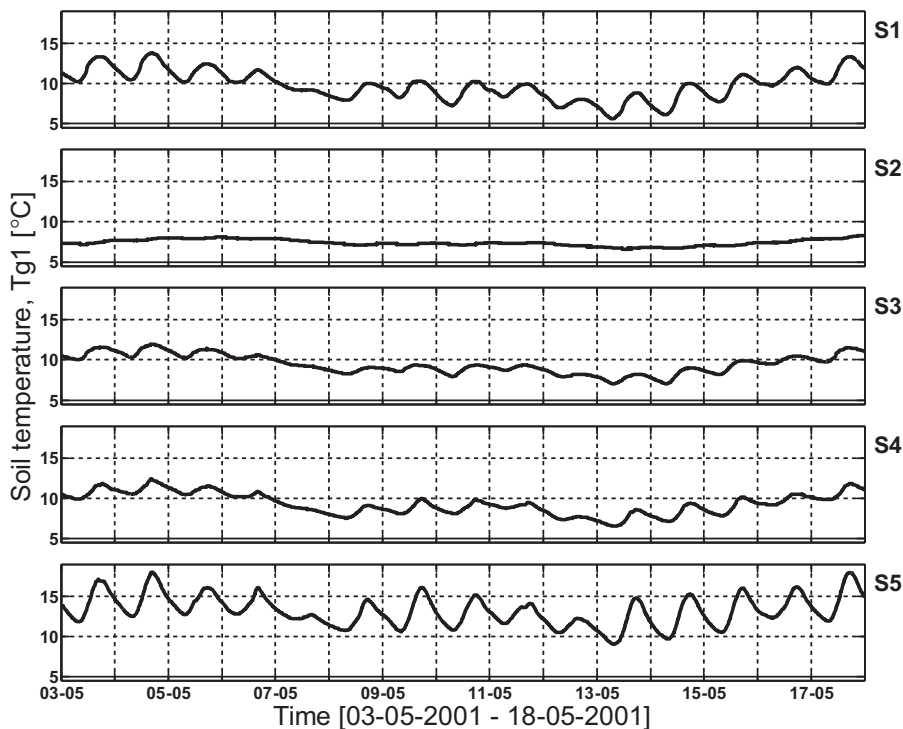


Fig. 3. Temperature data recorded in the top layer of soil on different sites in the Dupniński Stream catchment in the spring of 2001. A characteristic diurnal variation is very noticeable in the presented waveforms. It may be supposed that the observed variation is a result of random weather conditions (mainly irregular cloudiness), position and orientation of the analysed sites located on valley slopes (i.e. aspect and tilt angles, altitude etc., Table 1), as well as the impact of biometric features of stands in the immediate vicinity of temperature sensors (Table 2).

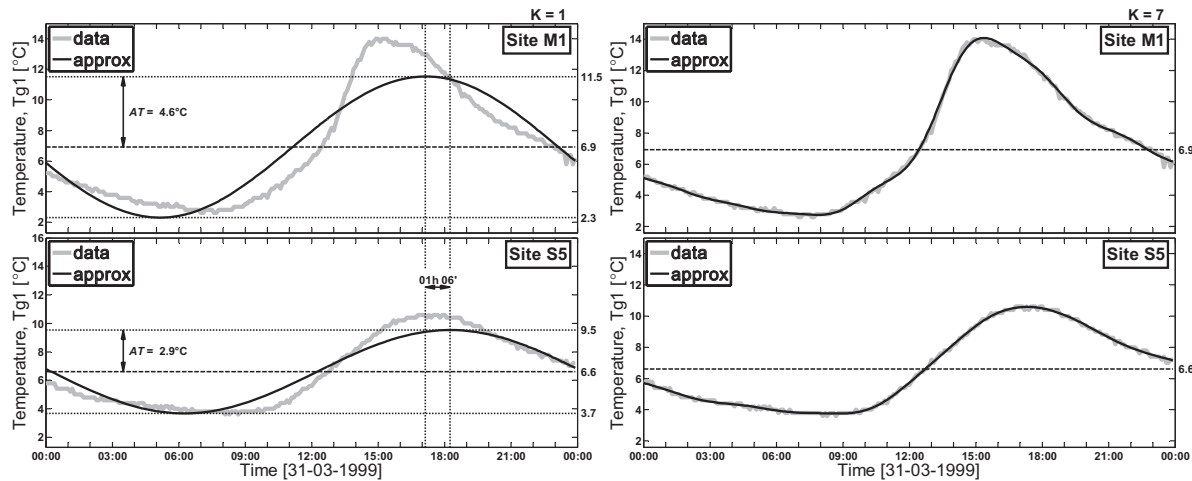


Fig. 4. Temperature waveforms in the top layer of soil (Tg1, approx. 0.08 m) recorded on inter-forest meadows M1 (situated on south-western slopes, aspect angle $\delta = 246^\circ$, tilt angle $\varepsilon = 18^\circ$, Table 1) and S5 (located on a westward slope, $\delta = 279^\circ$, $\varepsilon = 15^\circ$, Table 1) on a sunny spring day (31-03-1999) with an approximation based on only the diurnal component (general variability, left) and the first 7 harmonic, sinusoidal functions (more accurate approximation, right). The Fourier transform enables straightforward comparison of amplitudes (AT), frequencies and delays of approximated waveforms. In the presented example, the maximum on site S5 was delayed by more than 1 h compared to site M1, and the difference in amplitudes was 1.7°C . Furthermore, a small difference in the mean temperature, 6.9°C and 6.6°C , was noticeable on sites M1 and S5 respectively. The more harmonics taken into account, the more precise the approximation obtained. There are only rounding errors if all possible harmonics are used. K indicates the number of sinusoidal functions used in the approximation.

approximation that is obtained (Fig. 4, right). There are only rounding errors if all possible harmonics are used; 119 with 240 data points. The diurnal component represents the basic cycle resulting from soil heating by solar radiation. Higher order harmonics model the shape of the observed temperature variation (the rate of increase or decrease) caused by different topography, random weather conditions, the spatial arrangement of the flora, and the type of soil on research sites. In the presented example, the amplitudes of the 4th components (harmonics of a 6-h period) on sites M1 and S5 were equal to 0.35°C and 0.05°C , respectively. Taking into consideration the resolution of temperature measurement (0.2°C), it may be stated that the minimum value of the measured amplitude was 0.1°C . The obtained value of 0.05°C is below this limit, therefore it may be assumed that this harmonic variation did not occur in the recorded waveforms on site S5, but resulted only from mathematical computations in Eqs. (2) and (4). Thus, the observed temperature dynamic on site M1, i.e. the increment or decrement rate, was higher compared to site S5. This follows from observations that temperature oscillates as a sinusoidal function of time around an average value and that amplitudes attenuate exponentially with soil depth (Campbell, 1985).

3. Amplitude of diurnal variation

Fig. 5 presents variation of the diurnal temperature amplitude, AT in Eq. (4), in the top layer of soil Tg1 (at a depth of approx. 0.08 m), calculated on all measurement sites in the research area. A very characteristic feature of diurnal amplitude variation is its absence in the winter period when snow cover is present (from approx. mid-November to the end of March). In the latter half of February 1998, there was short-term melting of snow in the catchment area during which diurnal variation amplitudes varied considerably from zero (especially on an elevated mid-forest meadow, site S5). Non-zero amplitude values were observed on different days on different sites: first in the open field (site M1, M2 and S5) and then under the stands. This testifies to the different times at which the snow cover under the stand melted. The highest amplitude values occur in early spring immediately after snowmelt when the ground is very wet, which aids heat propagation, as well as in August and September. Amplitude values differ between sites located in the

stands. The highest values are observed on site S1, located in a thicket ($0^\circ < AT < 2^\circ$). In seed stands (S3, S4) the amplitude values are close to one another ($0^\circ < AT < 1^\circ$), while on site S2 (a pole-timber stand) diurnal variability is almost absent ($AT < 0.5^\circ$). It is probable that the presented variation is a result of overall climatic conditions which were modelled by the location of the research profiles on a valley slope (slope aspect and tilt), and the influence of stands, characterised by specific values of biometric features as well as physical characteristics of forest soils, typical of a given site.

