Folia Forestalia Polonica, series A, 2011, Vol. 53 (2), 114–122

ORIGINAL ARTICLE

Net radiation of mountain cultivated Norway spruce [*Picea abies* (L.) Karst.] stand: evaluation of short- and long-wave radiation ratio

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Abstract

The radiation exchange drives the plant ecosystems energy balance and provides the energy for photosynthesis, transpiration and plant growth. The investigation on net radiation and its component during vegetation season in relation to the clearness index and sun elevation in a cultivated 31-year-old mountain spruce [*Picea abies* (L.) Karst.] stand is presented. Downward short-wave radiation – S_d (incident on the spruce stand was the main part of the short-wave radiation balance during the whole growing season (April–October) 2008. The S_d amount is seasonally variable factor determined by the duration of solar shine and the atmosphere transmissivity. Obtained value of net radiation (R_n) and downward short-wave radiation (S_d) ratio amounts to 0.61 on average during the growing season 2008 documenting the importance of the downward short-wave radiation in the net radiation of investigated spruce stand.

Key words

downward short- and long-wave radiation, upward short- and long-wave radiation, sun elevation, clearness index

Introduction

Net radiation is an important variable in meteorology, hydrology and ecology, because it determines the degree of radiation exchange between an active surface and the atmosphere and it influences energy and mass fluxes (Baldocchi *et al.* 2000; Beringer *et al.* 2005; Gavilan *et al.* 2007). Thus, net radiation is regarded as a particular parameter in used surface energy partitioning models (Monteith and Unsworth 1990; Anthoni *et al.* 2000; Oliphant *et al.* 2003; Falge *et al.* 2005) including the realized tests of the validity of the eddy covariance technique (Aubinet *et al.* 2000; Baldocchi *et al.* 2001; Rannik *et al.* 2006).

Net radiation is the expression given to the net amount of energy incident on a certain surface. In numerical terms, it consists of the sum of the downward and upward short- and long-wave radiation. Thus, the net amount of radiation received by a surface is defined as:

Received 22 October 2010 / Accepted 29 June 2011

$$R_n = S_d - S_u + L_d - L_u$$

where R_n – net radiation (it means net all-wave radiation), S_d – downward short-wave radiation incident on the surface, S_u – upward short-wave radiation reflected by the surface to the atmosphere, L_d – downward long-wave radiation emitted from the atmosphere, L_u – upward long-wave radiation emitted from the surface to the atmosphere. All surfaces receive short-wave, radiation during daylight and exchange long-wave radiation continuously with the atmosphere. The main part of the plant ecosystems net radiation amount belongs to downward solar short-wave radiation. It is well supported by the existing linear relationship between downward short-wave radiation and net radiation of plant ecosystems (McCaughey 1978; Alados *et al.* 2003; Marková *et al.* 2006).

The exclusivity of plant ecosystems surface is primarily demonstrated by their considerable spatial and temporal variability caused by changing the stand canopy geometric relations, optical properties and cloud conditions (Gholz and Clark 2002; Betts *et al.* 2007). Moreover, the radiation exchange drives the plant ecosystems energy balance and provides the energy for photosynthesis, transpiration and plant growth (Fussler 1998; Oliphant *et al.* 2006; Flerchinger *et al.* 2009).

The objective of the presented paper is focused on an investigation on net radiation and its component during the growing season in relation to the clearness index and sun elevation in a cultivated 31-year-old mountain spruce [*Picea abies* (L.) Karst.] stand is presented.

Methods

Net radiation of mountain Norway spruce stand was observed and evaluated at the study site of Bílý Kříž during the growing season (May–October) in 2008. Description of the study site and studied stand is shown in Tab. 1.

