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LIGHT USE EFFICIENCY OF ABOVEGROUND BIOMASS PRODUCTION OF NORWAY SPRUCE STANDS

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Abstract

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Light use efficiency (LUE or photosynthetically active radiation use efficiency) in production of young spruce stands aboveground biomass was determined at the study sites Rájec (the Drahanská vrchovina Highland) and Bílý Kříž (the Moravian-Silesian Beskids Mountains) in 2014 and 2015. The LUE value obtained for the investigated spruce stands were in the range of 0.45–0.65 g DW MJ^{-1}. The different LUE values were determined for highland and mountain spruce stand. The differences were caused by growth and climatic conditions and by the amount of assimilatory apparatus (LAI).

Keywords: absorbed photosynthetically active radiation, aboveground biomass increment, allometric relation

INTRODUCTION

Study of forest stand functioning on various spatial and temporal scales is essential to explore the forest role as carbon sink because forest stands play an important role in transforming and storing atmospheric CO_2 in the living and dead biomass (Law *et al.*, 2001; Smithwick *et al.*, 2002; DeLucia *et al.*, 2005; Hardiman *et al.*, 2013; Park, 2015; Bottalico *et al.*, 2016, etc.). A new forest stand biomass is produced in photosynthetic process that is dependent on the amount of available light and atmospheric CO_2 concentration and other microclimatic factors like temperature, vapour pressure deficit, precipitation etc.

Mainly the amount of light was found to be most closely related to new forest stand biomass production (Linder, 1985; Monteith, 1994; Binkley *et al.*, 2013). Production of the forest stand biomass is affected not only by the light availability but also by the efficiency of light absorption with the assimilatory apparatus of the forest stand (Landsberg and Waring, 1997; Bartelink *et al.*, 1997; Marková *et al.*, 2011b; Binkley *et al.*, 2013; Forrester and Albrecht, 2014). The term light (or radiation) use efficiency – LUE (RUE, ε) was introduced (Goyne *et al.*, 1993) to quantify the forest stand ability to absorb light and to convert this energy into biomass:

$$\varepsilon = \Delta TBa / PARa \quad (1)$$

where:

ε – light use efficiency (g DW MJ^{-1} PARa)

ΔTBa – increment of total dry stand above-ground biomass (g DW m^{-2})

PARa – sum of light (photosynthetically active radiation) absorbed by the stand (MJ m^{-2} of ground surface)

DW – dry weight of aboveground biomass

The light use efficiency is strongly dependent on the ability of the forest stand to absorb light incident on the forest stand canopy and on the efficiency of assimilates conversion into biomass. Final amount of light absorbed by the given forest stand results from the amount of incident light, effectiveness of leaf area absorbed light, or the length of the growing season. Light use efficiency respond to different environmental factors related to energy balance, water availability and nutrient levels as well (Landsberg and Waring, 1997; Schwalm *et al.*, 2006; Linderson *et al.*, 2007; Goerner *et al.*, 2009;

Pangle *et al.*, 2009; Moreno *et al.*, 2012; Forrester and Albrecht, 2014).

A lot of empirical studies have supported the values of LUE for the forest stands (for example Jenkins *et al.*, 2007; Nakaji *et al.*, 2008; Soudani *et al.*, 2014; Nelson *et al.*, 2016; Serichol-Escobar *et al.*, 2016) but more work is needed to examine the variation of LUE over time and among the different tree species (Wang *et al.*, 2010). Direct estimation of LUE is an important benefit to LUE-based models which use values from remote sensing to estimate forest stand productivity (Goetz and Prince, 1996; Ahl *et al.*, 2004; Smith *et al.*, 2008; Huang *et al.*, 2010; Hilker *et al.*, 2010; Wu *et al.*, 2012; Yuan *et al.*, 2014; Masek *et al.*, 2015). The LUE-based models are built on two fundamental assumptions: (1) that the forest stand net primary production is directly related to the absorbed light through LUE, in which LUE is defined as the amount of carbon assimilated per unit of absorbed light, and (2) that the realized LUE may be reduced below its theoretical potential value by environmental stresses (Cannell, 1989; Wang *et al.*, 1991; McMurtrie *et al.*, 1994; Yuan *et al.*, 2007; Fang *et al.*, 2012; Alton, 2013).