3.1. Relationships between amplitudes of diurnal variation under the stands

Fig. 6 presents the relationships between the amplitudes of diurnal variation of temperature, AT Eq. (4), determined with the use of the Fourier transform in the top layer of soil under the stand (thicket, site S1) and the closest open area (site S5, Fig. 1). Three characteristic periods may be distinguished:

- I the winter period with the presence of the snow cover—diurnal variability does not occur,
- II snowmelt—diurnal variability begins to occur only in the open field (snow cover melting), and only later under the stands,
- III the vegetation period—diurnal variability occurs on all sites.

In the presented example, in the thicket (site S1) the snow cover remained unchanged for 3 days from the moment of complete snowmelt on the inter-forest meadow (site S5), as shown by the first 3 points on the diagram (Fig. 6, left, as denoted by circle markers) for non-zero values AT_{S5} and values AT_{S1} near zero. For the 5 following days gradual disappearance of the snow cover occurred (increase of values AT_{S1} from 0.3°C to 1.6°C with large amplitudes AT_{S5} : 2.3 – 3.1°C). When the snow under the thicket melted entirely, the relationships between the amplitudes of diurnal variation began to be characteristic of the vegetation period (as denoted by cross markers). Consequently, the total delay of snow cover melting on site S1 amounted to 8 days, compared to the neighbouring open area. However, under the seed stand (site S3) the snow cover melted 3 days earlier than on the mid-forest meadow (site S5).

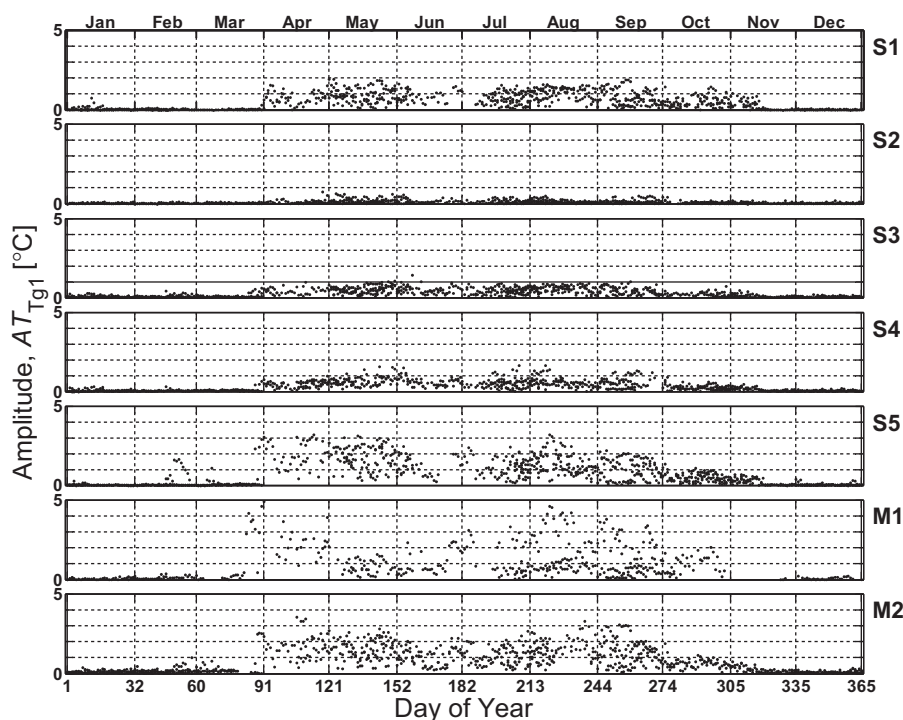


Fig. 5. Variation of the diurnal amplitude of temperature in the top layer of soil Tg1 (at a depth of approx. 0.08 m) for the research sites in the investigated area. It may be observed that diurnal variability does not occur when snow cover is present (from about mid-November to the end of March). The values of the diurnal amplitude in the vegetation period have the highest values in the open field (sites M1, M2 and S5) and the lowest values on the site in the pole-timber stand (S2). It is probable that the presented variation is a result of climatic conditions, the location of the research profiles (slope aspect and tilt), and biometric features of the stands that grow on the research sites (Table 1).

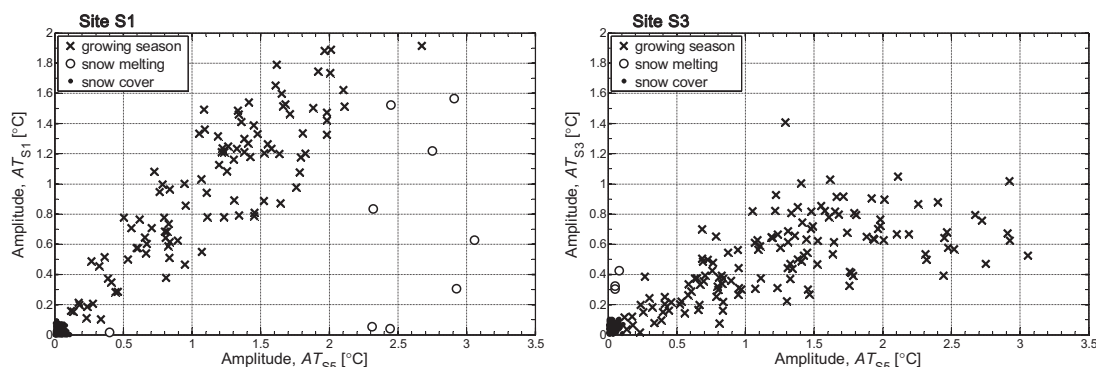


Fig. 6. Relationships between the amplitudes of the diurnal variation on sites S1 and S3 compared to the open area (site S5) located on a mid-forest meadow (Fig. 1), as exemplified by temperatures recorded in 1999. Three characteristic periods during the year can be seen. In the winter period, due to the presence of the snow cover, diurnal variation did not occur (as denoted by dot markers). Then the snow melted over variable periods, depending on the stand growing on the research site (as denoted by circle markers). In the thicket (site S1, left), the snow melted entirely 8 days later than on site S5 (left). On site S3, located nearly on the valley bottom (the seed stand), the snow cover melted 3 days earlier than on the mid-forest meadow (site S5, right). In the vegetation period (denoted by cross markers) diurnal variation occurs on all sites.

For further analysis, only the vegetation period lasting from the 1st of April to the 31st of October was selected. Site S5 was chosen as the reference site due to its position in the investigated area (located high on the western slopes of Mała Góra mountain in an inter-forest meadow) and its soil (acid brown podzolic, FAO, 1998), which is similar to other sites. Furthermore, it may be assumed that meteorological conditions at this site were unbiased over a long period (no tree stand development in the immediate neighbourhood and no seasonal variation of solar insolation caused by the topographic relief of the surrounding terrain). From a formal perspective, site M1 was situated in a natural regeneration area while site M2 was established at the valley bottom on the argillaceous, silty bed in the natural flood area of the Olza River (Fig. 1). Short-lasting transition periods resulting from snowmelt and the winter

period with the snow cover present were disregarded in the analysis. Assuming that the same stream of heat reaches the research sites (the soil cover on open-field sites and the canopy layer on sites located within stands), the relationships between the determined amplitudes of diurnal variation may be described by the following formula (a form of solution of the first-order differential equation):

$$AT_i = \alpha \cdot (1 - e^{-\beta \cdot AT_{S5}}) \tag{5}$$

where: AT_i is the amplitude of diurnal variation in the top layer of soil on the i -th site; AT_{S5} is the amplitude of diurnal variation in the top layer of soil on site S5 (open field); and α , β are coefficients to be calculated in the process of formula identification (5). The adopted formula of model (5) automatically takes into account the winter period if it is assumed that $AT_{S5} = 0$ and AT_i is 0. Approximation

Table 3
Goodness-of-fit statistics for model (5) based on temperature data measured under tree stand.

