Mendel University in Brno
Faculty of Forestry and Wood Technology

SEASONAL GROWTH DYNAMIC OF NORWAY SPRUCE AT THE STUDY SITE OF RÁJEC

(Drahanská vrchovina Highland)

Diploma thesis

2015/2016 Bc. Georges Herbert Chekuimo Tagne

Mendel University in Brno
Faculty of Forestry and Wood Technology
Institute of Forest Ecology

SEASONAL GROWTH DYNAMIC OF NORWAY SPRUCE AT THE STUDY SITE OF RÁJEC

(Drahanská vrchovina Highland)

Diploma thesis

2015/2016 Bc. Georges Herbert Chekuimo Tagne

ČESTNÉ PROHLÁŠENÍ

Prohlašuji, že jsem diplomovou práci na téma: ***"Seasonal growth dynamic of Norway spruce at the study site of Rájec (Drahanská vrchovina Highland)"*** *zpracoval sám a uvedl jsem všechny použité prameny.*

Souhlasím, aby moje diplomová práce byla zveřejněna v souladu s § 47b Zákona č. 111/1998 Sb., o vysokých školách a uložena v knihovně Mendelovy zemědělské a lesnické univerzity v Brně, zpřístupněna ke studijním účelům ve shodě s Vyhláškou rektora MZLU o archivaci elektronické podoby závěrečných prací.

Autor kvalifikační práce se dále zavazuje, že před sepsáním licenční smlouvy o využití autorských práv díla s jinou osobou (subjektem) si vyžádá písemné stanovisko univerzity o tom, že předmětná licenční smlouva není v rozporu s oprávněnými zájmy univerzity a zavazuje se uhradit případný příspěvek na úhradu nákladů spojených se vznikem díla dle řádné kalkulace.

STATUTORY DECLARATION

(In accordance with the Mendel University Chancellor's Decree No.5/2013)

I hereby declare that I compiled the Master's thesis on the topic of ***"Seasonal growth dynamic of Norway spruce at the study site of Rájec (Drahanská vrchovina Highland)"*** *by myself and have stated all sources used. I agree to my thesis being published in accordance with §47(b) of the Act No. 111/1998 Coll. on Higher Education Institutions including amendments to some other acts and in compliance with Mendel University Chancellor's decree on publishing final theses.*

I am fully aware that my thesis is subject to Act no. 121/2000 Coll., The Copyrights Act and that the Mendel University in Brno has the right to enter into licence agreements for use of this work as school work in accordance with §60 section 1 of the Copyrights Act.

I hereby agree to obtain a written statement from the University that any license agreement with a third party on the use of copyright does not contravene the rightful interests of the University prior to executing any such agreement, and agrees to disburse any compensation for costs incurred in association with the thesis compilation in compliance with the due calculation.

V Brně dne: ……………………………… ***Podpis studenta:***

ACKNOWLEDGEMENTS

This study was funded by the PROJECT CARIBU[*] to which I am very grateful, and this research was performed within the Institute of Forest Ecology (Faculty of Forestry and Wood Technology – FFWT) at Mendel University in Brno, Czech Republic.

- I am thankful to doc. RNDr. **Irena Marková**, CSc., for her tremendous supervision.
- In addition, I am greatly indebted to Ing. **Jan Světlík**, for his valuable support, comments and fruitful discussions.

This report has benefitted from substantial input from many people for their skilful technical assistance, and for their advice and guidance. I would like to thank:

- All the **lecturers, academic staff** and **fellow students** of the C-EUFO European Forestry Programme (2014 - 2016);
- **Friends** and **relatives**.

I dedicate this masterpiece to all my **family** to whom I simply express my entire gratitude.

Any use of trade, product or firm names is for descriptive purposes only.

---

[*] An Erasmus Mundus Action 2 (EMA2) partnership program that aims at increasing academic mobility, research and capacity building opportunities between some EU universities and some countries from the ACP region. The project is devoted to creating a mutual forum for scientific cooperation, learning enhancement and exchange of best practices (http://www.caribu.be/the-project/about-project-caribu/)

ABSTRACT

Name of the student: **Georges Herbert Chekuimo Tagne**

Title of the Diploma thesis: **Seasonal growth dynamic of Norway spruce at the study site of Rájec (Drahanská vrchovina Highland)**

Evaluation of the circumference increment of Norway spruce focused on the effect of inter-tree competition in the mature spruce stand was made at the study site of Rájec (Drahanská vrchovina Highland) over a 5-year period. Data were collected from 49 trees, which were monitored continuously with mechanical band dendrometers from 2010 to 2014. The dependency of the circumference increment on competition index, diameter at breast height, Lang's rain factor, mean temperature of various periods and sum of precipitation of various periods was evaluated. Climatic conditions of the study site are characterised with warm and wet summers and cold-dry winters. In 5 years average around 61 % of the annual precipitation falls during growing season. There was highly significant correlation between relative increment and temperature ($p=2.324e^{-13}$) and significant correlation between relative increment and precipitation ($p=0.0439$). The performed results confirmed that inter-tree competition and diameter at breast height are sufficient variables for circumference increment estimation of unmeasured trees in the particular year. Coefficient of determination reached 0.25 – 0.63 for competition and 0.40 – 0.84 for tree diameter at breast height. The present investigation brings important results about tree growth and seasonal growth dynamics and its relation with competition and microclimatic conditions in mature spruce stand. It is obvious that unsuitable climatic conditions for spruce can lead to stem shrinkage during growing season. Here we assume that these responses are caused mostly by water storage deficit in stem and this leads to decreasing of the tree vitality. Such phenomenon will have significantly negative ecological and economic consequences in expected climatic changes in the future.

Key words: growth, seasonality, manual band dendrometers, *Picea abies*, stem girth increment, competition.

ABSTRAKT

Jméno:	**Georges Herbert Chekuimo Tagne**
Téma diplomové práce:	**Sezónní dynamika růstu smrku ztepilého na výzkumné ploše Rájec (Drahanská vrchovina)**

Byl zhodnocen efekt kompetice okolních stromů a mikroklimatických faktorů na dynamiku obvodových změn kmene smrku ztepilého v dospělém porostu na výzkumné ploše Rájec (Drahanská vrchovina) v období 2010 až 2014. Výsledky vychází z kontinuálního měření obvodových změn kmenů 49 vzorníkových stromů pomocí mechanických přírůstoměrů. Byla postupně posuzována závislost obvodové změny kmene na kompetičním indexu, tloušťce kmene, Langově dešťovém faktoru, teplotě a srážkách. Klima sledované lokality je v létě teplé a vlhké a v zimě studené a suché. Ve sledovaném pětiletém období připadlo průměrně 61 % ročního srážkového úhrnu na růstové období. Byla prokázána vysoce významná závislost přírůstu na teplotě vzduchu ($p=2,324e^{-13}$) a pouze v jednom případě byla zjištěna významná závislost přírůstu na srážkách ($p=0,0439$). Z naměřených dat je zřejmé, že kompetice a tloušťka stromů mohou být vhodné parametry pro odhad přírůstu ostatních (neměřených) stromů v porostu v daném roce. Koeficient determinace se v jednotlivých letech pohyboval od 0,25 do 0,63 pro kompetici a 0,40 až 0,84 pro výčetní tloušťku kmene. Předkládaná práce poskytuje důležité informace o růstu a sezónní dynamice obvodových změn stromů v dospělém smrkovém porostu z pohledu kompetice, a základních mikroklimatických faktorů porostu. Je zřejmé, že nepříznivé klimatické podmínky mohou způsobovat smrštění kmene v průběhu růstové sezóny v důsledku vodního deficitu a snižovat tak vitalitu stromů. Toto může mít s předpokládanými klimatickými změnami v budoucnu významné ekologické a ekonomické dopady.

Klíčová slova: růst, sezónnost, manuální páskový přírůstoměr, *Picea abies,* obvodový přírůst kmene, kompetice.

TABLE OF CONTENTS

List of figures

List of tables

List of photos

List of symbols and abbreviations

%:	Percentage
°C:	degree Celsius
a.s.l.:	above sea level
CI:	competition index
cm:	centimeter
CZ:	Czech Republic
DBH:	diameter at breast height
E:	East
EMS:	Environmental Measuring Systems
FFWT:	Faculty of Forestry and Wood Technology
ha:	hectare
LRF:	Lang’s rain factor
m:	meter
m^3:	cubic meter
MENDELU:	Mendel University in Brno
mm:	millimeter
Mts:	Mounts
N:	North
P:	precipitation
SE:	South-East
T:	temperature

1. INTRODUCTION

Norway spruce (*Picea abies* (L.) Karst.) is one of the most important European tree species and also a tree species with the highest number of various health and growth problems which have appeared in the last decades (Rybníček *et al.*, 2010). It is amongst the trees most strongly affected by forest dieback in Central Europe, which is generally attributed to industrial and automobile pollution (Eckenwalder, 2009).

The seasonal periodicity of biological processes in a woody plant is determined by regular environmental fluctuations associated with the annual cycle (Vaganov *et al.*, 2006). The growth of a woody plant represents an increase in the weight and volume of the whole plant or its parts as the result of the formation of new cells and the increase in their size (Reimers, 1991). The radial increment of trees is a dynamic process, and the rate of accumulation of new woody material varies considerably during the year (Henttonen *et al.*, 2009).

2. MAIN OBJECTIVE OF THE RESEARCH

In this study, the investigation of seasonal growth dynamic of mature Norway spruce stand (*Picea abies* (L.) Karst.) at the study site of Rájec (the Drahanská vrchovina Highland, the Czech Republic) monitored with manual band dendrometers was done. The objective was to assess the progress of the radial stem increment focused on the effect of diameter, climatic parameters (mean air temperature, monthly sum of precipitation and Lang's rain factor) and inter-tree competition during the 2010 – 2014.

Additionally, identify significant climatic events leading to growing variances. Furthermore, establish minimal number of competing trees substituted to calculation of competition index sufficient for radial stem increment estimation.

3. LITERATURE REVIEW

Norway spruce (*Picea abies* (L.) Karst.) is one of the most important European tree species and also a tree species with the highest number of various health and growth problems which have appeared in the last decades (Rybníček *et al.*, 2010). It is amongst the trees most strongly affected by forest dieback in central Europe, which is generally attributed to industrial and automobile pollution (Eckenwalder, 2009).

The seasonal periodicity of biological processes in a woody plant is determined by regular environmental fluctuations associated with the annual cycle (Vaganov *et al.*, 2006). The growth of a woody plant represents an increase in the weight and volume of the whole plant or its parts as the result of the formation of new cells and the increase in their size (Reimers, 1991). Enlargement of tracheids is considered to represent the major driving force for radial stem growth (Deslauriers *et al.*, 2003). Stem growth can be defined as an increase in the number and size of xylem cells through the activity of meristematic tissues (Mäkinen, 2014). The radial increment of trees is a dynamic process, and the rate of accumulation of new woody material varies considerably during the year (Henttonen *et al.*, 2009).

Tree growth depends on both intrinsic and environmental variables: individual phenotype and genotype, age, plant-plant interactions (size, competition and facilitation), site and micro-site conditions (such as light, temperature, humidity, nutrients, geological bedrock, atmospheric precipitation, water, CO_2 concentration, air and soil moisture availability), biotic (insect attacks, mammals damages, fungi, etc.), abiotic (fires, windstorms, avalanches, landslides, etc.) and humans disturbances (silviculture, pollution, global change, etc.) (Schweingruber, 1996; Wang *et al.*, 2014). The radial growth rate also depends on the available resources. The growth of a tree is a function of resource acquisition, the efficiency of using resources to generate photosynthates to various functions in the trees (Binkley *et al.*, 2004).

Moreover, anthropogenic, abiotic and biotic factors (light, temperature, nutrient supply, mechanical damage of the crown, air pollution, fungi, animals, etc.) can influence the radial increment of a stem at any time, in any manner and intensity (Fritts, 1976;

Schweingruber, 1996; Barnes *et al.,* 1998). For these reasons, the effect of climatic parameters such as air temperature, precipitation, and derived vapour pressure deficit on the seasonal variations of the increments should also be taken into account. Even if these variables are often studied separately, they are interconnected (Kozlowski *et al.,* 1991). Climatic variation is a major driving force behind growth variation and changes of climate are known to have caused synchronous shifts in tree growth throughout Europe (Mäkinen *et al.,* 2002). The individual climate-growth relationships can be influenced by competitive processes. Moreover, plant-plant interactions can be altered by environmental (climatic) conditions. Relationships between climate and wood anatomy or ring development have been studied at intra-annual time scales in various tree species including Norway spruce (*Picea abies* (L.) Karst.) (Horacek *et al.,* 1999; Mäkinen *et al.,* 2003).

The seasonal growth dynamics were also observed in response to biotic factors, such as competition (Linares *et al.,* 2009), tree size and social status (Rathgeber *et al.,* 2011) or tree vigour (Gricar *et al.,* 2009). Competition has long been known as a primary process governing population and individual development. Competitive interactions arise when surrounding plants share limited resources, leading to a reduction in survivorship and/or growth rate (Begon *et al.,* 1996). Competition for resources among trees is one well-studied source of variation rates in individual tree growth; it also influences their subsequent stand structure, and density-dependent mortality rates (Ford, 1975; Fraver *et al.,* 2014).