Tab. 1. Description of the study site and the studied spruce stand

Study site	Bílý Kříž (Moravian-Silesian Beskids Mts., the Czech Republic) – geographic coordinates: 18°30′ E, 49°30′ N – altitude: 877 m – geological subsoil: flysh layer with dominant sandstone – soil type: typical humo-ferric podzol with mor-moder form of surface humus, medium depth up to shallow, loamy-sand or sandy loam, relatively low nutrient content, depth of 60–80 cm – mean annual temperature: 6.7 ± 1.2°C – mean annual sum of precipitation: 1374 ± 186 mm
Studied stand	*Picea abies* (L.) Karst – planted out in 1981 using four-years old seedlings – exposure: SSE – slope 12.5° – in the 2008: – trees age: 31 years – stand density: 1428 trees ha^{-1} – mean stand height: 12.5 ± 0.1 m – mean diameter at breast height: 15.4 ± 0.2 cm – maximum leaf area index: 9.5 ± 0.3 $m^2 m^{-2}$

Net radiation observation

Net radiation of mountain cultivated Norway spruce stand was measured by the Net Radiometer CNR 1 (Kipp-Zonen, the Netherlands) located 20 meters above the ground on a steel meteorological mast. Net radiometer recorded four net radiation components separately, i.e. downward short-wave radiation incident on the spruce stand (S_d), upward short-wave radiation reflected by the spruce stand to the atmosphere (S_u), downward long-wave radiation emitted from the atmosphere (L_d), upward long-wave radiation emitted from the spruce stand to the atmosphere (S_u). Moreover, the short-wave ($R_n$sw) and long-wave ($R_n$lw) net radiation were obtained as:

$$R_n sw = S_d - S_u; \; R_n lw = L_d - L_u.$$

All components of stand net radiation were automatically recorded per 30 seconds and 30-minute average values were automatically stored by a data-logger equipped with a managing single board computer with an integrated processor VIA 667 MHz with low consumption and operating system Windows XP Embedded which is installed on 512 MB CF disc without rotating parts. Modules ADAM (Advantech, USA) communicate with this computer after data bus RS-485.

Daily sums of above mentioned values were calculated for individual days of the growing season (May–October) in 2008.

Sun elevation determination

Sun elevation values for an individual day of the growing season (May–October) in 2008 at the study site of Bílý Kříž were calculated for each 30-minute interval (0:30, 1:00, 1:30, etc.) using the computer program "PhotosynAssistant ver 1.1 (Dundee Scientific, the Great Britain)". Intervals of 0–10, 11–20, 2–30, 31–40, 41–50, 51–60 and 61–70^{o} of sun elevation were used for an analysis of the relationship between the values of S_d, S_u, L_d, L_u, R_n and sun elevation.

Clearness index determination

The clearness index was obtained as the ratio between extra-terrestric irradiance at the north latitude of 50^{o} (Vaníček 1994) and a short-wave solar radiation incident on the studied spruce stand for each 30-minute interval (0:30, 1:00, 1:30, etc.) for an individual day of the growing season (May–October) in 2008. Intervals of 0.00–0.10, 0.11–0.20, 0.21–0.30, 0.31–0.40, 0.41–0.50, 0.51–0.60, 0.61–0.70, 0.71–0.80, 0.81–0.90 and 0.91–1.00 of the clearness index values were used for an analysis of the relationship between the values of S_d, S_u, L_d, L_u, R_n and the clearness index.

Results and Discussion

Short-wave radiation

The downward short-wave radiation incident on the spruce stand was the main part of the short-wave radiation balance as well as of the total net radiation during the growing season in 2008 (Fig. 1, Tab. 2). The S_d amount is a seasonally variable factor determined by the duration of solar shine and the atmosphere transmissivity and for these reasons the seasonal differences of the daily sums of S_d were substantial (variation coefficient: 55%). In agreement with published results (McCaughey 1978; Marková *et al.* 2006) the strongly correlated ($r^2 = 0.93$) linear relationship has been found between S_d and R_n (Fig. 2). The obtained value of R_n/S_d ratio amounts to 0.61 on average during the growing season in 2008 documenting the importance of the downward short-wave radiation in the net radiation balance of the investigated spruce stand. Similar results for coniferous stands were published by Tajchman (1972) and Jarvis *et al.* (1975).

