University of Tartu
Faculty of Science and Technology
Applied Measurement Science

Relationships between Environmental Factors and the Growth of Above-Ground Biomass in Boreal Forest

Master´s thesis

Xiaozhou Ye

Supervisors: PhD Kaido Soosaar
PhD Alar Läänelaid

Tartu 2016

Relationships between Environmental Factors and the Growth of Above-Ground Biomass in Boreal Forest

This study investigates the influence of shortwave radiation (albedo is calculated to characterize the absorption of shortwave radiation), temperature and relative humidity on biomass growth of two coniferous species in boreal forest. Stem circumferences are measured for calculating daily biomass growth rate and calculated growth rate is analysed by statistical method for revealing its possible correlations to environmental factors (shortwave radiation, temperature and relative humidity). Comparisons between biomass growth rate and environmental factors are also made for finding correlation. Temperature sets lower limit for biomass growth. Biomass growth rate is found dependent on the values of albedo, meaning absorption of shortwave radiation dominates growth. Relative humidity is found negatively dependent on temperature. However, there is no statistical dependence of growth rate found on temperature and relative humidity, although some extreme temperatures and relative humidity are noticed affecting growth rate through evaporation (temperature affects negatively and relative humidity affects positively). The model on the relationship between values of albedo and temperature in the process of glucose absorption is also revealed and albedo is regarded to dominate such a process. Connections among these environmental factors are found and the affecting mechanism is established finally. Besides, species-specific difference of response to shortwave radiation between Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L.) is revealed.

Biomass growth, boreal forest, albedo, temperature, relative humidity

CERCS code: B430 Sylviculture, forestry, forestry technology

Keskkonnaparameetrite ja maapealse biomassi kasvu vahelised seosed boreaalses metsas

Käesolevas magistritöös uuritakse lühilainelise kiirguse, temperatuuri ja suhtelise õhuniiskuse mõju kahe boreaalses metsas esineva okaspuuliigi biomassi juurdekasvule. Lühilainelise kiirguse neeldumise iseloomustamiseks arvutatakse välja albeedo väärtus. Päevase biomassi juurdekasvu arvutamiseks mõõdetakse tüvede ümbermõõdud ning saadud arvutuste tulemusi analüüsitakse statistilise meetodiga, et tuua välja võimalikud korrelatsioonid biomassi juurdekasvu ja keskkonnatingimuste vahel (lühilaineline kiirgus, temperatuur ja suhteline õhuniiskus). Biomassi kasvuks on vajalik täita temperatuuri alampiir. Uurimuses selgus, et biomassi juurdekasvu kiirus on kõige enam mõjutatud albeedo väärtusest ehk puude kasvukiirgus korreleerub positiivselt lühilainelise kiirguse neeldumise hulgaga. Suhteline õhuniiskus on negatiivses korrelatsioonis õhutemperatuuriga, kuid uurimuse põhiselt ei leitud olulist seost biomassi juurdekasvu kiiruse ning temperatuuri ja suhtelise õhuniiskuse vahel. Temperatuuri ja suhtelise õhuniiskuse mõju biomassi kasvule võib täheldada vaid ekstreemselt kõrgete väärtuste korral, kui aurustumine on suur (väga kõrged temperatuurid mõjutavad biomassi juurdekasvu negatiivselt ja kõrge suhtleine õhuniiskus mõjub positiivselt). Ühtlasi vaadeldi käesolevas töös ka albeedo ja temperatuuri mõju glükoosi imendumisprotsessidele ning leiti, et antud protsess on kõige enam mõjutatud albeedo poolt. Töö üldiseks eesmärgiks on eelpool mainitud keskkonnategurite mõju ja mõjumehhanismide selgitamine ning kahe uuritud puuliigi (harilik mänd ja harilik kuusk) liigiomaste erinevuste välja toomine seoses lühilainelise kiirguse mõjuga.

Biomassi kasv, boreaalne mets, albeedo, temperatuur, suhteline niiskus

CERCS kood: B430 metsakasvatus, metsandus, metsandustehnoloogia

TABLE OF CONTENT

1 INTRODUCTION

Boreal forests cover 36% of forest area worldwide and they are spread in Finland, Sweden, Norway, European part of Russia and part of Estonia [1-6]. Boreal forest is a kind of coniferous forests which mainly consist of three tree genera: pine, spruce and larch [7-8].