Site	Year	L	α	95% CI for α	β	95% CI for β	R	100 · R ²	σ	μ
S1	1998	87	2.493	1.676–3.310	0.309	0.172–0.445	0.93	86.19	0.15	19.92
	1999	102	1.802	1.439–2.165	0.749	0.474–1.024	0.82	66.92	0.26	26.04
	2000	53	2.084	1.251–2.917	0.559	0.236–0.881	0.84	69.92	0.22	27.41
	2001	98	1.682	1.491–1.873	0.931	0.716–1.145	0.91	82.55	0.21	23.09
	2003	67	3.501	–1.639–8.641	0.108	0.067–0.283	0.93	87.38	0.08	16.24
S2	1998	94	0.272	0.198–0.346	0.663	0.340–0.986	0.69	48.06	0.05	36.94
	1999	62	0.113	0.079–0.148	1.603	0.228–2.978	0.32	10.37	0.04	49.90
	2000	67	0.101	0.076–0.125	1.838	0.488–3.188	0.36	13.28	0.05	65.03
	2001	88	0.102	0.087–0.116	2.179	1.078–3.280	0.49	23.74	0.04	42.60
	2003	70	0.950	0.489–1.412	0.333	0.113–0.554	0.88	78.15	0.06	18.11
S3	1998	101	1.692	0.680–2.704	0.235	0.058–0.412	0.88	77.13	0.12	31.10
	1999	130	0.855	0.688–1.023	0.853	0.519–1.187	0.70	49.44	0.18	34.87
	2000	30	1.129	0.716–1.543	0.500	0.212–0.787	0.87	75.42	0.11	21.28
	2001	81	0.751	0.648–0.854	1.139	0.772–1.505	0.81	66.26	0.14	28.06
	2003	60	1.306	0.237–2.374	0.226	0.002–0.455	0.90	80.45	0.07	18.73
S4	1998	74	1.152	0.657–1.647	0.386	0.151–0.621	0.87	76.17	0.11	28.02
	1999	127	0.946	0.726–1.167	0.604	0.369–0.839	0.78	61.12	0.14	29.16
	2000	59	0.735	0.653–0.817	0.952	0.718–1.187	0.89	78.42	0.09	20.87
	2001	55	0.849	0.721–0.977	1.104	0.742–1.466	0.91	81.95	0.12	27.15
	2003	50	4.282	–0.512–9.076	0.181	0.059–0.421	0.91	82.92	0.15	15.03

L—number of cases (number of days used in estimation in a particular year); CI—confidence intervals; R—correlation coefficient, σ —standard deviation of estimation, μ —average error of estimation [%].

was conducted for each vegetation year separately due to the constant change caused by annual growth and management measures (thinning) carried out in 2002. Over the research period the biometric features of the stands (especially stand heights) increased from 0.6–0.9 m in the second age class maturing stands (20–40 years old) to 0.3 m in the oldest mature seed stands (over 100 years old). Detailed analysis of variability of the parameters α and β across the annual growing cycle did not reveal any noticeable dependence upon time or sub-periods of vegetation. The identification results are presented in Table 3 and Fig. 7.

Coefficient α of model (5) may be identified with the asymptote which determines the maximum possible value of the diurnal variation amplitude on a given site. Coefficient β (the temporal constant $\tau = 1/\beta$) characterises the dynamics of amplitude relations (for value $AT_{35} = 1/\beta$ amplitude AT_i reaches 63% of the maximum value α). The worst results of identification of Formula (5) are for site S2, where there is almost no diurnal variation (amplitude values are generally below the measurement resolution of 0.2 °C). For the remaining sites, tests of the identification conformity of model (5) are characterised by a correlation coefficient of 50–87% and by large values of the mean estimation error (16–34%). It should be noted that the observed temperature variation that results from heat propagation depends on many factors such as the soil thermal capacity, conductivity and activity (e.g. decomposition, organic matter mineralisation), evaporation from the inter-particle space in the soil, and air flow above the ground (wind). Another very important factor is the geographical and topographic situation (aspect and tilt angle of a site), both of which cause variations in the amount of solar radiation energy reaching a site. It should also be emphasised that the solar energy that reaches stands (the main and practically only source of heat) differs on individual research sites. This is mainly a result of the terrain and temporary shading of the research sites by the surrounding mountains and stands (Sypka et al., 2015). It may therefore be assumed that the form of model (5) was selected correctly.

The temporal variation of parameters α and β of model (5) is presented in Fig. 8. In the initial research phase (years 1998–2001) variation of parameters was mainly due to the variation of biometric features of the stands growing on the research sites. One may observe a general tendency towards a decrease of the values of parameter α with a simultaneous increase of parameter β . The

largest changes of the value of α were noted in the thicket (site S1), whereas in the pole-timber stand (site S2) the value of parameter α was practically constant. It is essential to remember that the value of parameter α , identified with the asymptote determining the maximum possible value of the diurnal variation amplitude on a given site, also largely depends on the mean meteorological conditions in a given calendar year (fluctuations of the values on sites S1 and S3). On the other hand, the value of parameter β increased with time. A large change in the values of both parameters occurred in 2003 following forest management measures carried out in 2002. As a result of intensive thinning on sites S1 (where 1/3 of the trees around the measurement point were removed) and S2 (where 21% of the trees were removed) as well as shelterwood cutting on sites S3 (where 8% of the trees were removed) and S4 (where 20% of the trees were removed), the forest litter layer became more exposed and the value of parameter α increased significantly. Also, due to those measures, the value of parameter β decreased, which is most evident on site S2. In 2003, the diurnal temperature variation began to appear again on that site and the maximum amplitudes of that variation began reaching values of approx. 0.5 °C.

The values of parameters α and β , determined in the process of identification, may be presented as functions of the calculated biometric features of the stands (Table 2) growing on the analysed sites and of the organic matter content in the top layer of soil (heat capacity $2.5 \cdot 10^6$ [J m⁻³ K⁻¹], thermal conductivity 0.25 [W m⁻¹ K⁻¹], Hillel, 1982; Kowalik, 2001). The form of the model, with a characteristic maximum, was selected due to the similarity of its shape to the curves describing the variation of various biometric and hydrological features in single-age and single-species stands managed with clear-cutting methods, such as diameter growth rate (Husch et al., 2003) and leaf area index (Yu et al., 2015). Furthermore, the largest culmination of annual height increment characterises spruce stands aged 20–40 years (annual current increment curve, Assmann, 1970; Jaworski, 2004). Similarly, it is in this age group that the maximum soil shading by stands occurs (Suliński, 1993), which may be associated with the stand reaching the maximum crown closure. Taking all of the aforementioned premises into account, the following models were assumed:

$$\alpha = A - B \cdot W_0^C \cdot e^{-D \cdot W_0} \quad (6)$$

$$\beta = E \cdot (M_t + M_0)^F \cdot e^{-G \cdot (M_t + M_0)} \quad (7)$$

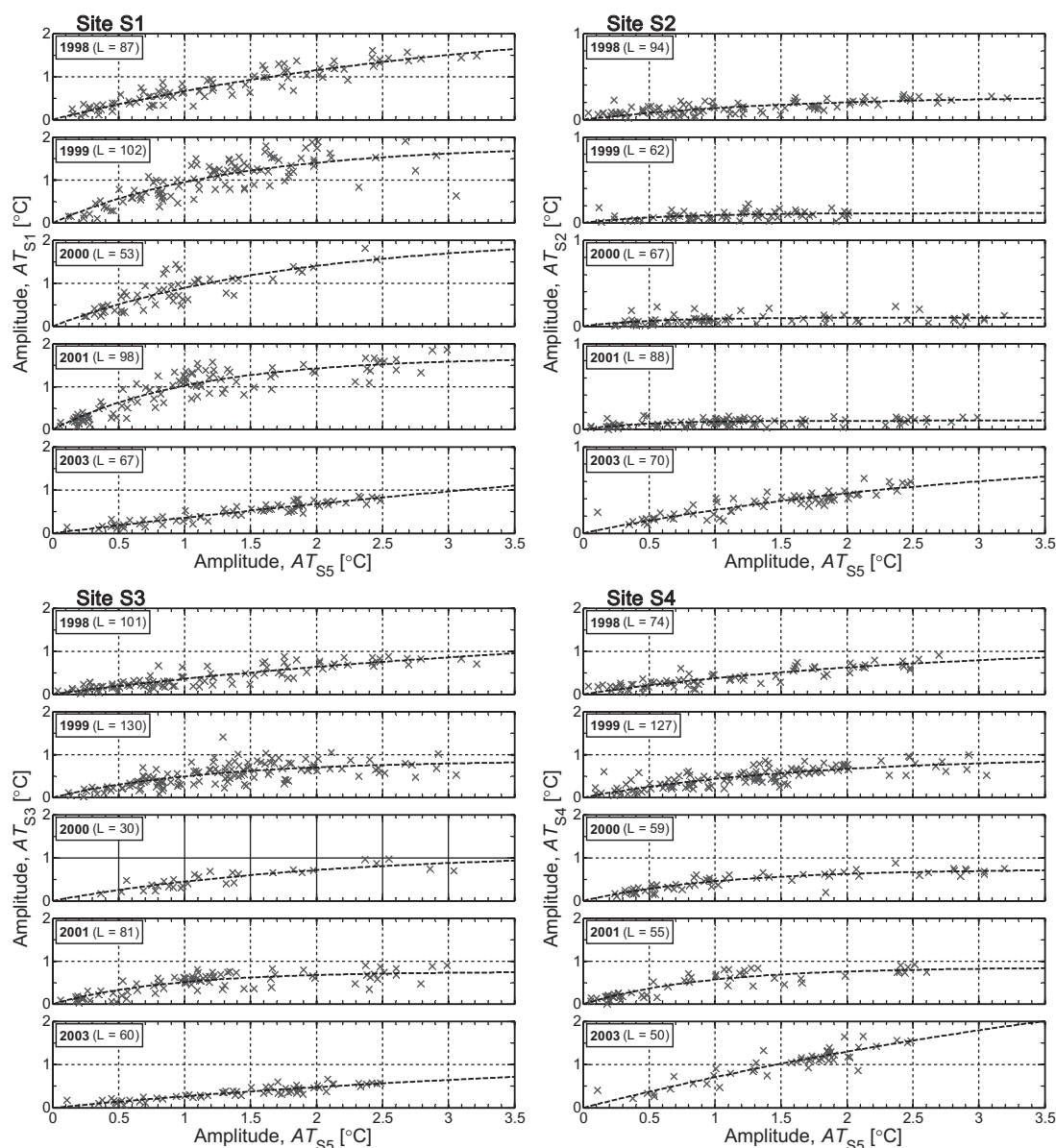


Fig. 7. Relationships between the amplitudes of diurnal variation on sites located in stands (S1, S2, S3 and S4) in comparison with the open area (site S5) located in the immediate neighbourhood. Variable suppression of diurnal variation depends mainly on biometric features of the stands on measurement sites (Table 2). The smallest suppression was observed on site S1 located in a thicket ($0^\circ < AT < 2^\circ$). In the seed stands (S3, S4) amplitude suppression is similar ($0^\circ < AT < 1^\circ$), while on site S2 (pole-timber stand) diurnal variation is almost non-existent ($AT < 0.3^\circ$). L indicates the number of cases, i.e. the number of days used in estimation in a particular year.

Table 4
Goodness-of-fit statistics for model (6).

A	B	C	D	R	$100 \cdot R^2$	σ	μ
3.028	2.961	1.179	0.438	0.97	94.12	0.17	18.05

R – correlation coefficient, σ – standard deviation of estimation, μ – average error of estimation [%].

where: W_0 is the soil exposure factor; M_t denotes the total mass of all trees with leaves [t ha^{-1} of the fresh mass of over ground plant parts]; M_o represents the total mass of dry organic matter in the top layer of soil up to a depth of 0.08 m [tonne per 1 ha]; A – G —coefficients to be calculated in the process of formula identification. The results of identification of Formulae (6) and (7) based on data from 1999 (biometric feature measurements) are presented, respectively, in Table 4 (Fig. 9, left) and Table 5 (Fig. 9, right).

Eqs. (6) and (7) explain the variation of coefficients α and β of model (5) with high precision of over 95%. However, it should be

Table 5
Goodness-of-fit statistics for model (7).

E	F	G	R	$100 \cdot R^2$	σ	μ
$8.25 \cdot 10^{-6}$	2.457	0.006	1.00	99.56	0.03	3.14

R – correlation coefficient, σ – standard deviation of estimation, μ – average error of estimation [%].

remembered that during identification of Formula (6) four coefficients were determined on the basis of 4 values. Yet, in that case, the most important factor was the form of Formula (6), which describes a very common relationship in forest environments: the extremes occurring in spruce stands aged from 20 to 40 years (in the presented case: an approx. 25-year-old pole-timber stand on site S2). In both cases, compatibility tests prove the proper choice of the form of the formulae. The values of the standard estimation error, respectively 18% and 3%, should above all be related to measurement conditions. Despite the number of analysed cases that was