Daily sums of upward short-wave radiation reflected by the spruce stand to the atmosphere showed high

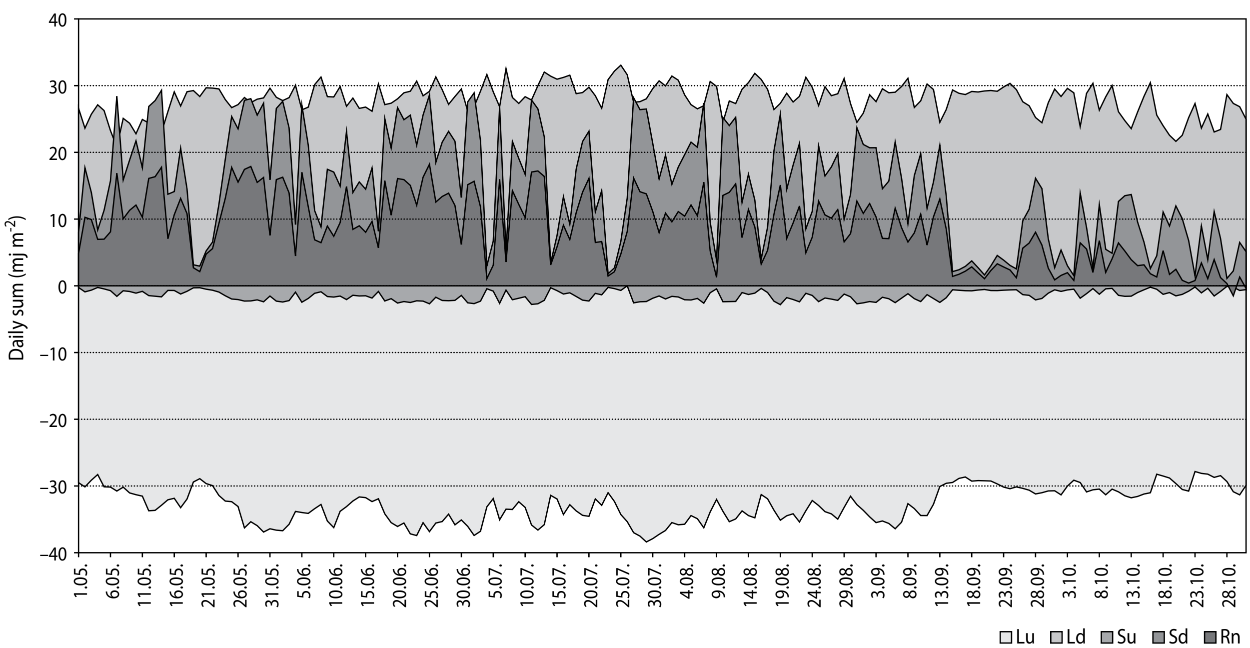

Fig. 1. Daily sums of net radiation components (Sd – downward short-wave radiation incident on the spruce stand, Su – upward short-wave radiation reflected by the spruce stand to the atmosphere, Ld – downward long-wave radiation emitted from the atmosphere, Lu – upward long-wave radiation emitted from the spruce stand to the atmosphere) and net radiation (Rn) of the spruce stand during the growing season (May – October) in the 2008

Tab. 2. Statistical characteristics of net radiation components (S_d, S_u, L_d, L_u), short-wave (R_nsw) and long-wave (R_nlw) radiation balance and total net radiation (R_n) of the studied spruce stand during the growing season (May–October) in the 2008

	May–October 2008			
	total sum	mean daily sum	minimum daily sum	maximum daily sum
	(MJ m^{-2})			
S_d	2734.9	14.9 ± 8.1	1.1	29.3
S_u	267.7	1.5 ± 0.7	0.1	2.8
L_d	5148.2	28.0 ± 2.3	20.8	33.1
L_u	6040.4	32.8 ± 2.6	27.8	38.4
R_nsw	2467.3	13.4 ± 7.5	1.0	27.6
R_nlw	–892.2	–4.8 ± 2.9	–10.6	0.0
R_n	1575.1	8.6 ± 5.1	–1.5	18.2