Boreal forests are highly sensitive to climatic and human impacts and therefore suitable as biological indicator for studying plant responses to global climate change and have therefore attracted more and more scientific attention [9-10]. The previous studies were focused on one or two affecting factors and there is no relationship among the possible affecting factors being connected systematically. Once the relationships being established, the value of specific factor for monitoring climate and environment changes could be utilized by observing the growth of boreal forests. In this research, the reflection coefficient albedo is applied as the parameter characterizing the level of radiation absorption for replacing photoperiod previously used. The value of albedo could be strongly affected by weather conditions especially in foggy weather or those days that air is heavily polluted. So the establishment of affecting mechanism of the growth of boreal forests could be useful for monitoring air pollution conditions by focusing on the effect of radiation absorption to growth rate. The application of dendrometer makes the monitoring of biomass growth in real time possible, which is superior compared with traditional methods. The Soontaga Forest Station is the only site that equipped with all instruments fulling the requirement of detection in this study in Estonia, making it the ideal sampling site for this research.

The aim of this research is to reveal the affecting mechanism of environmental factors to boreal forests. Stem increment of Norway spruce and Scots pine measured by band type dendrometer will be compared with values of albedo, temperature, relative humidity. The following questions would be answered: (1) Is there any dominant factor to above-ground biomass growth? (2) How does the mechanism of environmental factors to the growth of boreal forest work? (3) Does the relationship between boreal forest and environmental factors differ among different species?

The hypothesis has been made below: (1) The parameter albedo which is newly inserted for accurately characterize the sunlight radiation could be one of the affecting factors because the sunlight radiation directly affect the level of photosynthesis. (2)Temperature could be another affecting factor because it may control the quantity of photosynthetic production utilized. (3) The species-specific difference of different boreal forests could be existed and as the different sensitivity to sunlight radiation may exist between Norway spruce and Scots pine.

This master's thesis is organized as the following structure: In the literature overview chapter, physiology of two coniferous species is introduced. Different measurement technology for biomass growth is also explained. An overview of the all the possible environmental factors to biomass growth is introduced and they are connected for establishing the possible mechanism. The updated mechanism is shown after doing brief analysis then. Material and methods chapter describes the sampling site, all the measurands and their corresponding measuring instrument. Calculations of some parameters and statistical methods are also shown in this chapter. In results chapter, comparisons between accumulative growth and different environmental factors are shown respectively as well as the comparisons between biomass growth rate and these factors. In discussion part, the model on relationship between albedo and temperature is established. Affecting mechanism of biomass growth is analyzed and species-specific difference on growth is also discussed.

2 LITERATURE OVERVIEW

Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L.) together with Siberian larch (*Larix sibirica* L.) are dominant species in boreal forests and they are widely used for studies on boreal forests [11].

Scots pine (*Pinus sylvestris* L.) is a species of evergreen conifers which is widely distributed in boreal forests. It can grow up to 15 meters tall with a trunk diameter of 1 meter when mature [12]. Its bark is thick, scaly dark grey-brown on lower trunk, and thin,flaky and orange on upper trunk and branches [13]. Its northern limit in Norway, Sweden and Finland exceeds Arctic Circle [14] and it is also widely distributed in the forests in Estonia [4-6].

Norway spruce (*Picea abies* L.) is a fast growing evergreen coniferous tree which can reach 35-55 meters tall with a trunk diameter of 1 to 1.5 meters [15]. Their leaves are needle-like with length of 12-24 mm. Leaves' cross-sections are quadrangular with dark green on all four sides [11].

2.1 Measurement technology

Dendrometer was developed and introduced into dendrological studies and brought revolutionary progress to them. Compared with traditional measuring method, like pinning and micro-coring, which can only measure biomass growth in one-year interval through tree-ring, dendrometer makes the real time monitoring possible [16].

With the accomplishment of higher resolution, the need to implement a 'timer' into wood formation process became evident to precisely date the variation of stem increment. For this purpose, various tools and techniques have been tested and improved since 1970s, pinning, micro-coring and dendrometer for example. [10]..

Pinning method was developed by Wolter [18] and later applied by Yoshimura [19], Kuroda [20] and Schmitt [21]. In this method, researchers use a micro needle to make a small injury to the cambial zone and some specifically aberrant cell are formed. These aberrant cells are permanently retained as a mark in annual rings [18]. This method was later improved for marking xylem growth [19] and applied for marking xylem growth in hardwood species [20] as well as used in tree growth data preparation field [21]. However, the pinning method is laborious and the exact location of the cambial initials at the time of pinning cannot always be precisely determined [22].

In micro-coring method, researchers count total cell number, the number of xylem and phloem cells, in the cambial zone and these numbers are tabulated for each sample [23].