The objective of the presented paper is to assess light use efficiency and relationship between absorbed light and aboveground biomass production in the mountain and highland cultivated Norway spruce stands.

MATERIALS AND METHODS

Light use efficiency in production of spruce stands biomass was performed at the study sites of Rájec (the Drahanská vrchovina Highland) and Bílý Kříž (the Moravian-Silesian Beskids Mountains) in 2014 and 2015 (Tab. I and II).

I: *Description of the study sites*

Study site	RÁJEC	BÍLÝ KŘÍŽ
Geographic coordinates	49°02’ N, 17°58’E	49°30’ N, 18°32’ E
Altitude (above sea level)	610–625 m	865–890 m
Geological subsoil	acid granodiorit	flysch layer with dominant sandstones
Soil type	cambisol modal oligotrophic	modal podzol and modal kryptozol
Mean annual air temperature (period 1998 – 2014) ± standard deviation	7.1 ± 1.2 °C	6.9 ± 1.0 °C
Mean annual sum of precipitation (period 1998 – 2014) ± standard deviation	673 ± 144 mm	1265 ± 216 mm

II: *Description of the studied spruce stands*

Study site	RÁJEC		BÍLÝ KŘÍŽ	
Stand	spruce monoculture		spruce monoculture	
Species	*Picea abies* [L.] Karst.		*Picea abies* [L.] Karst.	
Altitudinal vegetation zone	5th		5th	
	2014	**2015**	**2014**	**2015**
Stand age (years)	36		33	
Stand density (trees ha^{-1})	1808	1808	1256	1252
Mean stand height (m) ± standard deviation	14.3 ± 3.8	15.0 ± 3.9	15.9 ± 1.9	16.4 ± 2.0
Mean stand diameter at the breast height (cm) ± standard deviation	14.8 ± 6.1	15.0 ± 6.2	19.2 ± 3.7	19.5 ± 3.9
Maximum leaf area index (m^2 m^{-2})	6.28	6.34	6.59	6.29
Duration of the growing season	19.4.–21.10.	26.4.–12.10.	24.4.–21.10.	28.4.–9.10.

Determination of light absorbed by the stand canopy

Photosynthetically active radiation absorbed by the stand canopy (PARa) was calculated after equation:

$$PARa = PARi - PARr - PARt \quad (2)$$

where:
PARi – photosynthetically active radiation incident on the stand canopy
PARr – photosynthetically radiation reflected by the stand canopy
PARt – photosynthetically active radiation transmitted below the stand canopy.

Photosynthetically active radiation incident on the stand canopy (PARi) was measured with the Quantum Sensor LI-190S (LI-COR, USA) at the study site of Bílý Kříž and with the Quantum Sensor EMS 12 (EMS Brno, Czech Republic) at the study site of Rájec. Sensors are regularly calibrated against a standard sensor. Sensors are placed four meters above the stand canopy on a steel meteorological tower. Photosynthetically active radiation reflected by the stand canopy (PARr) was measured with 5 Quantum Sensors EMS 12 (EMS Brno, Czech Republic) placed in the distance of 10 cm on the special linear holder system. The linear holder system was oriented in the opposite direction and was placed one meter above the stand canopy on a steel meteorological mast. Photosynthetically active radiation transmitted below the stand canopy was measured with 25 Quantum Sensors EMS 12 (EMS Brno, Czech Republic) placed on the steel holders approximately 1 meter above the ground level. The record of incident, reflected and transmitted PAR values was carried out at 30-seconds intervals, and 10-minute average values of these records were automatically stored by a data-logger.