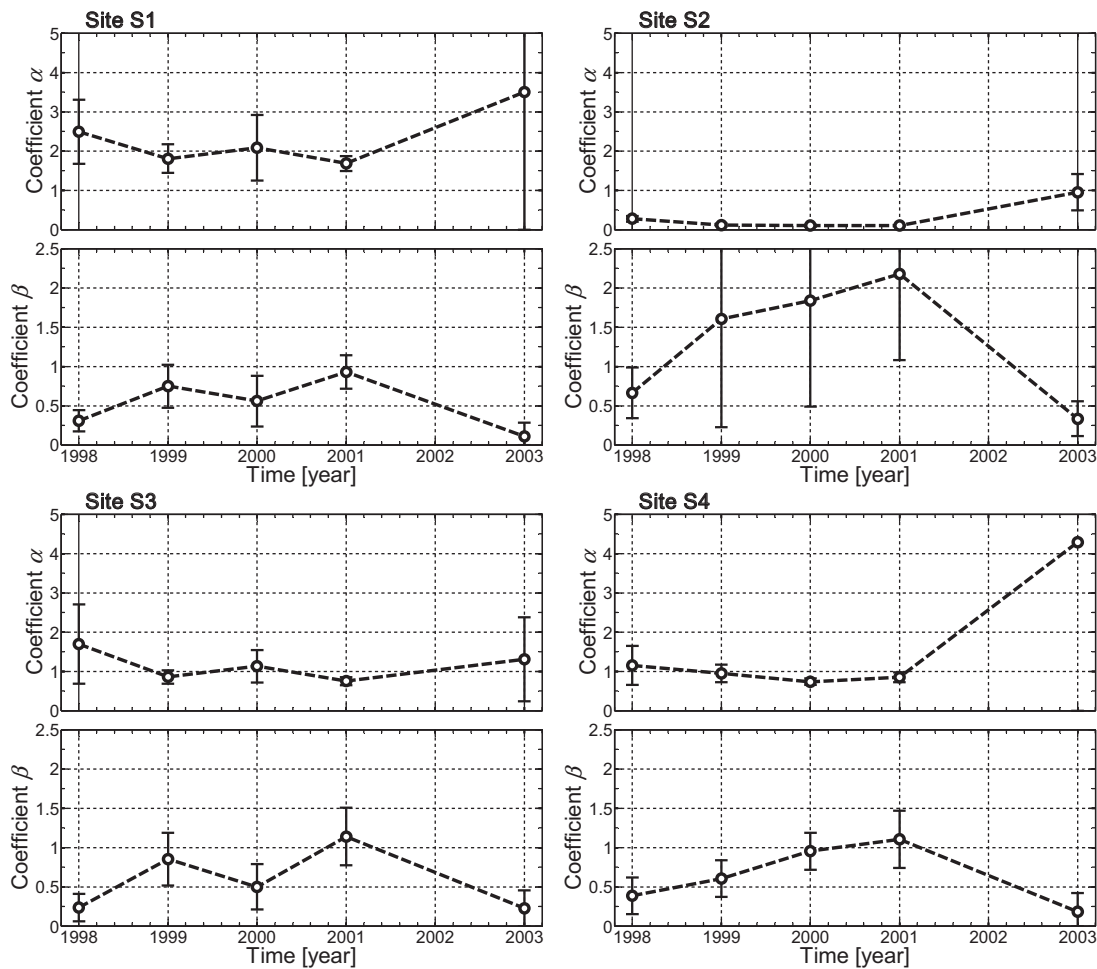


Fig. 8. Variation of parameters α and β of model (5) over time with 95% confidence intervals. Coefficient α may be identified with the asymptote determining the maximum possible value of the diurnal variation amplitude on a given site, whereas coefficient β (the temporal constant $\tau = 1/\beta$) characterises the dynamics of amplitude relationships (for values $AT_{SS} = 1/\beta$ amplitude AT_t reaches 63% of the maximum value α) – see Fig. 7. A very clear change in the values of the parameters and their uncertainty estimates occurred in 2003 following forest management measures conducted in 2002. In previous years, parameter variation resulted mainly from variability of biometric features of the stands growing on the research sites; annual growth ranged from 0.6–0.9 m in the second-age-class maturing stands (20–40 years old) to 0.3 m in the oldest mature seed stands (over 100 years old).

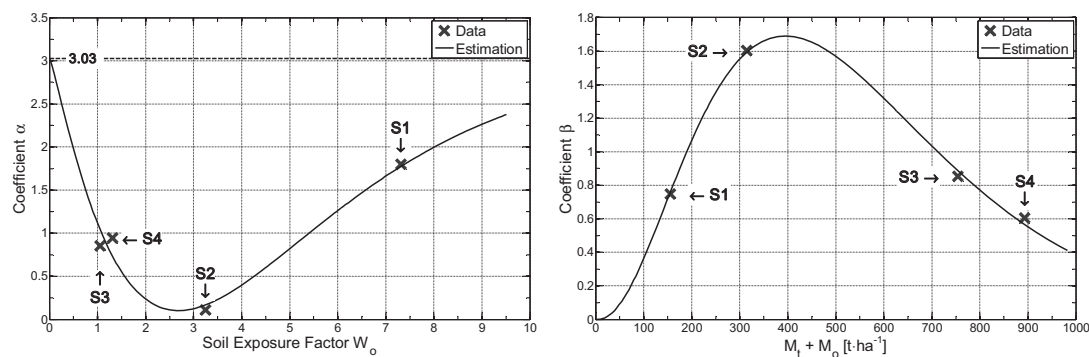


Fig. 9. Relationships between the coefficients of model (5) for measurements taken in 1999 (Table 3) depending on biometric features of the stands (Table 2). Coefficient α (left), Eq. (6), may be described by the dependence on the soil exposure factor. Coefficient β (right), Eq. (7), is the function of the total mass of the stand above the ground M_t and the dry mass of organic matter resting in the ground above the temperature sensors, M_o . Both functions reach extreme values, the minimum for model (5) and the maximum for Eq. (6), in values characteristic from the point of view of stand development.

sufficient from the formal point of view, i.e. from 62 to 130 during identification of Formula (5), the measurements were performed only in 4 stands; therefore the variation of the explanatory variables W_o as well as M_t and M_o is relatively small.

3.2. Amplitudes of diurnal variation in the open field

The dependencies between amplitudes of diurnal temperature variation in the top layer of soil in the open field have a different character than those under the stand (Fig. 10). On mid-forest meadows there is no such large limitation of the values of amplitudes

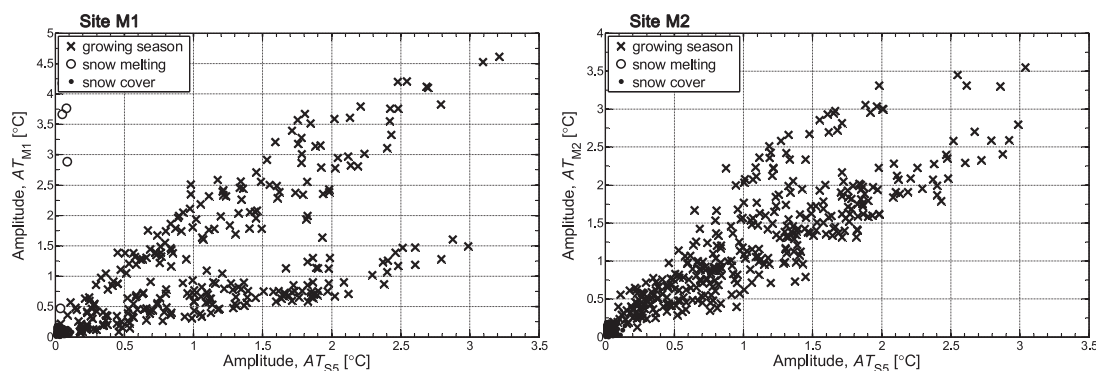


Fig. 10. Dependencies between amplitudes of diurnal variation on sites located in the open field (M1 and M2) compared to the open field (S5). At those sites, a large role may be played by their location within the valley as well as the angle and tilt of the slope. Site M2 was located at the valley bottom, on a meadow which is a natural flooding area of the Olza River. Site M1 was situated on a steeper and more southward slope than site S5 (Table 1), therefore the values of the amplitudes of diurnal variation reached higher values. Additionally, the relationships between the amplitudes of diurnal variation were shaped by stands growing in the closest neighbourhood of site M1 (see Fig. 11).

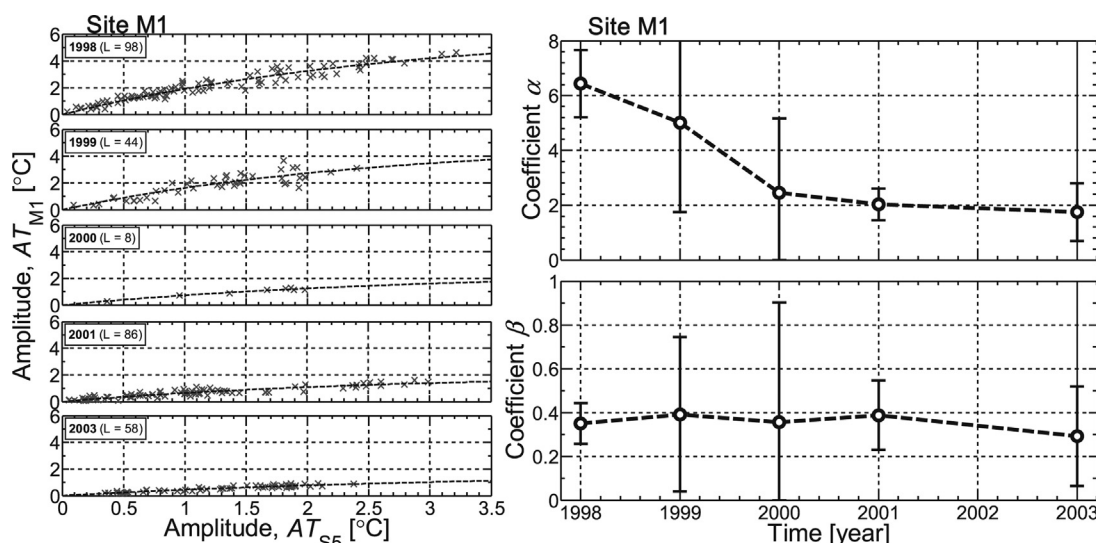


Fig. 11. Dependencies between the amplitudes of diurnal variation on site M1 located in the open field in relation to S5. The observed dependence may also be described by model (5) (left), but coefficient α , which may be identified with the asymptote determining the maximum value of the amplitudes of diurnal variation, changed its value (decreased with time, right). This change was related to the conditions of measurement performance on that site. Site M1 was set up in an area of natural forest renewal. The only trees that were cut were those growing on the measurement site, and not beyond it. With time, in late 1999 and early 2000, the neighbouring trees began to cast shade on the ground where thermometers had been placed. The value of parameter β did not change significantly over the course of the research. L indicates the number of cases; i.e. the number of days used in estimation in a particular year.