However, the disadvantage of these two traditional methods is they can only detect radial growth variance in relatively long intervals because of their relatively low sample taken frequency. Detailed information on intra-annual variation in radial increment of Norway spruce and Scots pine is scarce in Finland before 2003 and this lack of knowledge is due to difficulties in measuring wood formation in short intervals [22].

There are mainly two types of dendrometers which contact stem physically: point type dendrometer and band type dendrometer. Point type dendrometer measures the changes at a single point while band type dendrometer measures changes in stem circumference. In the band type dendrometer, a simple girth band for automatic measurement of short term changes in stem diameter was developed. Daily shrinking and swelling as well as cumulative increment can be monitored.The development of band type dendrometer can be traced to 1982 as a cooperation between Finnish Forest Research Institute and University of Oulu and the first prototype came out for field-testing in 1993 [17]. Band type dendrometer has been used by Neher firstly [24] and it is regarded to have better estimation on stem increment because it represents a mean of all radii over all directions [25]. So to this point, band type dendrometer has another advantage to pinning method and micro-coring method which cannot detect daily shrinking and swelling.

However, changes in stem dimensions are not sole the result of xylem formation, previous researches have shown that the stem dimensions reach a minimum in the mid- to late-afternoon and a maximum in the early morning [26-27]. The daily fluctuation in stem dimensions reflect decreasing stem water potential caused by transportation during the day while increasing stem water potential during night when transpiration ceases [28]. So stem dimension changes are also caused by other process, especially changes in stem hydration [29].

Since dendrometers measure stem circumference changes rather than wood formation, it is difficult to distinguish between true wood formation and daily hydrological shrinking and swelling [22]. However, the later research applied different approaches to extract time series of stem dimensions variation, daily mean and daily maximum value of stem radius. These time series of stem radius variation extracted with different approaches are produced with very high coefficients of correlation among the series [30]. This finding shows that we only need to extract the mean value or maximum value of stem dimension in everyday and then we can get stem growth trend in time series even stem dimension varies in one-day scale.

2.2 Environmental factors influencing above-ground biomass growth

Influences of environmental factors on above-ground biomass growth come from three parts mainly: photosynthesis, evaporation effects and usage of photosynthetic production. Several affecting factors on growth of conifers have been studied, including temperature, relative humidity, photoperiod and canopy nitrogen concentration. (Figure 1)

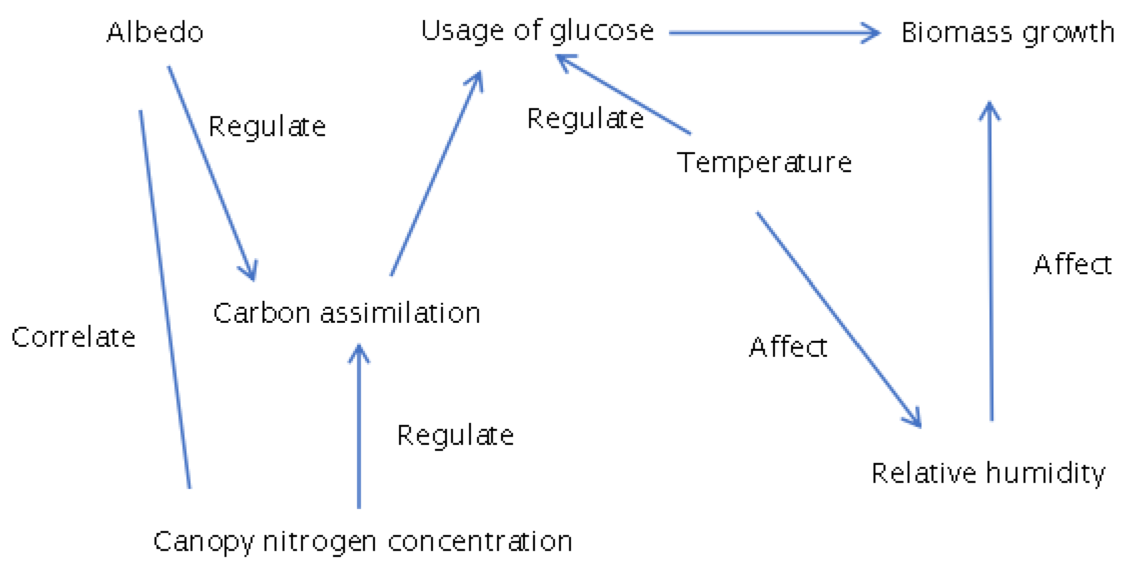

Figure 1. The mechanism of environment factors affecting biomass growth rate

Photosynthesis is the critical process for biomass growth as it produces glucose used for biomass growth. Photoperiod was used to characterize the level of photosynthesis [31]. However, albedo is thought to be more suitable to characterize it because how much carbon can be assimilated decides the level of photosynthesis and albedo is thought to be correlated with carbon assimilation [32-33]. Canopy nitrogen concentration was reported to regulate carbon assimilation in photosynthesis and canopy nitrogen is correlated with leaf photosynthetic capacity as well [34]. However, both carbon assimilation and canopy nitrogen concentration are positively correlated with shortwave surface albedo [35]. So it means the single calculation of albedo can represent the detection of carbon assimilation and canopy nitrogen concentration.