Burton (1993) stated that plant competition index (CI) characterizes the degree to which the growing space of an individual plant is shared by other plants. Individual based competition indices are used to predict the performance of focal individuals as a function of interference from a localized subset of other plants. It has been frequently expressed by allometric relationship between the growth of individual trees and different formulations of competition indices. Moreover, this variation strongly influences forest stand development and tree mortality, and it leads to diversity in tree sizes and tree spatial patterns (Franklin *et al.,* 2002). Tree growth rate varies considerably during a growing season, and growth rates vary markedly from tree to tree (Coomes and Allen, 2007). A group of trees growing together under similar conditions (soils, slopes, and species composition) and managed in the same way is called a stand.

Forests are comprised of stands, which may be defined in many ways on the basis of species composition, age, or location (Karen, 2010).

Historically, plant competition indices were developed to predict the growth of individual trees in monospecific stands (Brown, 1965; Bella, 1971; Daniels, 1976; Hegyi, 1974; Lorimer, 1983; Becker, 1992). Individual based competition indices have been used to evaluate the effect of intraspecific competition (McDonald *et al.*, 1990). A large number of surrounding competition indices are available for assessing the intensity or importance of inter-tree competition (Tomé and Burkhart ,1989; Biging and Dobbertin, 1992; Stadt *et al.,* 2007). Inter-tree competition here is meant to express competition effects between above-ground parts as well as those between roots of individual trees (Bella, 1971).

The basic density of Norway spruce (*Picea abies* (L.) Karst.) has been studied by numerous scientists in the present century and even earlier. The common model postulates that the density in a stem increases from mid-stem towards the top and stump. In the radial direction the density is high near the pith. After a decline it usually increases slowly towards the surface. The variation between stems is explained by the age, since the basic density of the stem increases with age. Another factor is the growth rate, which has a negative correlation with basic density. Thus the trees grown on fertile sites have a lower density than those from poorer sites. Similarly, planted spruces with good growing vigour have a lower density than trees from dense natural forests. However, few reports have been published on the role of the competition between trees within a stand and the effect of growth rate between stands. Yet it is important to distinguish the intra-stand and inter-stand variation between trees. It is possible that the effect of growth rate is different within a stand and between stands (Kärkkäinen, 1984).

According to Wang *et al.* (2014), altitude is considered as an important factor affecting tree growth in forest ecosystems. Altitude has a strong impact on local climate, but lapse rates differ between regions. It has already been stated in dendroclimatology that, in general, variations in tree-ring width at low altitudes are strongly positively correlated with precipitation and negatively correlated with temperature, while at high altitudes the correlation with temperature is likely to reverse as temperature becomes directly correlated with growth (Fritts *et al.,* 1965; Fritts, 1976). Based on this altitude-dependent hypothesis, numerous dendroclimatological studies have indicated that climate/growth relationships may vary with altitude, following the variations in temperature and precipitation (Peterson and Peterson, 2001; Mäkinen *et al.,* 2002; Takahashi *et al.,* 2005). Contrary to this general hypothesis, several studies have observed similar growth variation patterns along altitudinal gradients and have identified common limiting environmental factors that might synchronize tree growth at different elevations or latitudes (Morales *et al.,* 2004; Esper *et al.,* 2007).

Lang's rain factor (LRF) is one of the oldest and most frequently used parameters for classifying areas according to the availability of moisture. Its popularity is mainly due to its simplicity, since the LRF is merely the ration of the mean annual total precipitation to mean annual air temperature. By using the relation of air temperature to precipitation, one can compensate for the missing value of potential evapotranspiration, which partially correlate with the temperature (Tolasz *et al.,* 2007). Recognizing temperature as the major factor for evaporation, Lang (1920) had suggested one simple method. He used a coefficient of humidity which is defined as the ratio of precipitation or rainfall of a year to the sum of mean temperatures of the frost-free months divided by twelve (Paltasingh *et al.*, 2012). The Lang's rain factor, f = P/T, indicates that the effectiveness varies directly with precipitation or average annual rainfall sum (P) in mm and inversely with average annual air temperature (T) in °C (Thornthwaite, 1948). On the basis of this quotient commonly referred to as the P/T ratio, Lang classified the following humidity provinces and pointed out that types of natural vegetation classified as desert, semi desert, steppe, savanna, bush and deciduous forest, and rain forest (Table 1) (Lang, 1920; Lalita, 1992).

Table 1: Climatic and types of natural vegetation classification according to Lang's rain factor

Lang's rain factor *(P/T ratio)*	**Humidity provinces**		**Types of natural vegetation**
0-5	Hyper-arid	Arid	Desert
5-40	Semi-arid		Semi desert
40-160	Humid		Steppe
60-100			Savanna
100-160			Bush and deciduous forest
160 and above	Wet		Rain forest

Source: Lalita, 1992; Verheye, http://www.eolss.net/sample-chapters/c12/E1-05-06.pdf.

Since the radial growth of trees depends highly on site and weather conditions with inherent variability over the growing seasons, one must record growth dynamics in short intervals. Using band or point dendrometers helps to meet these conditions by recording the stem radius at defined time intervals during the growing season. Dendrometers were used by a variety of authors to quantify the seasonal progress of wood formation (Tardif *et al.,* 2001; Zweifel *et al.,* 2005; King *et al.,* 2013). According to Mäkinen *et al.* (2003), automatic point or mechanical (manual) band dendrometers have traditionally been used for measuring the intra-annual radial increment of trees with great precision. They have been used for continuous monitoring of stem radial variation throughout the year and determination of seasonal tree growth (Fritts, 1961; Herzog *et al.,* 1995; Carrer *et al.,* 1998; Tardif *et al.,* 2001; Bouriaud *et al.,* 2005).

But recently electronic dendrometers that are able to record the radial growth of trees in very short intervals (hours or minutes) have been released (Mäkinen *et al.,* 2003; Mäkinen *et al.,* 2008). Dendrometers record the intra-annual stem growth including cell division and enlargement of phloem and xylem (irreversible stem reaction) and reversible diurnal stem shrinkage and expansion caused by hydration shifts (Zabuga and Zabuga, 1991). However, it has proved difficult to distinguish between the changes caused by xylem formation and those related to swelling and shrinking of the stem (Zweifel and Häsler, 2000; Mäkinen *et al.,* 2003; Daudet *et al.,* 2005), and onset of wood formation (in spring) is masked by re-hydration of the stem (Kozlowski and Winget, 1964; Downes *et al.,* 1999; Zweifel and Häsler, 2001; Mäkinen *et al.,* 2003).

Due to this, dendrometers have been criticized when short-term growth is studied, when the reversible variations are higher than wood growth, inevitably introducing errors in the measured data (Zweifel and Häsler, 2001). Mäkinen *et al.*, (2003) found that stem increment recorded by dendrometers can be linked to climate, stem diameter increments in this highland tree species might be masked by changes in tree water status, especially in small trees. Because of the large and frequent changes in stem circumference associated with fluctuations in stem water potential, it is difficult to use dendrometer measurements to determine the rate of actual xylem formation (girth or circumference increment due to formation of new cells). On the other hand, it is laborious to monitor the rate of cell formation during a growing season.

4. MATERIAL AND METHODS

The samples for the study were obtained at the study site of Rájec (Figure 1), about 30 km to the north of Brno (geographic coordinates N49°26’37”; E16°41’48”). The study site is located in the natural forest area 30 Drahanská vrchovina Highland, forest vegetation zone 5 (fir-beech), representing about 2.7 % of the Czech Republic area. This study site was established for long-term detailed experiments for various scientific issues. The bedrock consists of intrusive rock acid granodiorite of Brno Massive (Hruška, 1980). The soil type was determined as unsaturated acidic brown forest soil (Klimo, 1992), and it is modal oligotrophic Cambisol (Němeček *et al.,* 2001). The site is situated at an altitude ranging between 620-630 m a.s.l. (Klimo, 1992) and in a moderate climatic region (Quitt, 1971). Mean annual air temperature at the study site is 7.1 ^{o}C and mean annual sum of precipitation 673 mm (Marková *et al.,* 2015).

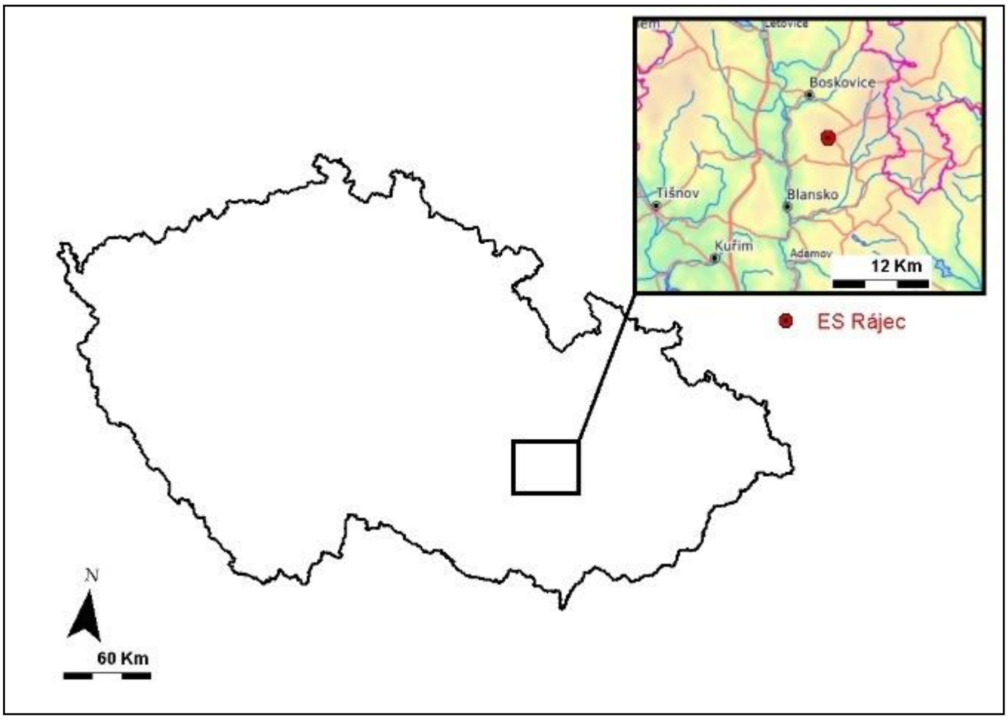


Figure 1: Location of the study site of Rájec (the Drahanská vrchovina Highland)

The potential natural vegetation type (i.e., the hypothetical plant society without anthropogeneous disturbances) or forest-type group at the Rájec site has been described as *Querci-fagetum abietinum* or *Querci-fageta abietis* (Vašíček, 1984; Čermák and Kučera, 1987) and the phytocoenosis of the research plot has been classified as belonging in the sub-group of forest types *Luzulo-Fagion* (Lohmeyer and Tüxen in Tüxen, 1954).

Based on forest management plan, the existing spruce stand growing at the study site is approximately hundred years old Norway spruce monoculture of the 1st generation and of an unknown provenance (Grabařová and Martínková, 2002). This actual spruce monoculture ecosystem was planted around 1905 with the following characteristics (1995): density - 830 trees per hectare, mean diameter at 1.3 m (DBH) – 26.6 cm and mean height - 27.7 m. Dendrometric stand characteristics in the 2010 are shown in Table 2.

Table 2: Dendrometric characteristics of the spruce stand at the study site of Rájec (the Drahanská vrchovina Highland) in 2010

Age	Tree species composition (%)	Number of trees per.ha	Mean diameter at the breast height (cm)	Mean height (m)	Mean living crown length (cm)	Stocking
106	SM 100	614	31.9	31.3	10.1	1

Source: Světlík *et al.*, 2016

The studied spruce stand (Photo 1) was selected for analysis because human impact on stand development after planting may be considered insignificant, thus the competition experienced is assumed to reflect natural differentiation. The stand was located towards the centre of a larger complex of similar stands and was thus not exposed to extreme edge effects. Furthermore, the availability of nutrients and water may be considered spatially homogenous within the stand.

Photo 1: Meteorological tower located in the studied spruce stand at the study site of Rájec (Drahanská vrchovina Highland)

4.1. Meteorological measurements

Air temperature and the sum of precipitation were measured near the studied spruce stand on the open area. Air temperature was measured automatically using sensor EMS 33 (EMS Brno, Czech Republic) and sum of precipitation was measured using automatic precipitation gauge (EMS Brno, Czech Republic).

4.2. Dendrometer and circumference measurements

Dendometers are devices for measuring the stem radius of a tree continuously. Before installing the stainless-steel band dendrometers on each tree, the outer bark under the band was lightly brushed to ensure smooth contact with the trunk (and also to reduce the influence of expansion and shrinkage processes of the bark). The principle and installation of mechanical band dendrometers are comprehensively discussed by Keeland and Young (available online: http://www.nwrc.usgs.gov/topics/Dendrometer/).

Periodic measurements of stem diameter or circumference increments (thereinafter increments) were conducted in a spruce stand at the breast height (DBH) – 1.3 meter above the ground using stainless steel mechanical band dendrometers (EMS Brno, Czech Republic – Photo 2) (Bošeľa *et al.,* 2013). The girth or circumference growth of stems was measured continuously in 49 chosen trees (trees without visible stem and crown injuries or anomalies sampled in a next-nearest-neighbour process) during five growing seasons. The changes in trunk girth at breast height were recorded in weekly intervals. Selection of sample trees was conducted with regard to the frequency of girth classes, i.e. the more numerous girth classes contain more trees. The girth increment can be taken by vernier with a tenth of millimetre accuracy (Vichrová *et al.*, 2013).