Determination of the total aboveground biomass increment of the spruce stand

The total aboveground biomass and the total aboveground biomass increment were obtained on the basis of spruce stand inventory realised in the end of each growing season. The procedure of the stand inventory consisted of measurements of the stem circumference at the breast height (1.3 m above the ground) of each individual tree located in the studied stands. Stem circumference was measured using a metal meter (accuracy: 0.1 cm) and the final value of stem diameter at the breast height (DBH) was calculated from the measured value of stem circumference. The total aboveground biomass (TBa) was obtained on the basis of local site-specific allometric relation with DBH (Tab. III):

The total aboveground biomass increment (DTBa) formed during investigated growing season was estimated as difference of TBa values of the current and the previous year.

Determination of light use efficiency in production of the spruce stand aboveground biomass

Values of light use efficiency (ε) were calculated for each studied spruce stand for each growing season after equation (1).

Determination of other microclimatic parameters at the study sites

During the studied growing seasons of 2014 and 2015 other microclimatic parameters characterized the study sites were measured – incident global radiation (Net Radiometer CNR1; Kipp-Zonen, the Netherland), air temperature (temperature sensor EMS 33; EMS Brno, Czech Republic), sum of precipitation (Precipitation Gauge 386C; MetOne Instruments, Inc, USA). Radiometer was placed 1 meter above the stand canopy and temperature sensor and precipitation gauge were placed at the top of the stand canopy on the meteorological mast. The record of above-mentioned values was carried out at 30-seconds intervals, and 10-minute average values of these records were automatically stored by a data-logger.

Determination of leaf area index of the spruce stand

Leaf area index (LAI) was evaluated by light transmittance method (Perry *et al.*, 1988, Chen *et al.*, 2006) using LaiPen LP 100 (Photon System Instruments, Czech Republic) during the growing seasons in 2014 and 2015. Measurements were provided on marked transect every three weeks.

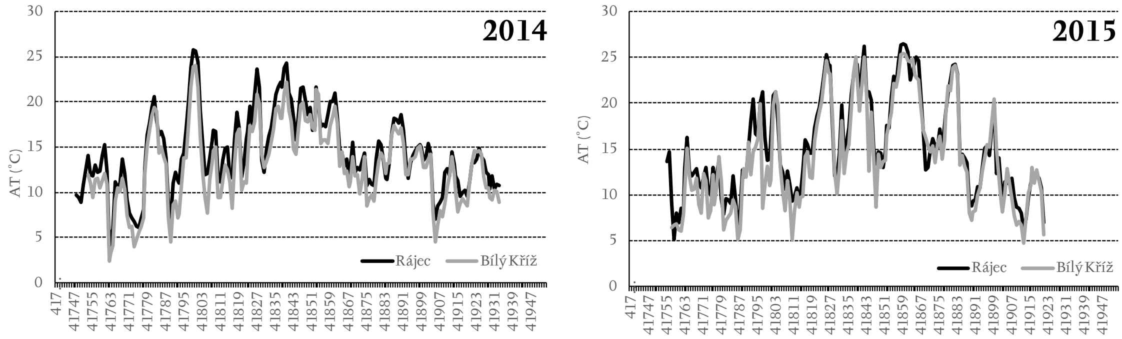
RESULTS AND DISCUSSION

The growing season length was in both investigated years 2014 and 2015 higher at the study site of Rájec – Tab. II. The growing season started later at the study site of Bílý Kříž compared with the study site of Rájec and the end of the growing season was the same at the both study sites both in 2014 and 2015.