Table 6
Goodness-of-fit statistics for model (5) based on data measured in the open field (site M1).

Year	L	α	95% CI for α	β	95% CI for β	R	100-R ²	σ	μ
1998	98	6.434	5.209–7.659	0.350	0.257–0.444	0.96	92.75	0.30	14.58
1999	44	5.006	1.749–8.262	0.392	0.039–0.745	0.88	77.53	0.41	22.09
2000	8	2.447	0.000–4.894	0.356	0.000–0.712	0.98	95.28	0.07	7.65
2001	86	2.026	1.445–2.607	0.388	0.230–0.546	0.92	84.33	0.15	24.44
2003	58	1.742	0.691–2.793	0.293	0.066–0.520	0.92	84.82	0.08	15.34

L – number of cases (number of days used in estimation in a particular year); CI – confidence intervals; R – correlation coefficient, σ – standard deviation of estimation, μ – average error of estimation [%].

resulting from the stand phase development and the soil cover. In the case of those sites, an additional role may be played by location within the valley as well as the aspect and tilt of the slope.

In the vegetation period, the values of the amplitudes of diurnal variation on site M1 reached higher values than on the mid-forest meadow S5. Site M1 was situated in the central part of the valley on a steeper and more southward slope than site S5 (Table 1). Additionally, this was the site least shaded by the surrounding mountain ranges and neighbouring stands (the ground on site S5 was 10% more shaded than on site M1, Sypka et al., 2015). In that case, it

is also possible to apply the model provided by equation (5) in the description. Determined for each research year, the parameters of model (5) together with the calculated compatibility tests are presented in Fig. 11 and Table 6. The regression statistics confirm that model (5) was correctly matched and – according to values of the correlation coefficient R or $100R^2$ – the variability of amplitudes of diurnal variation may be explained with good accuracy (from 78% to 95%). Precise analysis of the coefficient of model α , which may be identified with the asymptote determining the maximum value of the diurnal variation amplitude on a given site, shows that its value

changed significantly with time due to the fact that site M1 was established in a natural regeneration area where tree height was approx. 1 m. Despite cutting of the new tree regrowth inside the meteorological station (5×5 m), with time the surrounding trees began to cast more and more shade on the thermometer installation. The value of parameter β did not change considerably over the whole research period and may be regarded as constant. This may have been due to the fact that organic matter remained on that site after a mature stand that had been cut earlier and its amount did not change considerably in the course of the research (there was no organic deposit from trees).

Site M2 was situated on the valley bottom on a practically flat meadow (tilt $\varepsilon = 4^\circ$) which is the natural flood area of the Olza River. Due to this location the amplitudes of diurnal variation were very close to the amplitudes recorded on site S5 and may be described by a simple linear model: $AT_{M2} = p \cdot AT_{S5}$. The slope values for each research year and the calculated compatibility tests are presented in Fig. 12 and Table 7. The constant value of slope $p = 1$ may be explained by the measurement conditions: on both sites there was dense meadow vegetation and the analysed diurnal variation amplitude describes general variation disregarding differences due to e.g. the location of a site on the valley bottom of the azimuth and the tilt of the valley slope (Fig. 4, left). Another dependence of the amplitudes was observed over 35 days (almost 11% of 325 analysed days, August–September 1999 and July–August 2001) because the amplitudes of diurnal variation AT_{M2} were considerably larger than amplitudes AT_{S5} (as denoted by square markers). This was related to high moisture content in the argillaceous, silty bed after heavy rainfall in the catchment area or during raised water levels of the Olza River as a result of rainfall in its upper course. High moisture largely aided heat propagation in the top layer of soil; therefore, those values were excluded from analysis.

4. Concluding comments

The study presents analysis of diurnal temperature variation on research sites located within the V-shaped valley of the Dupniański stream. The developed model (5) allows for estimated determination of the amplitude of diurnal temperature variation in the top layer of soil under Istebna spruce stands on the basis of measurements of temperature at the same level in the ground in the open field. A simplified analysis which disregarded factors affecting heat propagation in the soil resulted in high mean estimation error values. Nevertheless, the large values of the mean estimation error may be explained by the measurement conditions. Temperature measurements were carried out only in four stands (relatively small differentiation of explanatory variables W_0 and M_t as well as M_0) located at considerable distances from one another (S1–S5: 301 m, S2–S5: 417 m, S3–S5: 1063 m, S4–S5: 1016 m, M1–S5: 1160 m, M2–S5: 1503 m), therefore the measurement points could be characterised by different meteorological conditions such as local cloudiness or fog, as well as varying forest litter moisture which determined the flow of heat. Taking into consideration all of the factors affecting the diurnal temperature variation together with analysis of data from the winter period may justify the construction of the model based on the function which is the solution of the second-order differential equation: the equation of heat conductivity (Mills, 1999; Rohsenow et al., 1998). However, the number of parameters of such a model will increase to four. Differences between the solution of the second-order differential equation and proposed model (5) are very small and occur mainly for small values of the amplitudes of diurnal temperature variation ($AT < 0.3^\circ\text{C}$). For larger values, AT differences are negligible.

Both parameters of model (5), α and β , have a physical interpretation. Coefficient α may be identified with the asymptote

determining the maximum possible value of the amplitudes of diurnal variation on a given site. Coefficient β characterises the dynamics of amplitude dependences. For value $AT_{S5} = 1/\beta$ amplitude AT_i reaches 63% of the maximum value α . Assuming that the amplitude on site S5 $AT_{S5} = 5/\beta$, then value AT_i would equal the value of coefficient α (exactly 0.993α). On all research sites (except M2) a change in the values of parameters α and β in time can be observed. It may be assumed that changes occurring on sites located in the stands were related to a change of the biometric features of the stands (Fig. 8). Large changes occurred only after forest management tasks in 2002. The largest number of trees were removed on sites S1 (33%) and S2 (21%). As a result of that process, the forest litter (ground) became more exposed and the values of parameter α increased considerably while the value of β decreased. On site S2 diurnal variation was observed, which had been practically absent before (Fig. 5). However, it is difficult to interpret or model such changes correctly because earlier measurements had been performed in stands that were characterised by certain uniformity and continuity of the canopy. The removal of some trees caused the appearance of “gaps” in the stand, very strongly affecting the local values of temperature and insolation. The biometric features presented in Table 2 were average for an area of 1 ha and temperature measurements were performed at certain points. Such a strong lack of continuity in the canopy may last from one to three years because the free space is quite soon used by the remaining, mainly dominant, trees (Czarnowski, 1989). Equally important are the issues of correctly determining parameters that describe the stand and, consequently, the dependences between the amplitudes. In the case of natural forest regeneration areas (site S1), there were also trees whose height was below 1.30 m; therefore, it was not possible to measure their breast-height diameter. In seed stands (sites S3 and S4), a very frequent feature is the presence of the litter layer, which also affects the temperature variation in the ground.