Photo 2: Mechanical dendrometer (EMS Brno, Czech Republic)
Source: http://www.usbe.cas.cz/lefr/img/biomasa/obr_02.jpg

4.3. Evaluation of the growing season length

One important issue is how to determine the growing season length from dendrometer measurements. Here, we defined the growing season as the period during which size increased, causing stem girth or circumference increments that could be recorded by the mechanical dendrometers. Since stem radius variations are related to changes in both girth or circumference growth and water status (Deslauriers *et al.,* 2003 and 2007; Krepkowski *et al.,* 2011), algorithms that are appropriate to distinguishing both sources of stem radius variability need to be considered. Data from the growing seasons 2010 to 2014 were used to perform our calculation.

4.4.Index designs or competition indices

The intensity of neighbourhood competition on individual tree growth was evaluated using one basic competition index (CI), not modified with various metrics of trees size and neighbour mortality weighting. The CI assumes a circular neighbourhood centred on the focal tree, thereby defining the focal tree's competitive neighbourhood. The circular area provides a tally of all potential competitors, with higher crowding suggesting greater competitive effects (Fraver *et al.,* 2014).

Hegyi's (1974) single tree competition index model is proposed to calculate the competition index. The most widely-used diameter-distance index is a sum of the ratios of diameters of a subject tree and its competitors weighted by the distance from the subject tree (Hamilton, 1969; Hegyi, 1974; Daniels, 1976; Alemdag, 1978; Meldahl, 1979). This CI includes information on tree-tree distance as follows:

$$CI = \sum_{j=1}^{n} \left(\frac{DBH_j / DBH_i}{DIST_{ij}} \right) \times w_n$$

where CI = competition index; DBH_j = diameter at breast height of competitor tree j; DBH_i = diameter at breast height of subject tree i; $DIST_{ij}$ = distance between trees i and j (i.e., distance between neighbour and focal tree); n = total number of competitors. w_n is a weighting factor to account for neighbour mortality *(w_n = 1 for this study as we did not take into account the mortality)*.

4.5.Statistical parameters

Various statistical parameters were calculated to assess the coefficient of correlation. The increment as a dependent variable, and the competition index, diameter at breast height and Lang's rain factor (LRF), monthly temperatures and precipitations as independent variables for the study area were used to calculate the correlations of values of girth or circumference increments with climatic factors. Pearson’s correlation analysis, Regression analysis and Lang’s rain factor were performed to compare competition and stem increment. The seasonal variability was created in STATISTICA 10 application.

a) Pearson product-moment correlation coefficient

In statistics, the *Pearson product-moment correlation coefficient* (sometimes referred to as the PPMCC or PCC or Pearson’s r) is a measure of the linear correlation between two variables X and Y, giving a value between +1 and −1 inclusive, where 1 is total positive correlation, 0 is no correlation, and −1 is total negative correlation. It is widely used in the sciences as a measure of the degree of linear dependence between two variables. Pearson’s correlation coefficient is the covariance of the two variables divided by the product of their standard deviations. The form of the definition involves a “product moment”, that is, the mean (the first moment about the origin) of the product of the mean-adjusted random variables; hence the modifier product-moment in the name (https://en.wikipedia.org/wiki/Pearson_product-moment_correlation_coefficient).

b) Regression analysis

It is a statistical tool for the investigation of relationships between variables. It is a statistical process for estimating the equation of the relationships among variables. It includes many techniques for modelling and analysing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables (or ‘predictors’) (https://en.wikipedia.org/wiki/Regression_analysis).

The climatic time series of average monthly temperatures was built from the research station and the series covers the period from 2009 to 2014. We tested 300 periods of the mean temperatures, and their correlations with increments, with the duration from one month up to January of the previous year to September of the current year. We combined all possible complex periods. We also tested the significance of correlation of increment on DBH, temperature, precipitations and competition at the 0.05 level (statistically significant) and 0.01 level (highly statistically significant).

5. RESULTS AND DISCUSSION

In this research a dendroclimatic investigation on Norway spruce from 2010 to 2014 (2009 was additionally included) was conducted. The number of trees (Figure 2) at the studied stand has decreased between 2010 and 2011 due to an intense cutting, as most trees have felt down because of the silvicultural management and/or severe climatic conditions.

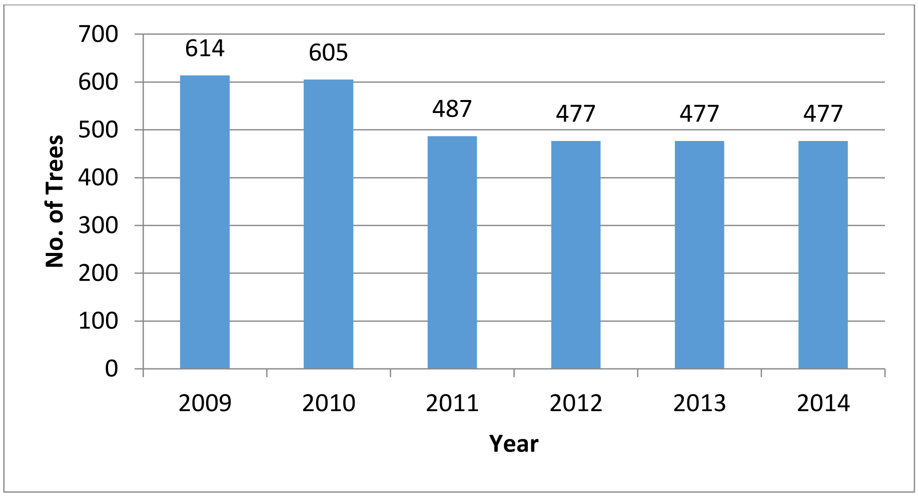


Figure 2: Number of trees per year at the study site of Rájec (Drahanská vrchovina Highland) in 2009 - 2014

Figure 3 illustrates the mean monthly temperature (°C) and monthly sum of precipitation between 2009 and 2014. Owing to limited climate observational data in the study site, the climate data used in our dendroclimatic analyses were based on the existing climate data station. The climate of the study site is characterized by warm-wet summers and cold-dry winters. From 2009 to 2014, the annual sum of precipitation accounted for around 61 %; while June seems to have more precipitations throughout the studied period, the most important decrease in monthly sums of precipitation was noted on July 2013 which was a very dry period as shown in the Figure 3.

- ☞ In 2009, half of the year experienced monthly sums of precipitation below 40 mm, even if June and August were the wettest month of the year, with respectively 120 mm and 100 mm of precipitation. September to December averaged around 40 mm of monthly sums of precipitation. February and April averaged 25 mm of precipitation. Mean monthly temperatures on the other side were below 0 °C in

January, February and December. They increased slightly to reach a peak between July and August (18 °C) before the drop.

☞ The wettest period in 2010 was between May and September, with June 2010 the very wetter (165 mm); there was less of precipitation in October (30 mm of precipitation). Mean monthly temperatures followed almost the same pattern like monthly precipitations to reach the highest in July. January, February, November and December experienced mean monthly temperatures below 0 °C.

☞ Only January and February experienced mean monthly temperatures below 0 °C in 2011. August was the warmest month (19 °C). The wettest months were July (130 mm of precipitation) and August (100 mm of precipitation). The year faced lower monthly precipitations, with eight months below 40 mm of precipitation.

☞ The first three months and the last month in 2012 had mean monthly temperatures below 0 °C; the peak was in August (19 °C). January (90 mm of precipitation) and June (100 mm of precipitation) were the wettest months of the year, with monthly precipitations of the rest of the year below 80 mm.

☞ 2013 was a particular year as July was almost dry with few rains (5 mm of precipitation) and higher mean monthly temperature (19.5 °C). June was very wet (170 mm of precipitation); overall eight months were above 40 mm of precipitation. The first three months experienced coldest mean monthly temperatures below 0°C.

☞ August and September 2014 were the wettest months of the year, with monthly precipitations between 110-130 mm. Half of the year received less than 40 mm of precipitation of monthly sum of precipitations. The peak of temperature was observed in July and there was almost no negative temperature.

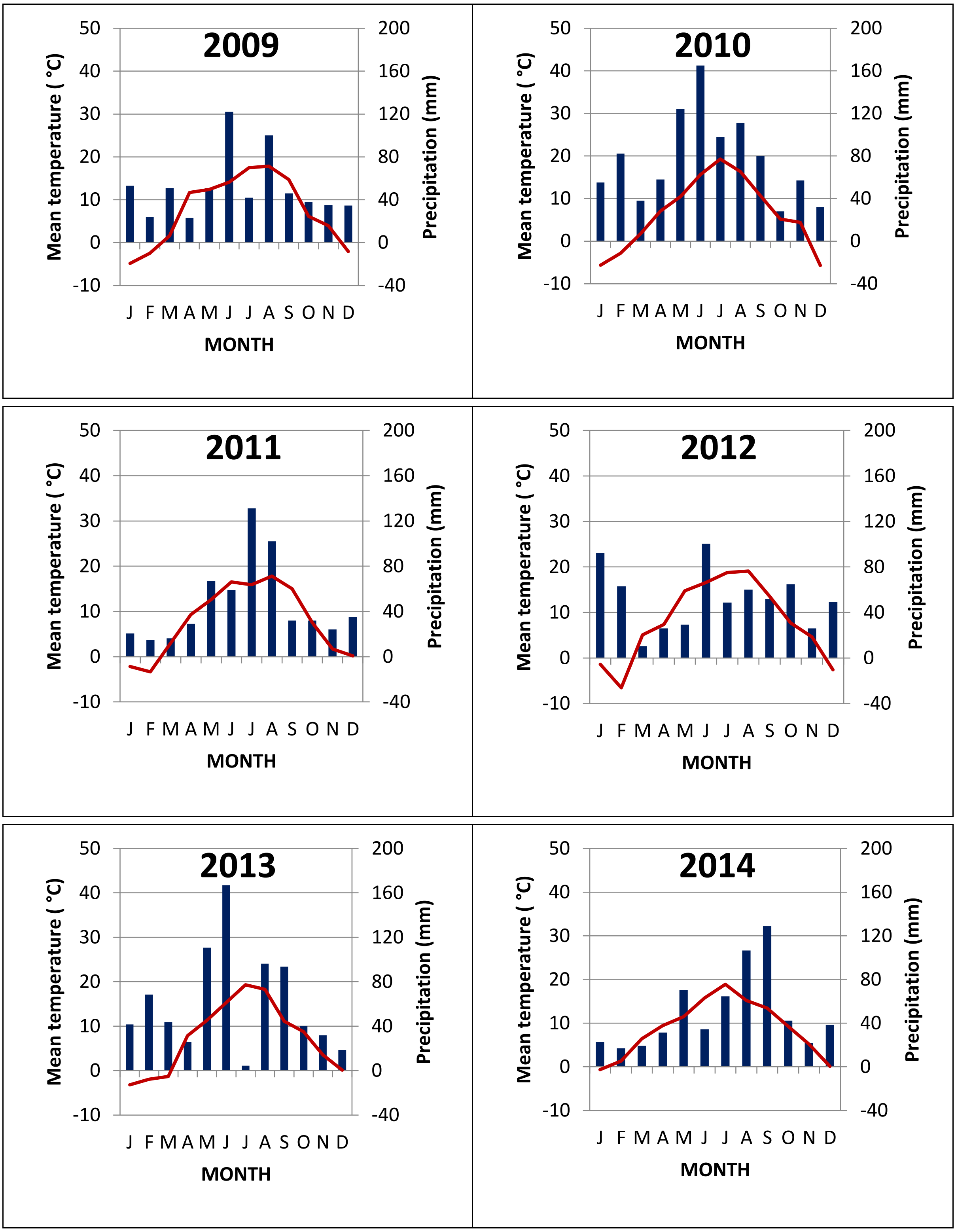


Figure 3: Climadiagrams for mean monthly air temperatures (red line) and monthly sums of precipitations (blue column) at the study site of Rájec (Drahanská vrchovina Highland) in the 2009–2014

The relative increment of the girth of the portion of stem in individual years (5-year increment is 100 %) is shown on Figure 4. To see the effect of climatic conditions on stem girth increment there are shown only trees with recorded stem increment in whole 5 years' period. Figure 5 describes the relative increment of the stem girth in the studied years 2010 – 2014; the confidence interval was very wide (for comparison year of 2011 with the highest value of confidence interval and year of 2013 with the lowest confidence interval). The year 2012 showed the second highest confidence interval. Trees increment in 2013 had significantly lower than in 2012 and 2014.

At each of the development stages, climatic factors manifest different degrees of impact.