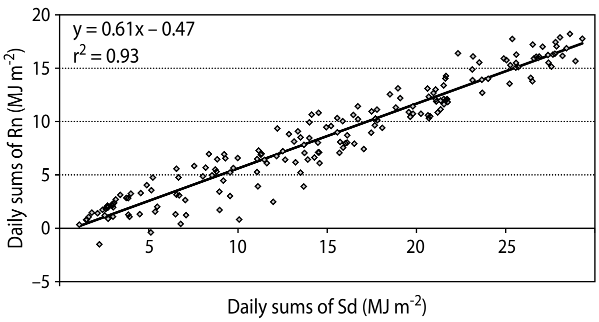

Fig. 2. Relationship between net radiation (Rn) of the spruce stand and downward short-wave radiation (Sd) incident on the spruce stand during the growing season (May–October) in the 2008

variability (variation coefficient: 51%) because the S_u amount was greatly dependent on the amount of seasonally changed stand optical properties and the amount of downward short-wave radiation (Fig. 3). Daily upward short-wave radiation loss varied between 3–33% and thus the mean daily albedo (S_u/S_d) of the studied spruce stand was only 11% during the investigated growing season in 2008. The low daily values of albedo of forest stands seem to be a common phenomenon (Jarvis *et al.* 1975; Eck and Deering 1992; Betts *et al.* 2007). The obtained results show a small effect of S_u on the short-wave radiation balance as well as on the total net radiation of the investigated spruce stand.

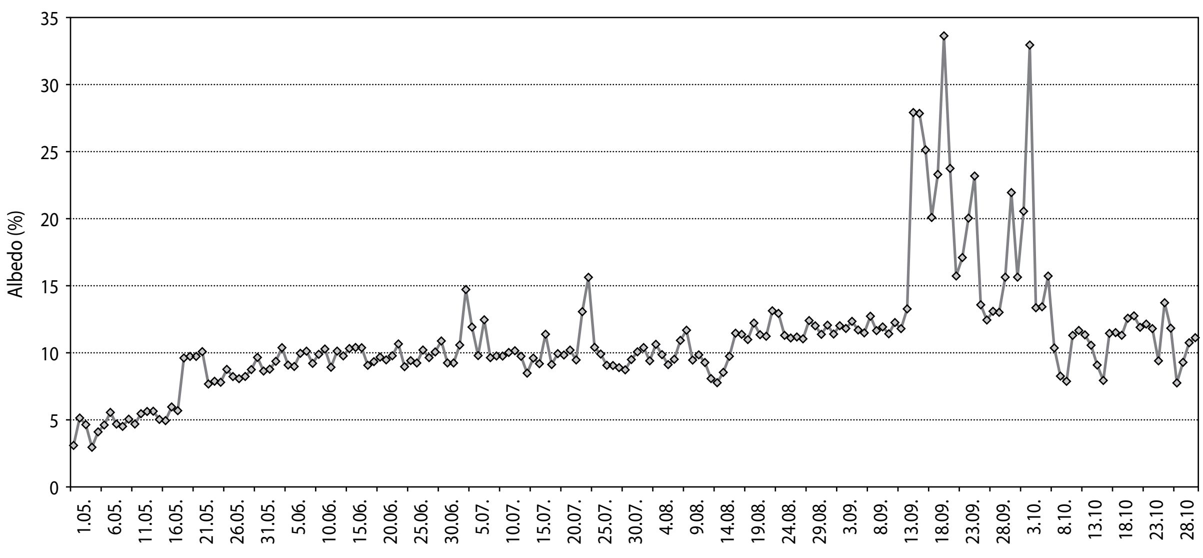

Fig. 3. Seasonal changes of albedo (S_u/S_d) of the spruce stand during the growing season (May–October) in the 2008