The largest variation of parameter α occurred on site M1 (Fig. 11, right upper graph), which was located in a natural regeneration area where the tree height was about 1 m. On the measurement site, tree regrowth was systematically removed and, from a formal perspective, on that site there was no stand. However, the surrounding trees (birches and spruces), which grew very fast, began to cast more and more shade on the thermometers installed in the ground. As a result of that process, the value α decreased from 6.43 to 1.74, reaching values close to those obtained in the 12-year-old thicket (S1, $\alpha = 1.80$ in 1999), where trees with a height of approx. 3 m grew in 1999. It may therefore be concluded that the observed variation of parameter α results directly from stand growth and the change of the value of soil exposure. From a formal point of view, there was no stand on the measurement site (due to successive removal of regrowth), which is why for that site it is not possible to calculate the value of soil exposure factor W_0 or the total stand mass M_t above the ground. However, it may be assumed that on that site there was accumulated organic matter remaining after a previously removed mature stand. Furthermore, the mass of organic matter on the soil surface could not have changed significantly in the course of the research because organic deposits (needles, leaves or branches) from stands should not have occurred. A young spruce stand from forest regeneration did not shed dead needles in the course of the research as needles can last for up to 7 years (Boratyński and Bugała, 1998) and the spruce thicket had not reached that age. Besides, the measurement site was devoid of small spruces. This is why the value of parameter β on site M1, as function M_t and M_0 , did not change considerably during the whole research and may be regarded as a constant (Fig. 11, bottom right graph). On the basis of model (7) (Fig. 9, right), one may estimate value M_0 for mean value $\beta = 0.342$ (Table 6) on that site as amounting to approx. $96.9 \text{ [t ha}^{-1}\text{]}$. The estimated value is very close to the dry mass of organic matter in samples collected from the measurement points ($85 < M_0 < 104$

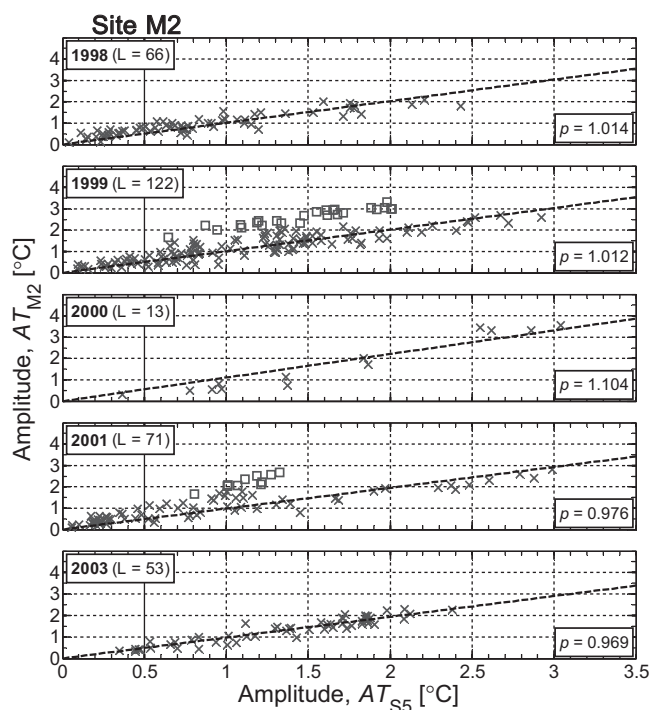


Fig. 12. Dependences between the amplitudes of diurnal variation on site M2 located on the bottom of the valley which is the natural flood area of the Olza River in relation to site S5. The observed dependence is linear with the regression coefficient equal to 1 (dense meadow vegetation occurred on both sites). In some cases, the amplitudes of diurnal variation AT_{M2} were considerably larger than amplitudes AT_{S5} (as denoted by square markers). This was related to high moisture content in the argillaceous, silty bed after rainfall in the catchment area of during elevated water levels of the Olza River due to rainfall in its upper course. These values were excluded from analysis. L indicates the number of cases, i.e. the number of days used in estimation in a particular year.

Table 7
Goodness-of-fit statistics for linear relationship $AT_{M2} = p \cdot AT_{S5}$ (site M2).

Year	L	p	95% CI for p	R	100· R^2	σ	μ	
1998	66	1.014	0.951–1.077	0.91	83.17	0.24	25.71	
1999	122	1.012	0.969–1.054	0.89	79.82	0.30	25.17	25 excluded days
2000	13	1.104	0.965–1.243	0.97	94.97	0.40	23.75	
2001	71	0.976	0.910–1.042	0.92	83.99	0.30	30.43	10 excluded days
2003	53	0.969	0.932–1.006	0.94	88.25	0.20	14.92	

L —number of cases (number of days used in estimation in a particular year); CI—confidence intervals; R —correlation coefficient, σ —standard deviation of estimation, μ —average error of estimation [%].

[t ha^{-1}], Table 1), which additionally confirms the correctness of the choice of the form of Formula (7) and sum M_t and M_o as the explanatory variable.

A different situation occurred on the second site, which was located in the open field (M2) at the valley bottom (Fig. 1, Table 1). Despite differentiation of the geographical location between sites M2 and S5 and differentiation of the amount of solar energy reaching those sites (Sypka et al., 2015), the observed dependences between the amplitudes had a linear character with a slope coefficient equal to 1 (Fig. 12, Table 7). This may be explained by the fact that both these sites were overgrown with dense meadow vegetation which equally suppresses solar radiation reaching the ground. Application of the Fourier transform and analysis of the diurnal component representing the general variation of temperature on a given level allowed for elimination of the influence of terrain topography (azimuth and slope angle). However, the influence of factors such as moisture, which determines the heat flow in the ground, was not eliminated. Site M2 was located in the natural flood area of the Olza River (Fig. 1). During heavy rainfall in the catchment area or when the river level was high (due to rainfall in the upper course of the Olza River), the argillaceous, silty bed was very moist and could maintain a high level of moisture for a long time, thus aiding heat propagation. Such a situation occurred

only in August and September 1999 and July and August 2000. At that time, the values of amplitudes AT_{M2} were almost twice as high as the values of amplitudes AT_{S5} , compared to the values of AT_{S5} when the water level in the Olza River was low (Fig. 12). Due to the small number of such days, it is difficult to unambiguously define the type of relationship $AT_{M2} = f(AT_{S5})$. On the basis of data from 1999 (25 days, Table 7, Fig. 12), it may be assumed that this is also dependence (5): $\alpha = 3.848$, $\beta = 0.796$, $R = 0.94$, $R^2 = 88.5\%$, $\sigma = 0.14$, $\mu = 5.34$.

An observation worth extended research concerns the extreme values of models (6) and (7). Formula (6) reaches the minimum value for $W_o = C/D = 2.69$ amounting to $\alpha_{min} = A - B \cdot (C/D)^C \cdot e^{-C} = 0.10$. Value 0.10 is the minimum value of the registered amplitude of the diurnal temperature variation, with a measurement resolution of 0.2°C . During a rapid change of soil exposure conditions on site M1 in the years 1999–2000, the value of parameter α changed from 5.0 to 2.4 (Fig. 11, Table 6), which considerably limited the maximum amplitude of diurnal variation. It may therefore be assumed that it is the determined value of the asymptote of model (6), coefficient $A \approx 3$ (Table 4) that is the boundary value of α , characterising the covering of soil by the stand. The function defined by Formula (7) assumes the maximum value equal

to $\beta_{max} = E \cdot (F/G)^F \cdot e^{-F} = 1.69$ for $M_t + M_o = F/G = 395$ [$t\ ha^{-1}$]. Assuming that $M_o \cong 100$ [$t\ ha^{-1}$] (Table 1), then β_{max} occurs at $M_t \cong 300$ [$t\ ha^{-1}$], which should correspond to the largest crown closure of the spruce stand. In single-species stands managed with clear-cutting methods, the age of 20–40 years (site S2), is a special period as culmination of height increment occurs which leads to increased need for both nutrients and water. Research done in single-species and single-age pine stands (Kucza and Suliński, 1987) showed that the age at which growth culmination occurs is accompanied by culmination of use of soil water. In the case of the analysed spruce stands, an increased need for water in that development phase should also be expected. Therefore, it is likely that the stand retains the maximum amount of rainwater while minimising possible evaporation from the soil surface. As far as water retention is concerned, research was done in 2003 on the organic matter absorptivity in ectohumus layers sampled under 13 spruce stands in the Dupniański stream catchment (Kucza and Urbaś, 2005). This research showed that the organic matter at site S2 had the greatest ability to retain rainwater and the smallest share of particles with hydrophilous properties. Water retention by the organic layers is particularly important for spruce stands because they have flat root systems. Young stands counteract the non-productive evaporation by suppressing both wind and solar radiation (W_o), therefore the temperature of the organic horizon is more stable and the humidity of atmospheric air on the forest floor should be high. Furthermore, it may be assumed that proper moisture in these layers and temperature stability under stands of this age may favourably affect the processes of mineralisation and release of necessary nutrients. This is a hypothesis that should be verified by specialised research as its confirmation would testify to the fact that a stand can regulate atmospheric and soil microclimate aspects. The presented results of the research on variation of amplitudes in the top layer of the analysed soils under spruce stands, which may be explained by the stand development phase, seem to initially confirm this hypothesis.