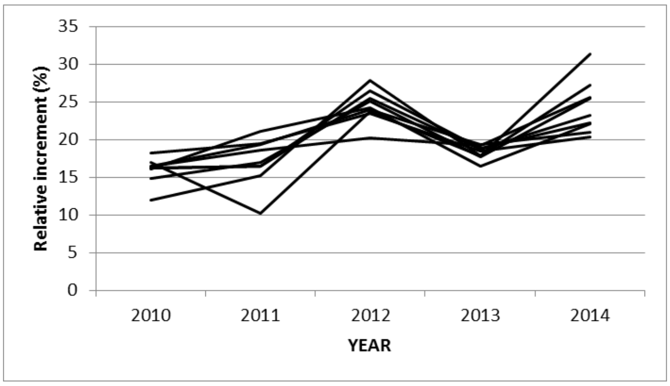


Figure 4: The relative stem increment in spruce stand at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014

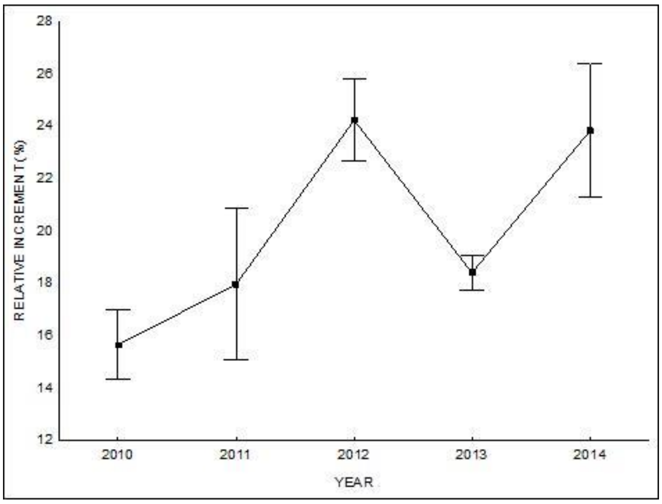


Figure 5: The mean relative stem increment in spruce stand at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014 (I - confidence interval)

The relative increment for any given year often integrates the effects of the previous and current's year's climate. There were tested 300 periods and combined all possible complex periods of the mean monthly air temperatures, and their correlations with stem increments, with the duration from one month up to January of the previous year to September of the current year, among which 25 best correlations of the girth or circumference increment with mean monthly air temperatures had positive highly statistical significant values. For all years, the green part on the Tables 3 and 4 represents the 25 best periods to estimate tree increments in current year; it is the indication of the best period to estimate tree growth. The period with the highest correlation of increment and mean monthly air temperature was from September of the previous year till September of the current year, i.e. the period of 13 months.

These best correlations of the girth increment with mean monthly air temperatures (Figure 6) had positive highly statistical significant values. It is the period that should have the highest influence on the girth or circumference increments in that particular year. Correlation was very high with air temperature (all the results have 2 stars, as shown in Table 3), and we can say that it is a good estimator in our case (***$p=2.324e^{-13}$***).

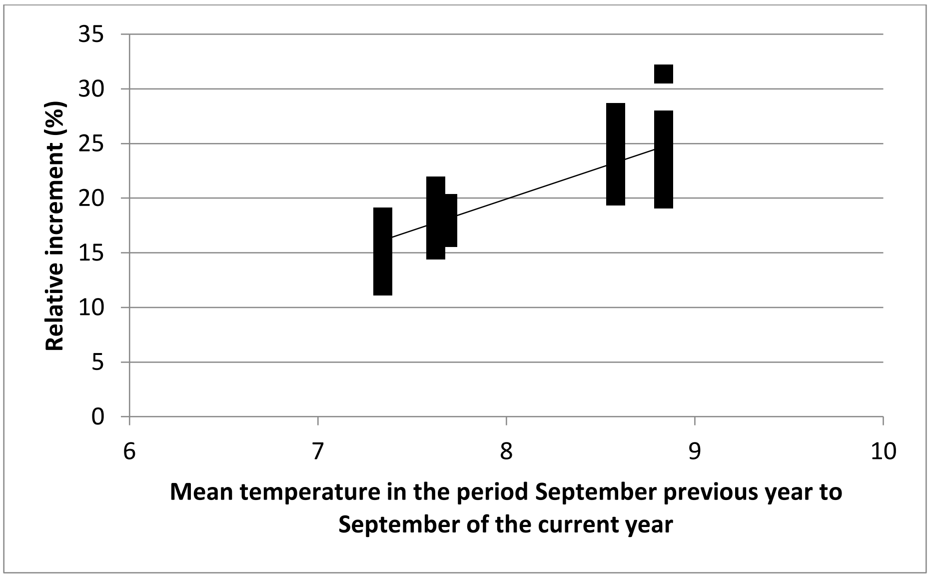


Figure 6: Effect of air temperature on relative stem increment of the spruce stand at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014

From 2009 to 2014, the annual sum of precipitation total accounted for around 61 %; while June seems to have more precipitations in the studied period. The relative stem increment increased from 2010 to 2014; however, it was too dry in July 2013 as shown in Figure 3 and this could have affected the stem increment (Figure 5). The stem increment in Norway spruce was not significantly correlated with precipitation sums of any period (Table 4), except May of previous year (Figure 7). It might be due to short evaluation period (only 5 years). Presumably, shorter rainy periods would explain more variability of stem increment.

The growth of Norway spruce was statistically significantly affected only by precipitation in May of the previous year. In our case, the correlation was not good enough with precipitation to estimate the stem increment, as we had one result between significant and non-significant (***p=0.0439***). The second best correlation of the girth or circumference increment with precipitation is from July to September, either of the previous year was not statistically significant. The growth of Norway spruce was less statistically significantly affected by precipitation in September of the previous year and the precipitation in September of the current year.

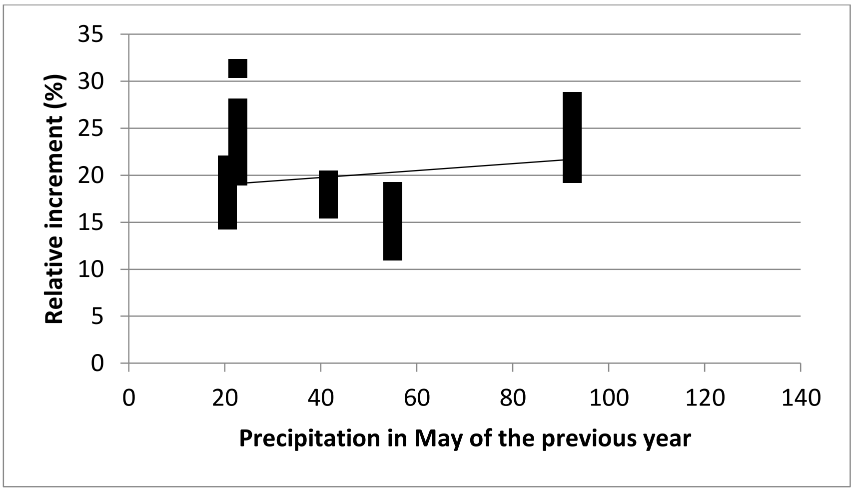
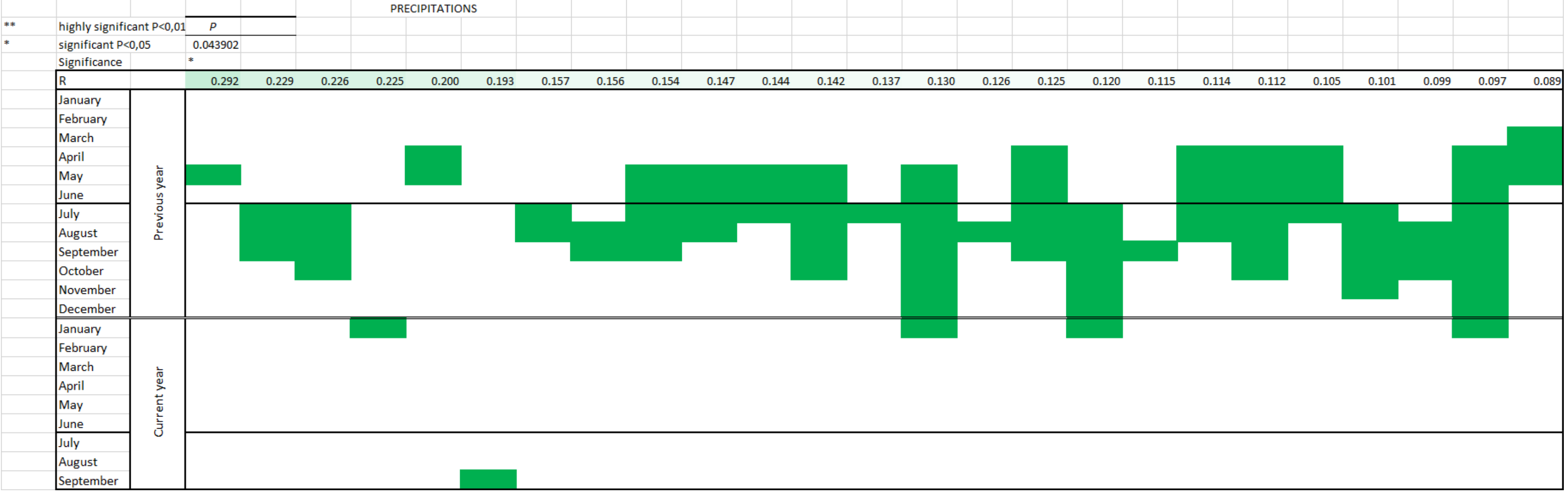


Figure 7: Effect of precipitations on relative stem increment of the spruce stand at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014

Table 3: Effect of air temperature on relative increment of the spruce trees at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014

**	highly significant P<0,01					TEMPERATURE																					
*	significant P<0,05		P	[redacted]																							ýznamnost
			2.324E-13																								3.255E-10
	Significance		**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	R		0.832	0.825	0.822	0.819	0.810	0.808	0.807	0.800	0.798	0.796	0.795	0.794	0.792	0.790	0.787	0.787	0.786	0.785	0.778	0.775	0.775	0.769	0.766	0.765	0.762
	January	Previous year																									
	February												🟩														
	March												🟩														
	April												🟩				🟩										
	May												🟩			🟩	🟩										
	June						🟩						🟩			🟩	🟩					🟩					
	July						🟩				🟩		🟩			🟩	🟩					🟩					
	August			🟩			🟩				🟩		🟩			🟩	🟩		🟩			🟩		🟩			
	September		🟩	🟩			🟩		🟩		🟩		🟩			🟩	🟩		🟩		🟩	🟩		🟩			🟩
	October		🟩	🟩			🟩		🟩	🟩	🟩		🟩		🟩	🟩	🟩		🟩		🟩	🟩		🟩			🟩
	November		🟩	🟩			🟩		🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩		🟩	🟩		🟩		🟩	🟩
	December		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩		🟩	🟩		🟩	🟩	🟩	🟩
	January	Current year	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩
	February		🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩
	March		🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩
	April		🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩
	May		🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩
	June		🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	July		🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩		🟩		
	August		🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩				
	September		🟩	🟩			🟩	🟩		🟩	🟩		🟩			🟩	🟩	🟩									

Table 4: Effect of precipitation amount on relative increment of the spruce trees at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014



						PRECIPITATIONS																					
**	highly significant P<0,01		P																								
*	significant P<0,05		0.043902																								
	Significance		*																								
	R		0.292	0.229	0.226	0.225	0.200	0.193	0.157	0.156	0.154	0.147	0.144	0.142	0.137	0.130	0.126	0.125	0.120	0.115	0.114	0.112	0.105	0.101	0.099	0.097	0.089
	January	Previous year																									
	February																										
	March																										🟩
	April						🟩											🟩			🟩	🟩	🟩			🟩	🟩
	May		🟩				🟩				🟩	🟩	🟩	🟩		🟩		🟩			🟩	🟩	🟩			🟩	🟩
	June										🟩	🟩	🟩	🟩		🟩		🟩			🟩	🟩	🟩			🟩	
	July			🟩	🟩				🟩		🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩		🟩	🟩	🟩	🟩		🟩	
	August			🟩	🟩				🟩	🟩	🟩	🟩		🟩		🟩	🟩	🟩	🟩		🟩	🟩		🟩	🟩	🟩	
	September			🟩	🟩					🟩	🟩			🟩		🟩		🟩	🟩	🟩		🟩		🟩	🟩	🟩	
	October				🟩									🟩		🟩			🟩			🟩		🟩	🟩	🟩	
	November															🟩			🟩					🟩		🟩	
	December															🟩			🟩							🟩	
	January	Current year				🟩										🟩			🟩							🟩	
	February																										
	March																										
	April																										
	May																										
	June																										
	July																										
	August																										
	September								🟩																		

***p<0.01 (highly significant)*

**p<0.05 (significant)*

Lang’s rain factor (ratio of the annual sum of precipitation and mean annual air temperature) of the growing seasons ranked between 70–140 in the 2010 – 2014 (Figure 8). According to Tolasz *et al.* (2007) the Lang’s rain factor is above 60 for the Czech Republic (humid climate).