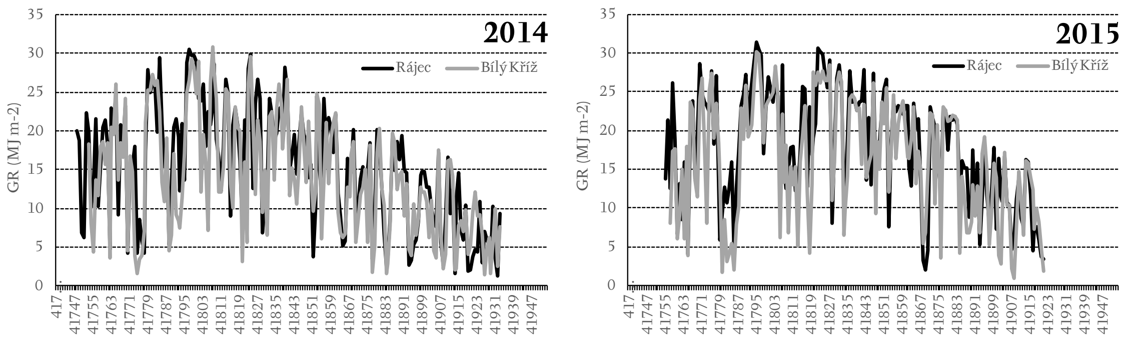
The growing season length is controlled by the air temperature. Used definition of the growing season length is five consecutive days with mean daily air temperature above 5 °C for the beginning of the growing season and below 5 °C for the end

III: *Allometric relations used for a calculation of the spruce stand total aboveground biomass*

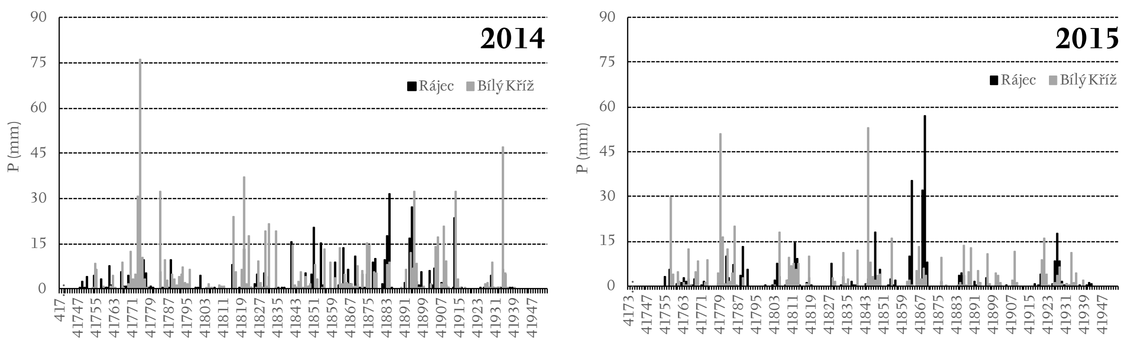
Study site	Allometric relation	Author
BÍLÝ KŘÍŽ	$TBa = 0.1301\ DBH^{2.2586}$ ($r^2 = 0.98$)	Pokorný and Tomášková (2007)
RÁJEC	$TBa = 0.2002\ DBH^{2.2718}$ ($r^2 = 0.98$)	Marková and Pokorný (2011a)



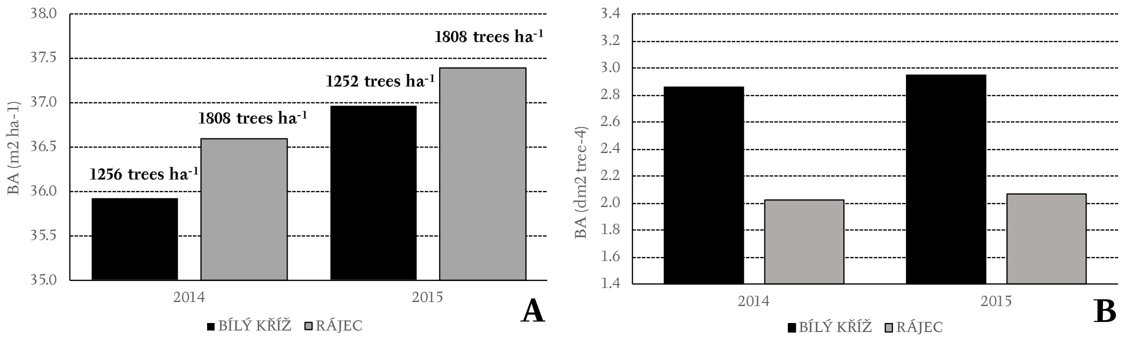
1: *Mean daily air temperature (AT) at the study sites of Rájec and Bílý Kříž during the growing seasons in 2014 and 2015*