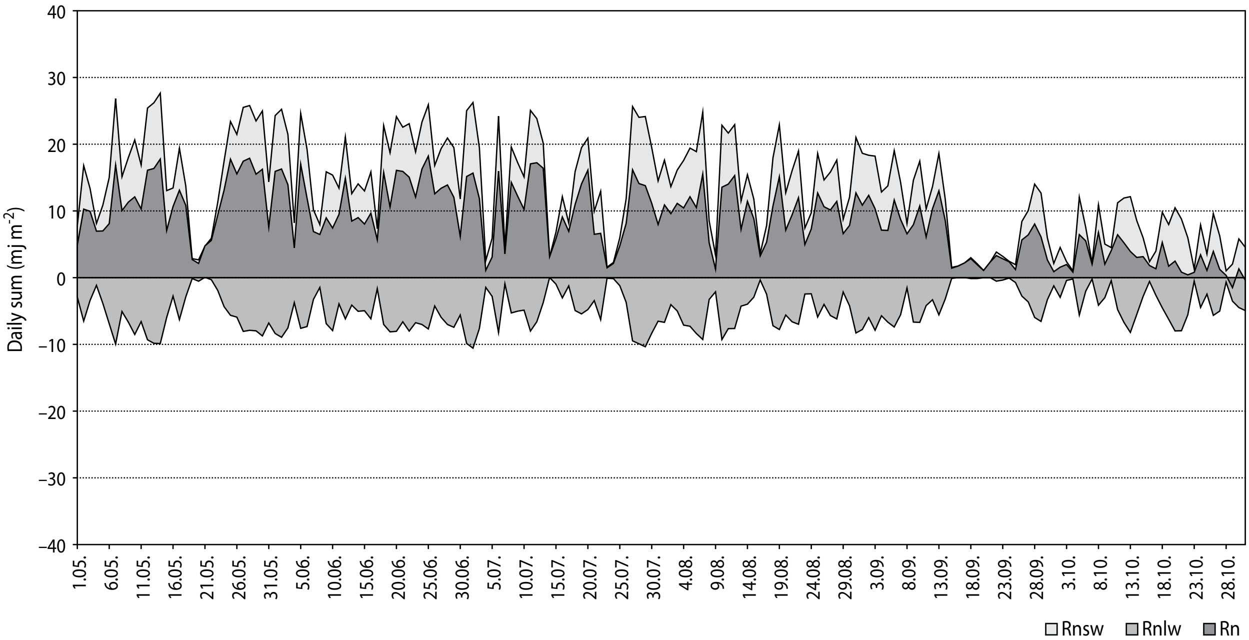

Fig. 4. Daily sums of short-wave (Rnsw) and long-wave (Rnlw) radiation balance and net radiation (Rn) of the spruce stand during the growing season (May–October) in the 2008

Long-wave radiation

The components of long-wave radiation balance (L_d and L_u) were much more equable compared to the components of short-wave radiation balance (Fig. 1, Tab. 2). A seasonally obtained variation coefficient of L_d as well as L_u daily sums amounts only 8%. The energy dissipation within spruce stand is responsible for the higher amount of the upward long-wave radiation which is emitted to the atmosphere compared to the downward long-wave radiation emitted by the atmosphere. It is opposite to the short-wave radiation balance.

Net radiation

Net radiation of studied spruce stand was positive practically during the whole growing season (Fig. 4) in 2008. Differences in daily sums of R_n were substantial after the variation coefficient (60%). Thus, from the energy supply point of view, the conditions of the investigated mountain spruce stand on given locality during growing season were favorable.

Short-wave radiation balance was during the whole studied period positive indicating permanent input of energy available for the stand processes (mainly photosynthesis). The negative long-wave radiation balance (its loss amounts to 32% of total downward short-wave radiation) results from the intensive energy dissipation (evapotranspiration) and optical properties of foliage (reflectance of foliage, trunks and soil surface) spectral. Thus, for the studied mountain spruce stand the most important component of net radiation was the downward short-wave radiation (Fig. 4).

Relationship between net radiation and its component, clearness index and sun elevation

The relationship between the values of S_d, S_u, L_d, L_u, R_n and the clearness index and the sun elevation was analyzed during the growing season (May–October) in 2008 (Fig. 5, 6 and 7). Whereas relations between S_d as well as S_u and the clearness index and sun elevation intervals were linear, the same for L_d as well as L_u was square (slope and correlation coefficient for determined relationships are shown in Tab. 3). A strong linear relationship was found between the R_n of spruce stand and the clearness index at all chosen sun elevation intervals (Fig. 7). This finding once again supports the importance of the downward short-wave radiation on final spruce stand net radiation.