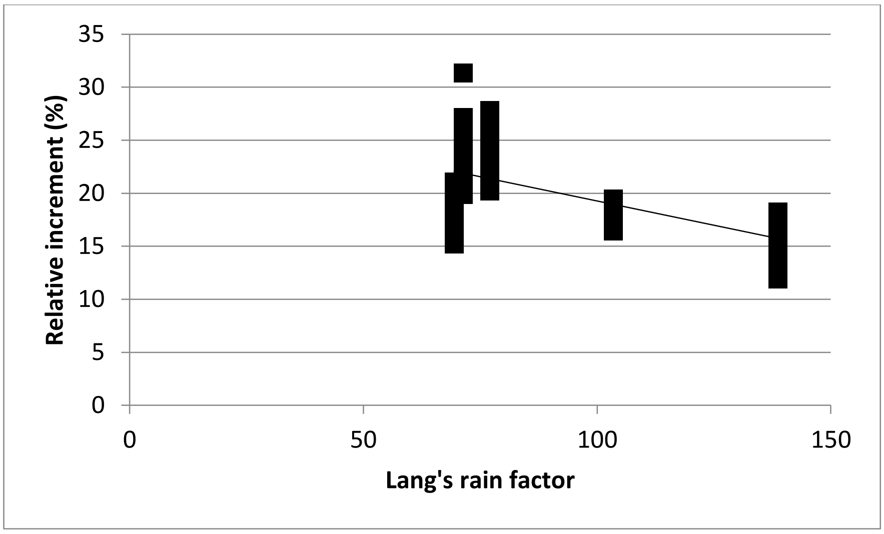


Figure 8: Correlation of the relative stem increment of the spruce stand on Lang’s rain factor at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014

Figure 9 illustrates the correlation between the number of competitors and the circumference increment of the focal tree. We can see that between 4 and 10 competitors, there is no great increase of correlation and the result is not even better.

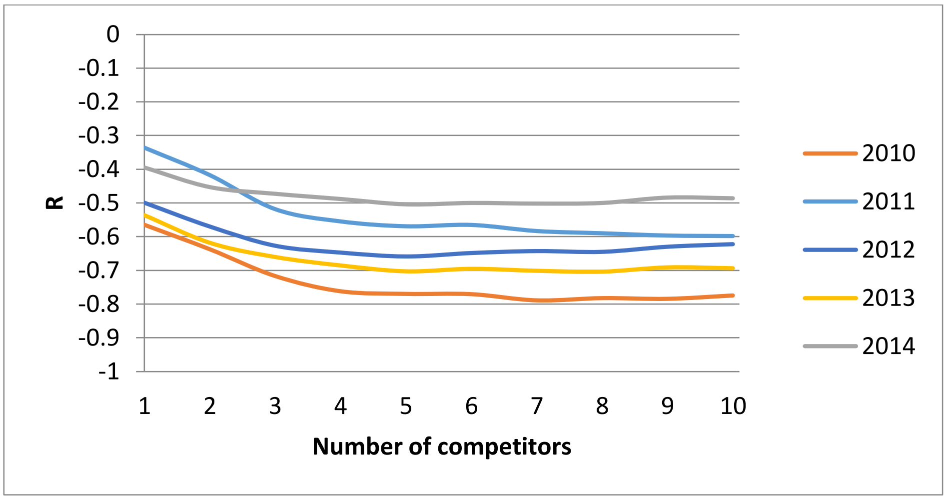


Figure 9: Correlation between competition index and tree growth in the spruce stand at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014

Figures 10 and 11 shows how the competition index has an effect on tree growth. In 2010, some values of circumferential increment were negative. The conditions of the growth in July 2013 year were not very good with climatic conditions from our viewpoint. With more data clumped in 2014, conditions of the tree growth were very good with climatic conditions. In 2010 some values of circumferential increment were negative and could be simply explained by the fact that we can expect the shrinkage of trees (physiological processes as small trees have negative values). Horáček (1994) concluded lack of water has a significant effect on the final girth or circumference dimension of tracheids in spruce. Girth or circumference expansion is dependent on the accumulation of vacuoles into one central vacuole, and this process is influenced by an active water intake (Kozlowski, 1971; Kozlowski *et al.*, 1991).

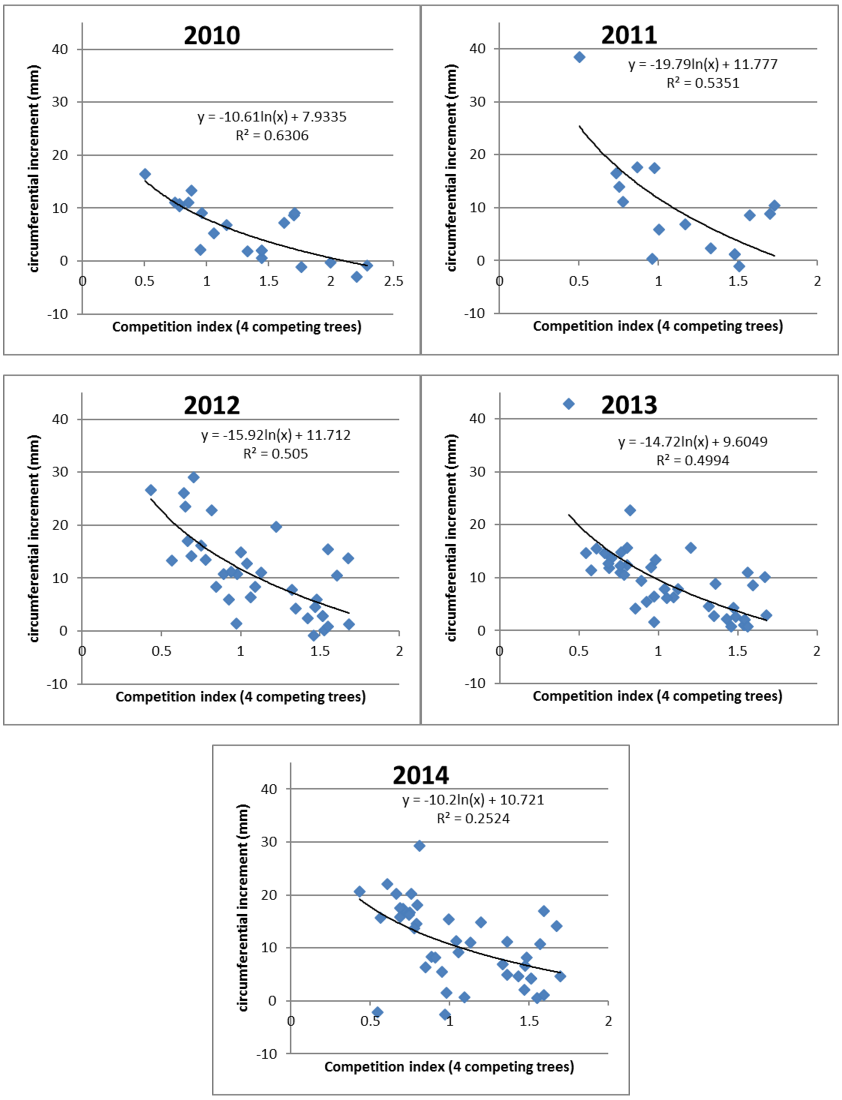


Figure 10: Correlation between competition index and circumferential increment in the spruce stand at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014

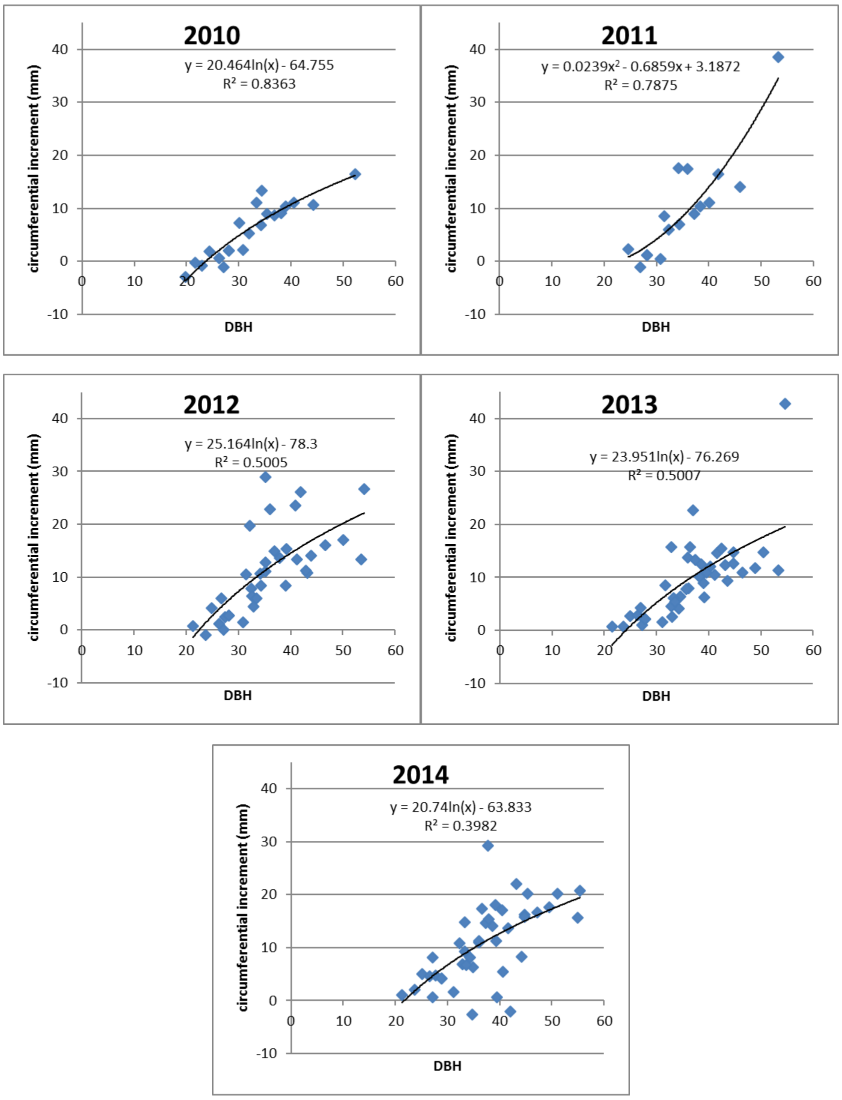


Figure 11: Correlation between DBH and circumferential increment in the spruce stand at the study site of Rájec (Drahanská vrchovina Highland) in 2010 – 2014

Correlation (Figure 10):

- *2010: $y = -10.61\ln(x) + 7.9335$, $R^2 = 0.6306$*
- *2011: $y = -19.79\ln(x) + 11.777$, $R^2 = 0.5351$*
- *2012: $y = -15.92\ln(x) + 11.712$, $R^2 = 0.505$*
- *2013: $y = -14.72\ln(x) + 9.6049$, $R^2 = 0.4994$*
- *2014: $y = -10.2\ln(x) + 10.721$, $R^2 = 0.2524$*

Difference between the correlation between competition index (4 competing trees) and circumferential increment for the study period: $R^2 = 0.6306$ [2010] - 0.2524 [2014]

Correlation (Figure 11):

- *2010:* $y = 20.464\ln(x) - 64.755$, $R^2 = 0.8363$
- *2011:* $y = 0.0239x^2 - 0.6859x + 3.1872$, $R^2 = 0.7875$
- *2012:* $y = 25.164\ln(x) - 78.3$, $R^2 = 0.5005$
- *2013:* $y = 23.951\ln(x) - 76.269$, $R^2 = 0.5007$
- *2014:* $y = 20.74\ln(x) - 63.833$, $R^2 = 0.3982$

Difference between the correlation between DBH and circumferential increment for the study period: $R^2 = 0.8363$ [2010] – 0.3982 [2014]

The best correlation was in 2010; the differences of R^2 (coefficient of determination) between years are not great enough, and overall $R^2 = [0 - 1]$. The number of trees in the study site has decreased between 2010 and 2011 (Figure 2).

We can expect trees that are suppressed to have lower growth; opened and/or larger trees to have better growth. Competition index and DBH are good parameters for tree growth prediction in our case.

The circumference increment since the beginning of the growing season was more intensive up to 14 mm (Figure 12). With increasing diameter at the breast height (DBH) there was a high variability of circumference increment during the growing season. Large trees after one year have the greatest stem increment. There was almost no increment for small trees throughout the year. For small competition index (for 4 competing trees), there was higher variability of circumference increment during the season. However, competition index between 1.45-1.78 also showed variability of circumference increment during the season.

In 2011, we have almost the similar approach since the beginning of the growing season as in 2010, but with a circumference increment of more than 20 mm, as shown in Figure 13. With increasing DBH, there was a high variability of circumference increment during the season (almost no variability found for DBH 20-34mm). Competition index between 1.1-1.75 did not exhibit variability of circumference increment during the growing season.

There was almost no variability of circumference increment for small trees (DBH = 20-32cm) throughout the year, even if we can notice some changes for medium to large trees there is a high variability in circumference increment for medium trees (Figure 14). In 2012, there is a high variability for very small competition index. Here, the circumference increment since the beginning of the growing season is more intensive up to 25 mm. Competition index between 1.3-1.6 showed no variability of circumference increment during the growing season.

There was variability for circumference increment between two measurements and increment started around the 150th day of the year (Figure 15). There was almost no variability of circumference increment for small trees (DBH 22-35cm), as well as high competition index (1.3-1.7) throughout the year. The circumference increment since the beginning of the growing season was more intensive up to 22 mm. Large trees (DBH 35-55 cm) exhibited high variability of circumference increment throughout the year, as well as small competition index (0.4-0.8) and 1.2 during the growing season.

On the Figure 16, we can say that with increasing DBH (36-55cm), there was a high variability of circumference increment during the growing season. Once more, large trees after one year have the largest increment. There is no variability of circumference increment in DBH for small trees (DBH 20-35 cm) throughout the year, while there is a high variability in small competition index for during the year. For small competition index (for 4 competing trees), there was higher variability of circumference increment during the season. However, competition index between 0.45-0.78 also showed high variability of circumference increment during the season (almost no variability observed for competition index between 0.8-1.7). The circumference increment since the start of the growing season is more intensive up to 25 mm.