2: *Daily sum of incident global radiation (GR) at the study sites of Rájec and Bílý Kříž during the growing seasons in 2014 and 2015*



3: *Daily sum of precipitation (P) at the study sites of Rájec and Bílý Kříž during the growing seasons in 2014 and 2015*



4: *Total stem basal area per hectare (A) and average stem basal area per tree (B) at the study sites of Rájec and Bílý Kříž in 2014 and 2015*

IV: *Sums of photosynthetically active radiation absorbed by the spruce stand (Σ PARa) and the total above ground biomass increment (Δ TBa) of the spruce stand at the study sites of Rájec and Bílý Kříž in 2014 and 2015*

	Σ PARa (MJ m^{-2} $season^{-1}$)		DTBa (g DW m^{-2})	
	2014	2015	2014	2015
Bílý Kříž	1032.5	1089.6	5.29	4.88
Rájec	1190.4	1009.3	6.49	6.52

of the growing season (Chen *et al.*, 2000; Groot and Saucie, 2008; Wu *et al.*, 2012). Mean growing season air temperature was 15.3 ± 7.55 °C in 2014 and 17.7 ± 7.33 °C in 2015 at the study site of Rájec and 13.9 ± 7.57 °C in 2014 and 16.2 ± 7.53 °C in 2015 at the study site of Bílý Kříž (Fig. 1). Therefore, the air temperature at the mountain study site was almost about 9 % lower compared with highland study site. Mean growing season air temperature was higher about 14 % in 2015 compared with 2015 both at the study sites of Rájec and Bílý Kříž.

One factor influencing production of the forest stand biomass is the light availability. The growing season length can affect the amount of light incident at the given study site (Kimball *et al.*, 2004; Hall *et al.*, 2012) – Fig. 2. The growing season sums of incident global radiation was 2851 MJ m^{-2} in 2014 and 2948 MJ m^{-2} in 2015 at the study site of Rájec and 2521 MJ m^{-2} in 2014 and 2654 MJ m^{-2} in 2015 at the study site of Bílý Kříž. The growing season sums of incident global radiation was higher in 2015 at both study sites even when the growing season length was shorter. This was due to higher input of global radiance in 2015. Clearness index expressing atmospheric transmittance for solar radiation was 0.41 ± 0.25 in 2014 and 0.46 ± 0.24 in 2015 at the study site of Rájec and 0.37 ± 0.24 in 2014 and 0.41 ± 0.25 in 2015 at the study site of Bílý Kříž.

Production of new forest stand biomass responds to water availability. The growing season sums of precipitation was 462 mm in 2014 and 374 mm in 2015 at the study site of Rájec and 833 mm in 2014 and 555 mm in 2015 at the study site of Bílý Kříž (Fig. 3). The growing season sums of precipitation was lower in 2015 at both study sites. For the new tree biomass production is important not only the precipitation sum but also the precipitation distribution during the growing season. Mainly the precipitation sum at the beginning of bud burst and during the current shoots development is important (Schleip *et al.*, 2008; Pokorný *et al.*, 2010; Bednářová and Merklová, 2011). The beginning of Norway spruce bud burst is in the Central Europe on average around 125 day (May 5th) and the current shoots are usually fully developed on average between 196 and 214 day (July 15th–August 15th) depending on climatic conditions. Sum and distribution of precipitation were worse at both study sites in 2015 compared with 2014.