Because of the direct connection to the solar radiation, the values of S_d, S_u and R_n were increasing together

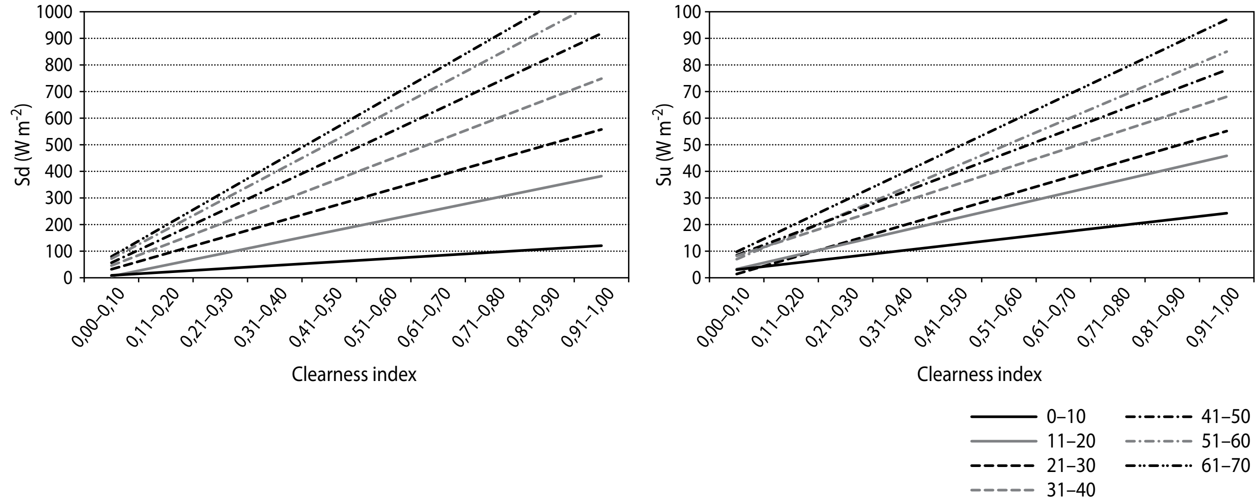

Fig. 5. Relationship between the downward short-wave radiation incident (Sd) and upward short-wave radiation reflected by the spruce stand (Su) and the clearness index for the chosen sun elevation intervals (0–10, 11–20, …, 61–70°) during the growing season (May–October) in 2008

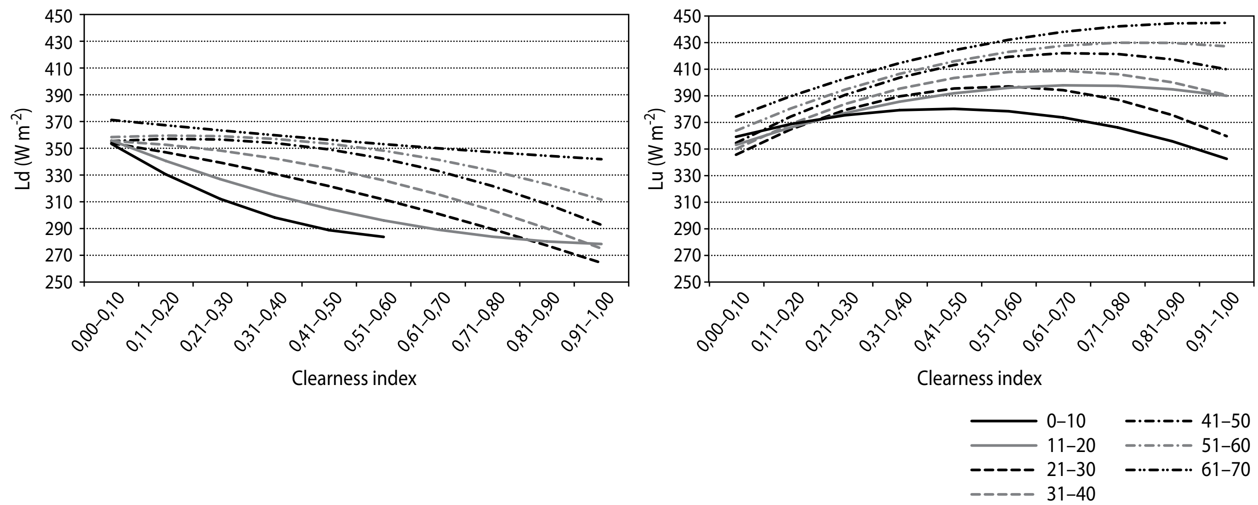

Fig. 6. Relationship between downward long-wave radiation emitted from the atmosphere (Ld) and upward long-wave radiation emitted from the spruce stand to the atmosphere (Lu) and the clearness index for the chosen sun elevation intervals (0–10, 11–20, …, 61–70°) during the growing season (May–October) in the 2008