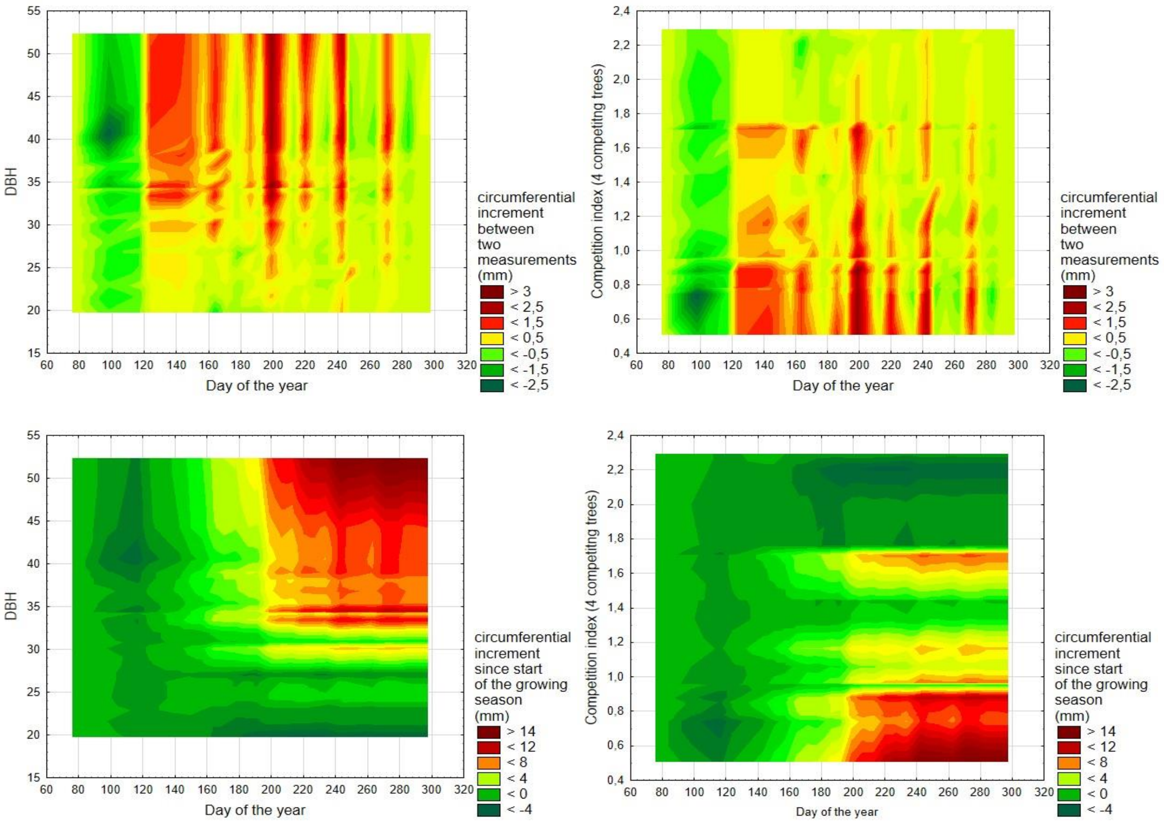


Figure 12: Dependence of circumference increment on diameter at the breast height (DBH) and Competition Index according to the number of Day of the year in 2010

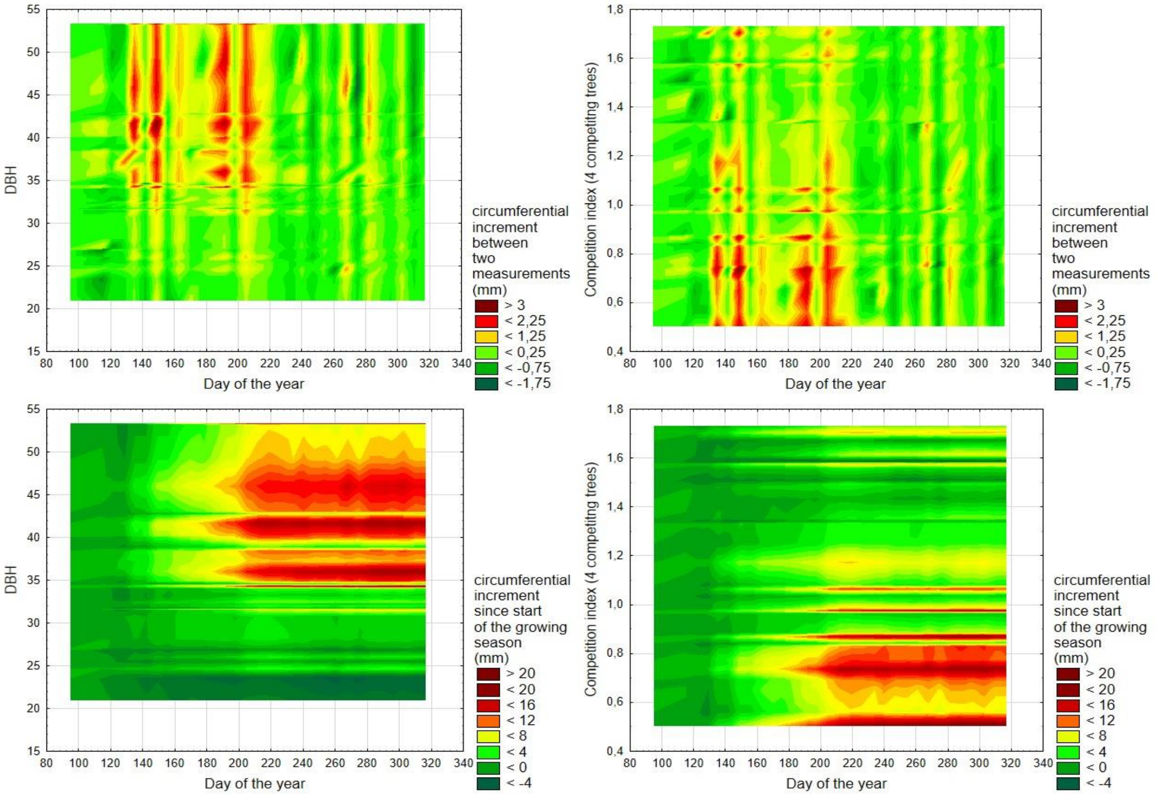


Figure 13: Dependence of circumference increment on diameter at the breast height (DBH) and Competition Index according to the number of Day of the year in 2011

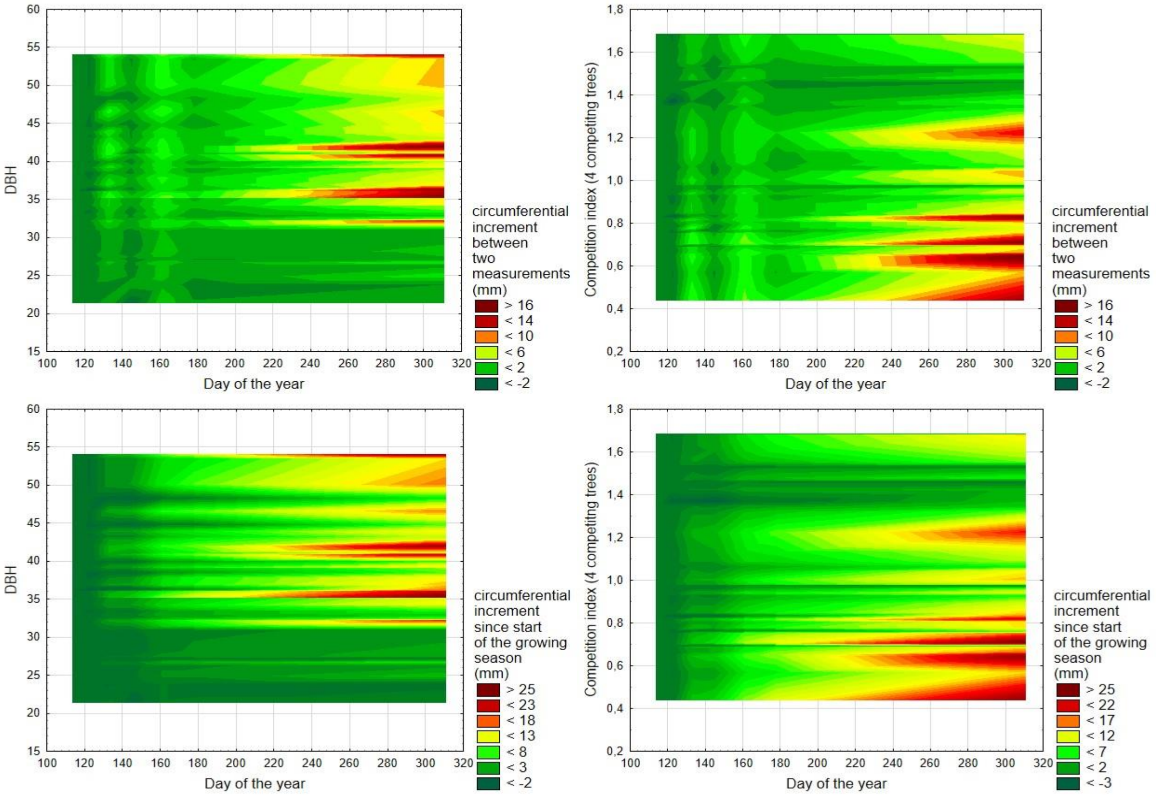


Figure 14: Dependence of circumference increment on diameter at the breast height (DBH) and Competition Index according to the number of Day of the year in 2012

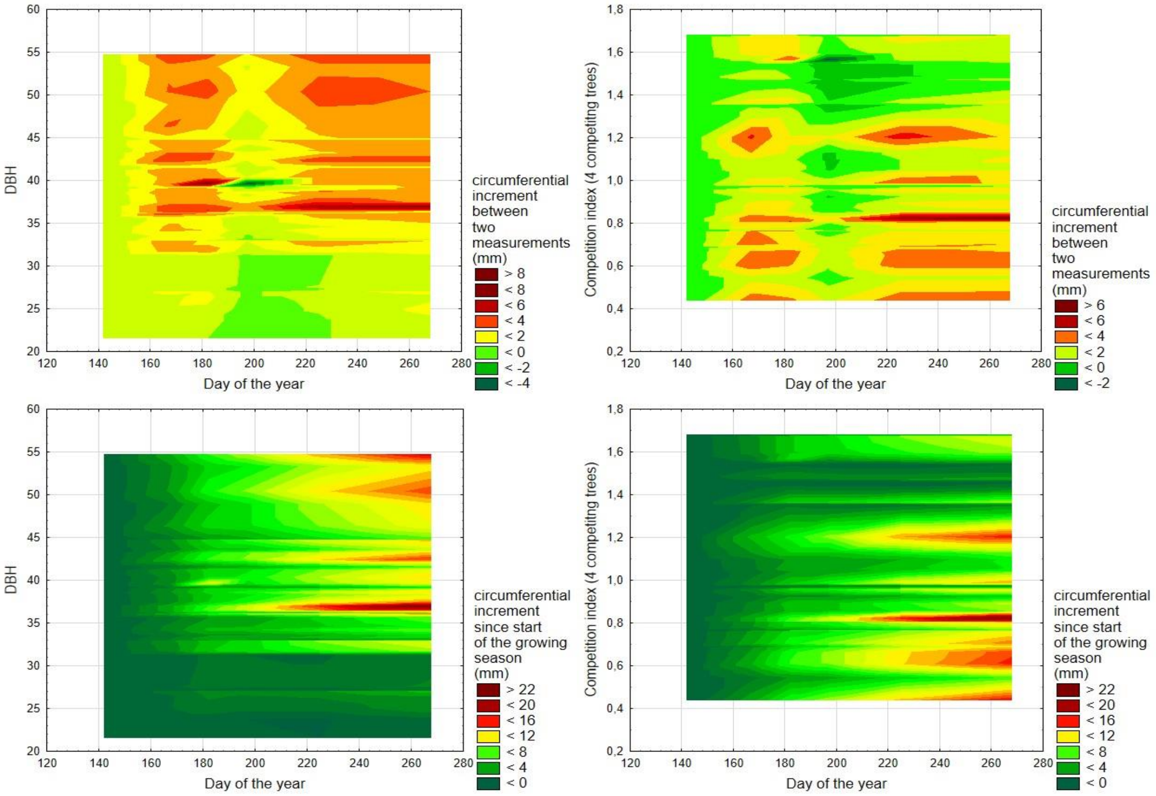


Figure 15: Dependence of circumference increment on diameter at the breast height (DBH) and Competition Index according to the number of Day of the year in 2013