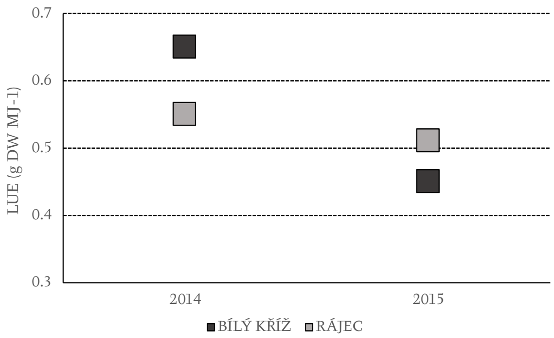
Total stem basal area was different at both studied spruce stand due to the different stand density (Fig. 4A). Thus average stem basal area per tree was calculated in order to compare the stands (Fig. 4B). Average stem basal area per tree of mountain spruce stand at the study site of Bílý Kříž was more than 30 % higher compared with the highland spruce stand at the study site of Rájec both in 2014 and 2015. It corresponds to the site conditions in which the spruce stands are growth. Naturally spruce stands occur on sites with mean annual air temperature below 6 °C and mean annual sum of precipitation above 800 mm (Souček and Tesař, 2008). The site conditions at the study site of Bílý Kříž are much better for the spruce stand growth.

LUE values are often used for modelling of forest stands net (or gross) primary production (Bartelink *et al.*, 1997; Landsberg and Waring, 1997; Ahl *et al.*, 2004; Wirth *et al.*, 2004; Smith *et al.*, 2008; Hilker *et al.*, 2012). The used models are often not accurate and therefore it is necessary to obtain data for their validation.

Light use efficiency was calculated for young spruce stands at the study sites of Bílý Kříž and Rájec using data obtained for the growing seasons in 2014 and 2015 (Tab. IV).

LUE in production of spruce stand biomass was higher at the study site of Rájec in 2014 compared with 2015 even when LAI was higher in 2015 (Fig. 5). This could be caused especially due the different growth and climatic conditions in 2014 and 2015. In 2015 there were shorter growing season and mainly higher air temperature a much lower sum of precipitation. Thus water stress could affect the new biomass production (Goetz and Prince, 1996; Schwalm *et al.*, 2006; Welp *et al.*, 2007). LUE in production of spruce stand biomass was higher at the study site of Bílý Kříž in 2014 compared with 2015 (Fig. 5). This could be caused by the different growth and climatic conditions in 2014 and 2015 (the same as at the study site of Rájec), by reducing of the stand density (reducing of LAI) in 2015. LUE decreased about 7 % at the study site of Rájec and about 31 % at the study site of Bílý Kříž in 2015 compared with 2014.

A large variation of LUE among spruce stands was reported, i.e. 0.2–1.4 g DW MJ-1 (Goetz and Prince, 1996; Nichol *et al.*, 2000; Marková *et al.*, 2011b; Wu *et al.*; 2012; Gspaltl *et al.*, 2013; Forrester and Albrecht, 2014; Nelson *et al.*, 2016). The LUE value obtained for the investigated spruce stands are in the range of published reports. The variations in published LUE values are given by many factors influencing the spruce stands growth – geographic and orographic position, site condition, forest management (thinning), etc.



5: *Light use efficiency (LUE) determined for the spruce stands at the study sites of Rájec and Bílý Kříž in 2014 and 2015*

CONCLUSION

Light use efficiency in production of young spruce stands biomass was performed at the study sites Rájec (the Drahanská vrchovina Highland) and Bílý Kříž (the Moravian-Silesian Beskids Mountains) in 2014 and 2015. The LUE value obtained for the investigated spruce stands were in the range of 0.45–0.65 g DW MJ^{-1}. The LUE value was higher for mountain spruce stands in 2014 and for highland spruce stand in 2015. Decrease of LUE value for mountain spruce stand was caused by decrease of stand density and thus LAI value in 2015. The differences of LUE amounted to 15 % in 2014 and 12 % in 2015. The LUE values were lower at both investigated spruce stands in 2015 compared with 2014. This was caused by different growth and climatic conditions at investigated years.

Because LUE values are often used for modelling of forest stands biomass production more work is needed to understand the factors that affect LUE and to determine if LUE varies over longer time scales.

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