with the increasing clearness index and sun elevation (Fig. 5, 7). However, values of L_d were decreasing with increasing clearness index and increasing with increasing sun elevation. This finding well documents the situation when clear sky produces small fraction of long-wave radiation (low occurrence of clouds), shorter path of sun beam during higher sun elevation is connected with higher illumination. The values of L_u were increasing with sun elevation (except sun elevation interval of 11–30º). The trajectory of the relationship between L_u and the clearness index is similar to obtained relations for short-wave radiation and R_n. By the acceptance of the premise, that L_u values are a form of energy dissipation manifestation within forest stand, this finding is not surprising (Fig. 6).

A forest stand as a distinctive spatial unit shows huge energy exchange strongly related to the solar radiation input. External conditions, particularly atmospheric transparency characterized by the values of the clearness index affects the participation of the long-wave radiation on the whole radiation budget. Thus, from the point of view of the autotrophic energy conversion into energy of chemical bounds the favorable participation of the short-wave energy rich radiation is of great advance from the photosynthetic activity point of view (Marek *et al.*1999; Šprtová and Marek 1999; Urban *et al.* 2008). Forest stand long-wave radiation balance is connected with the temperature regime affecting especially respiration and stand evapotranspiration. The importance of short-wave radiation and positive net radiation in the investigated spruce forest stand energy balance is evident.

Tab. 3. Slope and correlation coefficient (r^2) for determined relationship between the amount of net radiation components (S_d, S_u, L_d, L_u) and total net radiation (R_n) of the studied spruce stand and clearness index for chosen sun elevation intervals during the growing season (May–October) in the 2008

			S_d	S_u	L_d	L_u	R_n
Sun elevation	0–10°	slope	12.4	2.4	2.2	–1.4	–
		r^2	0.85	0.98	0.96	0.82	–
	11–20°	slope	41.8	4.7	0.8	–1.1	20.6
		r^2	0.98	0.98	0.98	0.92	0.83
	21–30°	slope	58.4	6.0	–0.4	–2.2	39.1
		r^2	0.99	0.98	0.99	0.79	0.98
	31–40°	slope	78.1	6.7	–70.8	–1.8	56.9
		r^2	0.99	0.99	0.99	0.87	0.99
	41–50°	slope	95.8	7.7	–1.1	–1.7	74.3
		r^2	0.99	0.99	0.96	0.93	0.99
	51–60°	slope	108.2	8.7	–0.8	–1.2	86.9
		r^2	0.99	0.99	0.97	0.97	0.99
	61–70°	slope	117.3	9.7	0.1	–0.9	94.4
		r^2	0.99	0.99	0.92	0.98	0.97

Deeper investigation of the net radiation balance brings an improvement of the production models directly used in forestry or in an evaluation of the forest stands ecosystems services.

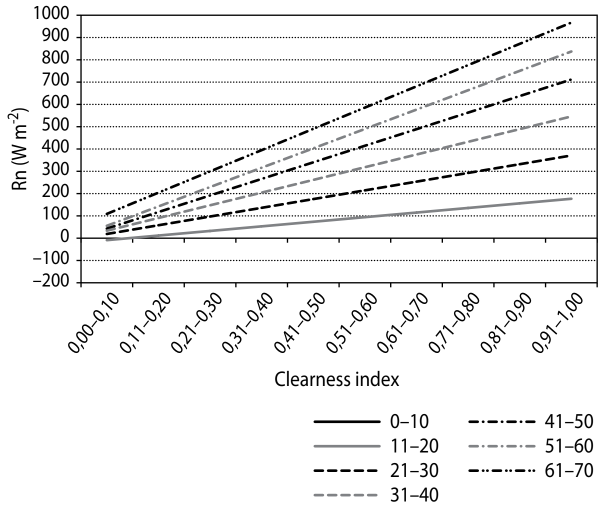

Fig. 7. Relationship between net radiation of the spruce stand (Rn) and the clearness index for the chosen sun elevation intervals (11–20, 21–30, …, 61–70°) during the growing season (May–October) in the 2008

Acknowledgement

The Ministry of Education, Youth and Sports of the Czech Republic (Project No. MSM 6215648902) financially supported this research.

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