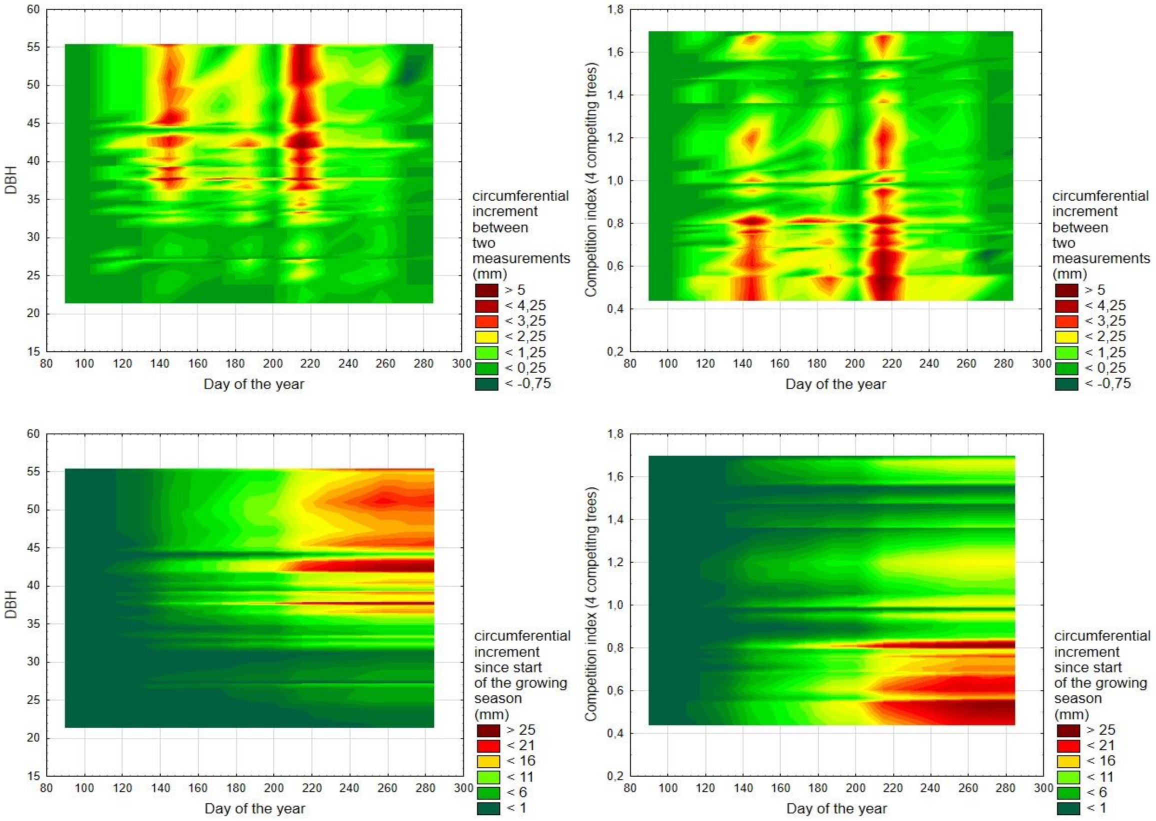


Figure 16: Dependence of circumference increment on the diameter at the breast height (DBH) and Competition Index according to the number of Day of the year in 2014

The high variability of circumference increment during the season might be due to physiological process resulting in stem saturation of water dynamics. Variability of circumference increment differed according the size of the trees, competition index and the number of days in a given period. For instance, there was a high variability of circumference increment for large trees and small competition index during the season in 2010 and 2011.

In 2012, there was almost no variability of circumference increment for small trees (DBH 20-32cm) throughout the year, even if we could notice some changes for medium to large trees there was a high variability in circumference increment for medium trees; there was a high variability for very small competition index. Increment started in the second semester in 2013 and there was a variability for circumference increment between two measurements, and almost no variability of circumference increment for small trees (DBH 22-35cm), as well as high competition index (1.3-1.7) throughout the year. In 2014, large trees after one year had the largest increment. There was no variability of circumference increment in DBH for small trees (20-35 cm) throughout the year, while there was a high variability in small competition index for the year.

6.CONCLUSIONS

The effect of climate, tree size (characterized with diameter at the breast height) and competition on variations in annual circumference increment of Norway spruce (*Picea abies* (L.) Karst.) trees were investigated in a mature spruce stand located at the study site of Rájec (Drahanská vrchovina Highland, the Czech Republic).

There were tested 300 periods of the mean monthly air temperatures, and their correlations with stem increments, with the duration from one month up to January of the previous year to September of the current year. All possible complex periods were combined. 25 best correlations of the girth or circumference increment with mean monthly air temperatures had positive highly statistical significant values.

The microclimate at the study site is characterized by warm-wet summers and cold-dry winters. This study revealed that competition index and stem diameter at the breast height were good parameters for tree growth prediction; correlation was very good with air temperature [$p<0.01$ (highly significant)], and it is possible to say that it is a good estimator in this case. The growth of Norway spruce was less statistically significantly affected only by sum of precipitation. Overall, there was highly significant correlation between air temperature and relative stem increment, and significant correlation between sum of precipitation and relative stem increment was confirmed.

Variability of circumference increment differed according the size of the trees, competition index and the number of days in a given period. The high variability of circumference increment during the season might be due to physiological process resulting in stem saturation of water dynamics.

The performed results declare that inter-tree competition and diameter at breast height are sufficient variables for circumference increment estimation of unmeasured trees in the particular year. Coefficient of determination reached 0.25 – 0.63 for competition and 0.40 – 0.84 for tree diameter at breast height.

Tree growth does not follow simple age trends, since it depends on several factors varying during stand development, such as soil characteristics, climate, silvicultural practices, plant to plant interaction, etc. Values of ring-width variation can be used as a basis for evaluating growth responses of trees to their environment.

It is obvious that unsuitable climatic conditions for spruce can lead to stem shrinkage during growing season. Here we assume that these responses are caused mostly by water storage deficit in stem and this leads to decreasing of the tree vitality.

This study provides new data revealing the basic growth processes of Norway spruce trees, and provides significant information to quantify the responses of tree growth to expected global warming. This approach provided a great opportunity to deepen our understanding and knowledge about the interactions of different environmental factors with the short-, medium- and long-term growth dynamics of one of the most important forest tree species.

7. SUMMARY

The effect of climate, tree size (characterized with diameter at the breast height) and competition on variations in annual circumference increment of Norway spruce (*Picea abies* (L.) Karst.) trees were investigated in a mature spruce stand located at the study site of Rájec (Drahanská vrchovina Highland, the Czech Republic).

There were tested 300 periods of the mean monthly air temperatures, and their correlations with stem increments, with the duration from one month up to January of the previous year to September of the current year. All possible complex periods were combined. 25 best correlations of the girth or circumference increment with mean monthly air temperatures had positive highly statistical significant values.

Variability of circumference increment differed according the size of the trees, competition index and the number of days in a given period.

The performed results declare that inter-tree competition and diameter at breast height are sufficient variables for circumference increment estimation of unmeasured trees in the particular year.

It is obvious that unsuitable climatic conditions for spruce can lead to stem shrinkage during growing season. Here we assume that these responses are caused mostly by water storage deficit in stem and this leads to decreasing of the tree vitality.

This study provides new data revealing the basic growth processes of Norway spruce trees, and provides significant information to quantify the responses of tree growth to expected global warming. This approach provided a great opportunity to deepen our understanding and knowledge about the interactions of different environmental factors with the short-, medium- and long-term growth dynamics of one of the most important forest tree species in the Czech Republic.

8. SOUHRN

Byl posouzen efekt klimatu, velikost stromu (charakterizovaný tloušťkou stromu ve výčetní výšce) a kompetice okolních stromů na roční přírůst smrku ztepilého (*Picea abies* (L.) Karst.) v dospělém smrkovém porostu na výzkumné ploše Rájec (Drahanská vrchovina, Česká republika).

Testována byla závislost ročního přírůstu na průměrné teplotě různě dlouhého období od měsíce ledna předešlého roku po měsíc září aktuální vegetační sezóny (celkem 300 různých období). 25 nejlepších korelací vykazovalo vysoce významnou závislost (p<0.01).

Vlastní sezónní dynamika přírůstu stromů byla odlišná u stromů různých velikostí i u stromů s různě velikým kompetičním indexem.

Bylo prokázáno, že parametry kompetice a tloušťka stromu ve výčetní výšce mohou být vhodné pro odhad přírůstu ostatních (neměřených) stromů v porostu v daném roce.

Je zřejmé, že nepříznivé klimatické podmínky mohou způsobovat smrštění kmene v průběhu růstové sezóny v důsledku vodního deficitu a snižovat tak vitalitu stromů.

Předkládaná práce poskytuje důležité informace o růstu a sezónní dynamice obvodových změn stromů v dospělém smrkovém porostu z pohledu kompetice a základních mikroklimatických faktorů porostu. Prohlubuje tak znalosti o vlivu různých faktorů na růst nejdůležitější dřeviny v České republice.

9. REFERENCES

Alemdag I. S., 1978. *Evaluation of some competition indexes for the predictions of diameter increment in planted white spruce*. Inf. Rep. FMR-X-108, Canadian Forestry Management Institute, Ottawa, Ont., 39 pp.

Barnes B.V., Zak D.R., Denton, S.R. and Spurr S.H., 1998. *Forest ecology*. John Wiley and Sons Inc, New York

Becker M., 1992. *Deux indices de compétition pour la comparaison de la croissance en hauteur et en diamètre d'arbres aux passés sylvicoles variés et inconnus*. Ann. Sci. Forest. 49: 25–37.

Begon M., Harper J.L. and Townsend C.R., 1996. *Ecology: individuals, populations, and communities*. 3rd ed. Blackwell Science Ltd., London, UK.

Bella I. E., 1971. *A new competition model for individual trees*. For. Sci: 17: 364–372.

Biging G. S. and Dobbertin M., 1992. *A Comparison of Distance-Dependent Competition Measures for Height and Basal Area Growth of Individual Conifer Trees*. Forest Science, Volume 38, Number 3. pp. 695-720(26)

Binkley D., Stape J. L. and Ryan M. G., 2004. *Thinking about efficiency of resource use in forests*. Forest Ecol. Manage., 193 (2004), pp. 5–16.

Bošeľa M., Šebeň V., Pajtík J., Konôpka B. and Vida, T., 2013. *Modelling effects of weather condition on seasonal dynamics of the stem circumference increment in a mixed stand of Norway spruce and European beech.* Lesnícky časopis - Forestry Journal, 59(3): 180-188.

Bouriaud O., Leban J.M., Bert D. and Deleuze C., 2005. *Intra-annual variations in climate influence growth and wood density of Norway spruce*. Tree Physiology, 25, 651–660.

Brown G. S., 1965. *Point density in stems per acre*. New Zeal. For. Res. Notes 38, 11 p.

Burton P. J., 1993. *Some limitations inherent to static indices of plant competition*. Can. J. Forest Res.: 2141–2152.

Carrer M., Anfodillo T., Urbinati C. and Carraro V., 1998. *High-altitude forest sensitivity to global warming: results from long-term and short-term analyses in the Eastern Italian Alps*. In: Beninston M. and Innes J.L. (Eds.), The impacts of climate variability on forests, Springer, Berlin, Heidelberg, New York, pp., 171–189.

Čermák J. and Kučera J., 1987. *Transpiration of mature stands of spruce (Picea abies* (L.) Karst.*) as estimated by the tree-trunk heat balance method*. Forest Hydrology and Watershed Management – Hydrologie Forestiere et Amenagement des Bassins Hydrologiques (Proceedings of the Vancouver Symposium, August 1987; Actes du Colloque de Vancouver, Aout 1987):IAHS-AISH Pubi.no.167,1987.

Coomes D. A. & Allen R. B., 2007. *Effects of size, competition and altitude on tree growth.* Journal of Ecology, 95(5), 1084-1097.

Daniels R. F., 1976. *Simple competition indices and their correlation with annual loblolly pine tree growth*. For. Sci., 22: 454--456.

Daudet F. A., Ameglio T., Cochard H., Archilla O. and Lacointe A., 2005. *Experimental analysis of the role of water and carbon in tree stem diameter variations.* J. Exp. Bot. 56: 135–144.

Deslauriers A., Morin H., Urbinati C., Carrer M., 2003. *Daily weather response of balsam fir (Abies balsamea (L.) Mill.) stem radius increment from dendrometer analysis in the boreal forests of Québec (Canada) Trees*., 17:477–484.

Deslauriers A., Rossi S. and Anfodillo T., 2007. *Dendrometer and intra-annual tree growth: What kind of infor-mation can be inferred?* Dendrochronologia 25(2): 113-124 .

Downes G, Beadle C, Worledge D., 1999. *Daily stem growth patterns in irrigated Eucalyptus globulus and E. nitens in relation to climate*. Trees., 14:102–111.

Eckenwalder J. E., 2009. *Conifers of the World: The Complete Reference*., 1st ed. Timber press. Portland-London.

Esper J., Frank D.C., Wilson R.J.S., Büntgen U. and Treydte K., 2007. *Uniform growth trends among central Asian low- and high elevation juniper tree sites*. Trees 21:141–150

Ford E.D., 1975. *Competition and stand structure in some even aged plant monocultures*. J. Ecol. 62: 311–333.

Franklin J.F., Spies T.A., Van Pelt R., Carey A.B., Thornburgh D.A., Berg D.R., Lindenmayer D.B., Harmon M.E., Keeton W.S. & Chen J., 2002. *Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example*. Forest Ecology and Management 155: 399–423.

Fraver S., D’Amato A.W., Bradford J.B., Jönsson M. and Esseen P.A., 2014. *Tree growth and competition in an old-growth Picea abies forest of boreal Sweden: influence of tree spatial patterning*. Journal of Vegetation Science 25: 374–385. Doi: 10.1111/jvs.12096.