The soil exposure factor characterises the balance of solar radiation at the forest litter level and the mean wind speed within a stand (Suliński, 1993). Adopting a general assumption that the rate of water evaporation from soil depends on temperature, water surface, and the movement of air above the ground (wind), coefficient W_o is a reliable numerical value which can express the integrated influence of a stand on the temperature or evaporation conditions on the forest floor. Forest litter or meadow vegetation, which is low but thick and directly adjacent to the ground, produces a protective effect that is similar to dense but tall tree crowns (Rauner, 1972). When modelling the parameters of water exchange balance between the atmosphere, the stand and the ground, two basic indices, LAI or LAD , are very often used (Sonohat et al., 2004; Yi, 2008). In contrast to N , DBH or calculated M_t , LAI is difficult to measure precisely. Leaf area index is determined by methods based on either direct or indirect photometrical measurements. The direct method requires stripping and measuring the foliage of the plant canopy samples, with the disadvantage that this is destructive, time consuming and expensive, especially if the study area is very large. The disadvantage of the indirect method is that in some cases it can underestimate the value of LAI in very dense canopies, as it does not account for leaves that obscure each other and essentially act as one leaf according to the theoretical LAI models (Wilhelm et al., 2000). Additionally, all biometric features of a stand (N , DBH , H , LAI) are dependent upon one another. Such relationships between these biometric features are the subject of interest of dendrometry (Fassnacht et al., 1994; Jonckheere et al., 2005; Turner et al., 2000). Determination of value W_o on the basis of measurements that can be easily performed on the ground, or based on data contained in forest management plans, creates the possibility of easy extrapo-

lation of the model on large spatial scales, e.g. on the whole forest inspectorate with an area of approx. 10,000 ha. LAI measurement in such a large area is not practically feasible.

The development and miniaturisation of data recording equipment and measurement sensors makes it possible to measure a growing number of parameters in any place and at any time interval. The application of objective numerical methods and calculation algorithms used in signal processing theory makes it possible to understand differences or similarities in recorded temperature patterns in the top layer of soil at a depth of approx. 0.08 m (Figs. 3 and 5). Calculated with the use of the Fourier transform, the diurnal amplitude values make it possible to easily determine the moment (counted in days) of the melting of the snow cover under the stand in relation to an open area nearby. Precise analysis of the amplitudes of diurnal temperature variation also revealed the speed of snow melting under the stand (Fig. 6). The end of snowmelt is the day when the relations between the amplitudes of diurnal temperature variation are typical of the vegetation period (III, Fig. 6) and can be described by relation (5). During the growing season the observed changeability of diurnal temperature variation in the top layer of soil largely depended on biometric features of the stands and soils on the research sites (Figs. 3, 5 and 7). In winter, with the presence of the snow cover, such changeability did not exist. A thorough understanding of the impact of hydro-meteorological factors, i.e. soil temperature and its variability, on the water exchange balance within forest complexes would considerably expand the capability for predicting the results of silvicultural measures as well as the estimation of site productivity, which determines the growth of stands and the survival rate of forest complexes. The presence of spruce stands in the study area was quite phenomenal as spruce stands are only generally found in this temperate climate zone in the higher montane zone above 1100 m AMSL. Furthermore, it may be suggested that vegetation conditions in the study area were different from those usually found in the foothills (up to 600 m AMSL) and in the lower montane zone (from 600 to 1100 m AMSL). The best quality Istebna spruce stands with heights up to 44 m covered the eastward slopes of the Dupniański stream valley.

Concerning the analysed data, the relation that was found has an application in single-species and even-age stands. A significant question arises over whether this analytical description can have a more general character and may concern stands with a more complex structure. Models using biometric features should be easily adaptable to other species, while appropriate coefficients that account for differences between species are preserved. Necessary improvements of the model presented above should be possible after a series of more precise measurements (e.g. water content in soil, solar energy reaching the ground, etc.) in experimental catchments that differ in terrain as well as in different types of single- and multi-species stands. Such more precise measurements should be performed in a larger number of stands so that the variation of explanatory parameters W_o , M_t and M_o is larger, with more research sites in those stands where model functions, Eqs. (6) and (7), reach their extreme values: minimum for $W_o = 2.39$ and maximum for $M_t + M_o = 395$ [$t\ ha^{-1}$].

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Appendix A. : Calculations of biometric features of a tree stand

The total mass of all trees with leaves [t ha^{-1} of fresh mass of over ground parts of plants] of an investigated stand may be calculated by field measurements taking into consideration: the number of trees per hectare (N); the diameter at breast height DBH ; the height of a stand (H); and the elevation of the canopy (the height of the lowest 'green' branches, H_s). The necessary empirical equations were proposed by Suliński (1993, 2007). After calculating the mean \overline{DBH} , the mean biomass of leaves of the mean tree (m_l) may be determined by the following empirical formula (Suliński, 2007):

$$m_l = 1.38 + 0.0766 \cdot \overline{DBH}^{1.71}, \quad (8)$$

where m_l is the leaf biomass of the mean model tree [kg]; \overline{DBH} denotes the mean diameter at breast height [cm]. The constant coefficients in Eq. (8) were identified based on data included in the yield tables (Schwappach, 1943). Taking into account the mean tree height of a considered stand by using Lorey's equation (\bar{H}), the volume of the stem and branches of the mean model tree was estimated using the consecutive empirical equation:

$$v = 1.1 \cdot \left(\frac{\overline{DBH}}{100} \right)^{1.88} \cdot (\bar{H} - 1.3)^{0.68}, \quad (9)$$

where v is the volume of the mean model tree (stem and branches) [m^3]; \overline{DBH} represents the mean diameter at breast height [cm]; \bar{H} denotes the height of the mean model tree [m]. The constant coefficients in Eq. (9) were evaluated based on data published in the volumetric tables (Czuraj et al., 1966). The total biomass of a stand was approximated by the subsequent formula:

$$M_t = N \cdot \frac{m_l}{1000} + N \cdot \rho \cdot v, \quad (10)$$

where M_t is the total biomass of a stand [tonne of fresh mass per hectare]; N denotes number of trees per hectare; m_l represents biomass of leaves of the mean model tree [kg]; ρ is green wood density, for spruce $\rho = 0.75$ [t/m^3] (Suliński, 1993, 2007); and v is the volume of the stem and branches of the mean model tree [m^3]. The biomass located in the stem layer was calculated by applying the following formulae:

$$M_s = N \cdot \rho \cdot H_s \cdot \frac{\pi}{4} \cdot \left(\frac{D_{0.5}}{100} \right)^2, \quad (11)$$

where M_s is the total biomass inside the stem layer [tonne of fresh mass per hectare]; N represents the number of trees per hectare; ρ is spruce green wood density, 0.75 [t m^{-3}] (Suliński, 1993, 2007); H_s denotes the height of the stem layer [m]; and $D_{0.5}$ is the diameter of the stem at the stem mid-height [cm]:

$$D_{0.5} = \overline{DBH} - t_s \left(\frac{H_s}{2} - 1.3 \right), \quad (12)$$

where \overline{DBH} is the mean diameter at breast height [cm]; H_s is the height of the stem layer [m]; and t_s describes the mean stem taperness in a stand:

$$t_s = \frac{\overline{DBH}}{H}, \quad (13)$$

where \overline{DBH} is the mean diameter at breast height [cm] and H represents the mean height of a stand. The total biomass inside the canopy, M_c [tonne of fresh mass per hectare], was calculated as the difference between the total biomass of a stand, M_t , and the total biomass inside the stem layer, M_s :

$$M_c = M_t - M_s \quad (14)$$

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