Fritts H. C., 1976. *Tree rings and climate*. Academic Press, New York.

Fritts H.C., 1961. *An evaluation of three techniques for measuring radial tree growth*. Bull. Ecol. Soc. Am. 42: 54–55.

Fritts H.C., Smith D.G., Cardis J.W. and Budelsky C.A., 1965. *Tree-ring characteristics along a vegetation gradient in northern Arizona*. Ecology 46:394–401

Grabařová S. and Martinková M., 2002. *Climatic risk factors for spruce (Picea abies [L.] Karst.) stands in lower altitudinal vegetation zones*. Ekológia (Bratislava), Vol., 21. Supplement 1/2002, p., 136-151.

Gricar J., Krze L. and Cufar K., 2009. *Number of cells in xylem, phloem and dormant cambium in silver fir (Abies alba), in trees of different vitality*. IAWA J, 30, p., 121-133.

Hamilton G. J., 1969. *The dependence of volume increment of individual trees on dominance, crown dimensions, and competition*. Forestry, 42: 133--144.

Hegyi F., 1974. *A simulation model for managing jack-pine stands*. In: J. Fries (Editor), *Growth Models for Tree and Stand Simulation*. Royal College of Forestry, Stockholm, Sweden, pp. 74--90.

Henttonen H.M., Mäkinen H. & Nöjd P., 2009. *Seasonal dynamics of wood formation of Scots pine and Norway spruce in southern and central Finland*. Canadian Journal of Forest Research 39(3): 606-618.

Herzog K.M., Hasler R., and Thum R., 1995. *Diurnal changes in the radius of a subalpine Norway spruce stem: their relation to the sap flow and their use to estimate transpiration*. Trees 10: 94–101.

Horáček P., 1994. *The dynamics of radial growth of Norway spruce (Picea abies L. (Karst.)) in relation to environment conditions*. Doctoral thesis. Brno: VŠZ v Brně, 114 pp (in Czech).

Horacek P., Slezingerova J., Gandelova L., 1999: *Effects of environment on the xylogenesis of Norway spruce (Picea abies [L.] Karst.)*. In: WIMMER, R., VETTER, R.E., (eds.): Tree-ring analysis. Biological, methodological and environmental aspects. Oxford: CAB International, p 33-54.

Hruška B., 1980. *Geological petrographic ratios, physical weathering processes, nutrient releasing and classification of physical weathering processes inf spruce forest ecosystem.* Final report VI-2-2-20, VŠZ Brno, 51 pp (in Czech).

Karen P. B. (eds)., 2010. *Good Forestry in the Granite State: Recommended Voluntary Forest Management Practices for New Hampshire (second edition)*. University of New Hampshire Cooperative Extension, Durham, N.H.

Kärkkäinen, V.-M., 1984. *Effect of tree social status on basic density of Norway spruce.* Silva Fennica, vol. 18 No 2: 115-120.

King G., Fonti P., Nievergelt D., Büntgen U., Frank, D., 2013. *Climatic drivers of hourly to yearly tree radius variations along a 6°C natural warming gradient*. Agricultural and Forest Meteorology, 168, p. 36-46.

Klimo E., 1992. *Geographical and soil conditions*. In: Klimo, E. and Marsalek, J. (eds.). *Manmade spruce ecosystem (structure, function, production, processes)*. Inst. of forest ecology Mendel Univ. of Agriculture and Forestry. Brno. Pp. 4–8.

Kozlowski T. T., Kramer P. J. and Pallardy S. G., 1991. *The Physiological Ecology of Woody Plants*. Academic Press, San Diego, CA, USA.

Kozlowski T.T. and Winget C.H., 1964. *Diurnal and seasonal variations in radii of tree stems*. Ecology 45: 149–155.

Kozlowski T.T., 1971. *Growth and development of trees. Vol. II. Cambial growth, root growth and reproductive growth*. Accademic Press, New York, 514 pp.

Krepkowski J., Bräuning A., Gebrekirstos A. and Strobl S., 2011. *Cambial growth dynamics and climatic control of different tree life forms in tropical mountain forest in Ethiopia*. Trees 25:59–70.

Lalita D., 1992. *Climatic Characteristics and Water Balance: A Study of Uttar Pradesh.* New Delhi: Concept Pub. Co. 207p

Lang F., 1920. *Verwitterung und Bodenbildung als Einfilhrung in die Bodenkunde*. Schweizerbatsche Verl., Stuttgart.

Linares J.C., Camarero J.J. and Carriera J.A., 2009. *Plastic responses of Abies pinsapo xylogenesis to drought and competition*. Tree Physiology, 29, p., 1525-1536.

Lorimer C. G., 1983. *Test of age independent competition indices for individual trees in natural hardwood stands*. For. Ecol. Manage. 6: 343–360.

Mäkinen H., 2014. *Wood formation under varying environmental conditions (WOVEN).* WoodWisdom-Net Research Programme 2006-11. FINAL REPORT.

Mäkinen H., Nöjd P, Kahle H.P., Neumann U., Tveite B., Mielikäinen K. and Röhle H., 2002. *Radial growth variation of Norway spruce (Picea abies* (L.) Karst.*) across latitudinal and altitudinal gradients in central and northern Europe*. For Ecol Manag171:243–259

Mäkinen H., Nöjd P. and Saranpää P., 2003. *Seasonal changes in stem radius and production of new tracheids in Norway spruce*. Tree Phys., 23:959–968.

Mäkinen H., Seo J.-W., Nöjd P., Schmitt U. and Jalkanen R., 2008. *Seasonal dynamics of wood formation: a comparison between pinning, microcoring and dendrometer measurements*. European Journal of Forest Research 127: 235-245.

Marková I., Pavelka M., Krejza J. and Janouš, D., 2015. *Ročenka meteorologických měření 2012.* Brno: Keloc PC, spol.s.r.o. 167 s. ISBN 978-80-87902-13-4.

Mcdonald G.B., Morris D.M. and Marshall P.L., 1990. *Assessing components of competition indices for young boreal plantations.* Can. J. Forest Res. 20: 1060–1068.

Meldahl R. S., 1979. *Yield projection methodology and analysis of hybrid poplars based on multispaced plots*. Ph.D. Thesis, University of Wisconsin, Madison, WI, 228 pp.

Morales M.S., Villalba R., Grau H.R., Paolini L., 2004. *Rainfall controlled tree growth in high-elevation subtropical treelines*. Ecology 85:3080–3089

Němeček J., Vokoun, J., Smejkal, J., Macků, J., Kozák, J., Němeček, K., Borůvka, L., 2001. *The system of soil classification in the Czech republic*, Praha: ČZU a VÚMOP, 79 pp (in Czech).

Paltasingh K.R., Goyari P. and Mishra R. K., 2012. *Measuring Weather Impact on Crop Yield Using Aridity Index: Evidence from Odisha*. Agricultural Economics Research Review. Vol. 25(No.2) pp 205-216

Peterson D.W. and Peterson D.L., 2001. *Mountain hemlock growth responds to climatic variability at annual and decadal timescales*. Ecology 82:3330–3345

Quitt E., 1971. *Climatic areas of Czechoslovakia*. Brno, Geografický ústav ČSAV, 80 pp(in Czech).

Rathgeber C.B.K., Rossi S., Bontemps J.-D., 2011. *Cambial activity related to tree size in a mature silver-fir plantation*. Annals of Botany, 108, p. 429-438.

Reimers N. F., 1991. *The Popular Biological Dictionary*. Moscow: Nauka. 544 p. In Russian.

Rybníček M., Čermák P., Žid T. and Kolář T., 2010. *Radial growth and health condition of Norway spruce (Picea abies* (L.) Karst.*) stands in relation to climate (Silesian Beskids, Czech Republic)*. Geochronometria 36 (2010) 9-16. DOI 10.2478/v10003-010-0017-1.

Schweingruber F. H., 1996. *Tree rings and environment dendroecology*. Haupt Publishers, Berne, Stuttgart, Vienna.

Stadt K. J., Huston C., Coates K. D., Feng Z., Dale M. R. T. and Lieffers V. J., 2007. *Evaluation of competition and light estimation indices for predicting diameter growth in mature boreal mixed forests*. Annals of Forest Science 64: 477–490.

Světlík J., Krejza J., Menšík L, Pokorný R, Mazal P. and Kulhavý J., 2016. *Carbon sequestration into a spruce stand (Picea abies* (L.) Karst.*) in the Drahanská vrchovina upland (Czech Republic)*. ZPRÁVY LESNICKÉHO VÝZKUMU, 61(1): 42-53

Takahashi K., Tokumitsu Y., Yasue K., 2005. *Climatic factors affecting the tree-ring width of Betula ermanii at the timberline on Mount Norikura, central Japan*. Ecol Res 20:445–451

Tardif J., Flannigan M. and Bergeron Y., 2001. *An analysis of the daily radial activity of 7 boreal tree species, northwestern Quebec.* Environmental Monitoring and Assessment, 67: 141-160.

Thornthwaite C. W., 1948. *An Approach toward a Rational Classification of Climate*. Geographical Review, Vol. 38, No. 1. pp. 55-94.

Tolasz R., Brázdil R., Bulíř O., Dobrovolný P., Dubrovský M., Hájková L., Halásová O., Hostýnek J., Janouch M., Kohut M., Krška K., Křivancová S., Květoň V., Lepka Z., Lipina P., Macková J., Metelka L., Míková T., Mrkvica Z., Možný M., Nekovář J., Němec L., Pokorný J., Reitschläger J.D., Richterová D., Rožnovský J., Řepka M., Semerádová D., Sosna V., Stříž M., Šercl P., Škáchová H., Štěpánek P., Štěpánková P., Trnka M., Valeriánová A., Valter J., Vaníček K., Vavruška F., Voženílek V., Vráblík T., Vysoudil M., Zahradníček J., Zusková I., Žák M. and Žalud Z., 2007.

Altas podnebí Česka (Climate atlas of Czechia). 1. vydání. Praha, Olomouc: Český hydrometeorologický ústav, Universita Palackého. 256 s. ISBN 978-80-86690-26-1.

Tomé M. and Burkhart H. E., 1989. *Distance-dependent competition measures for predicting growth of individual trees*. For. Sci., 35: 816–831.

Tüxen R., 1954. *Über die räumliche, durch Relief und Gestein bedingte Ordnung der natürlichen Waldgesellschaften am Rande des Harzes*.- Vegetatio 5–6: 454–478. Den Haag.

Vaganov E. A., Hughes M. K., and Shashkin A. V., 2006. *Growth Dynamics of Conifer Tree rings Images of Past and future Environments*. XIV, 354 p., 178 illus., Hardcover ISBN 978-3-540-26086-8

Vašicek F., 1984. *The characteristics of the geobiocenoses*. In: Vasicek, F. (ed.). *Ecophysiological and ecomorphological studies of individual trees in the spruce ecosystems of the Drahanska Vrchovina uplands* (Czechoslovakia). Folia Universitatis Agriculturae. Brno. Pp.4–12.

Vichrová G., Vavrčík H., Gryc V. and Světlík J., 2013. *The analysis of radial growth in stem of norway spruce by means of different methods and assessment of effect of climatic conditions in relation to the growth.* Wood Research 58 (2) 217-230

Wang Z., Yang B., Deslauriers A., Bräuning, A., 2014. *Intra-annual stem radial increment response of Qilian juniper to temperature and precipitation along an altitudinal gradient in northwestern China*. Springer-Verlag Berlin Heidelberg. Trees DOI 10.1007/s00468-014-1037-7

Zabuga V.F., Zabuga G.A., 1991. *On the methods for measurement of Scots pine stem radial growth in ecophysiological studies.* 3: 63-67.

Zweifel R. and Hasler R., 2000. *Frost-induced reversible shrinkage of bark of mature, subalpine conifers*. Agric. For. Meteorol., 102: 213–222.

Zweifel R. and Häsler R., 2001. *Dynamics of water storage in mature subalpine Picea abies: temporal and spatial patterns of change in stem radius*. Tree Phys., 21:561–569.

Zweifel R., Zimmermann L. and Newbery D.M., 2005. *Modeling tree water deficit from microclimate: an approach to quantifying drought stress*. Tree Physiology, 25, p., 147-156.

9.1.Online resources

- **http://en.wikipedia.org/wiki/Dendroclimatology**
- **http://en.wikipedia.org/wiki/Dendrometry.**
- **http://www.eolss.net/sample-chapters/c12/E1-05-06.pdf** (**Verheye W.** *Dry Lands and Desertification*. Land use, land cover and soil sciences – Vol. V)
- **http://www.nwrc.usgs.gov/topics/Dendrometer/**
- **http://www.usbe.cas.cz/lefr/en_biomasa.htm**
- **http://www.usbe.cas.cz/lefr/img/biomasa/obr_02.jpg**
- **http://www.woodwisdom.net/wp-content/uploads/2014/08/WOVEN_final_report.pdf** *[Mäkinen H., 2014. Wood formation under varying environmental conditions (WOVEN). WoodWisdom-Net Research Programme 2006-11. FINAL REPORT]*.
- **https://en.wikipedia.org/wiki/Pearson_product-moment_correlation_coefficient**
- **https://en.wikipedia.org/wiki/Regression_analysis**