One of the effects of temperature on biomass growth is it sets the temperature limit for biomass growth [36]. Early summer temperature was found as the most important factor that affects seasonal growth [37].

Besides, temperature can affect the tree growth temporarily by evaporation [38]. And relative humidity is regarded as an affecting factor combining with temperature because relative humidity is regulated by temperature [39].

Temperature has another effect on biomass growth by affecting the usage of photosynthetic production. It was reported that how much glucose can be utilized that limits growth but not carbon assimilation [40]. This means more assimilated carbon can be utilized in higher temperature. But it doesn't mean that temperature is the decisive factor and we don't need to detect other factors, albedo and soil nitrogen concentration. Because the assumption is that there is enough glucose produced can be utilized by tree.

The updated affecting mechanism for biomass growth shows as the following (Figure 2):

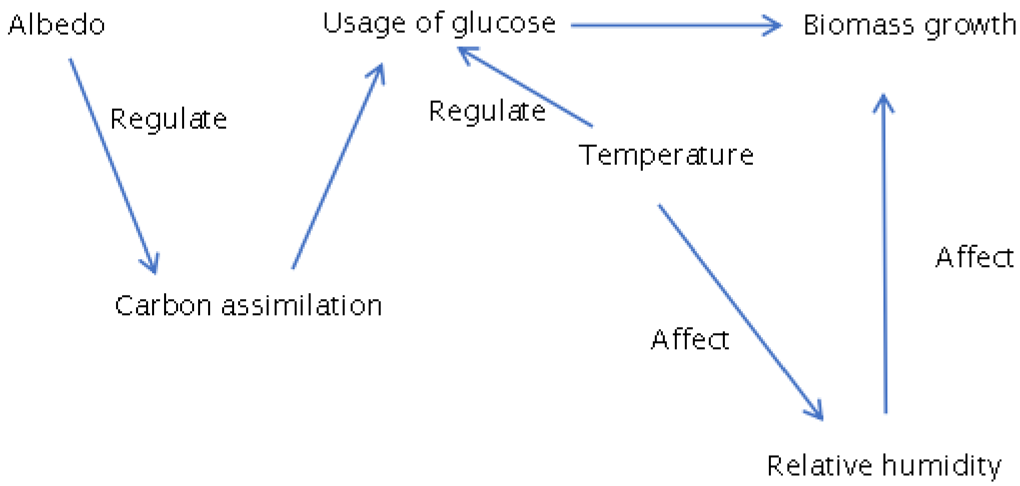

Figure 2. The updated mechanism of environment factors affecting biomass growth rate

2.2.1 Photosynthesis

Besides temperature and precipitation, the photoperiod has also been included into affecting factors. Signal from light condition was found to determine the start of bud ontogenesis when testing the timing of bud burst in mature birch in 60-year time series. Effects of photoperiod has also been noticed in Norway spruce: Continuous lengthening of photoperiod hastened bud burst while shortening of photoperiod delayed bud burst. Through this observation, he concluded that onset of growth predicted by computer with models that only consider temperature regulation of bud burst [31].

However, photoperiod cannot accurately characterize how much photosynthetic production has been used by trees for growth. For example, in the following cases we cannot take photoperiod as the parameter describing photosynthetic usage: firstly, even when the photoperiod are equal with each other, the sunlight radiation may differentiate for photosynthesis; Secondly, the tree leaves could be covered by snow in winter and it almost cannot absorb any radiation even the photoperiod does exist. However, albedo is such kind of parameter which is the diffuse reflectivity of a surface that can perfectly characterize the absorption of sunlight radiation by trees. Another reason why we take albedo into account is that the snow cover the trees in winter and it would prevent trees absorb sunlight radiation as we referred before, but albedo can characterize such phenomenon well: when the snow cover the trees, the value of albedo detected would show the fact of coverage, that the value of photoperiod cannot do. So albedo is important especially when we do research on such boreal forests which are located in high latitudes.

Shortwave radiation from sunlight does provide necessary energy to photosynthesis for tree growth and we use albedo to characterize it. However, the critical point is the ability of carbon assimilation that determines the level of photosynthesis and how much photosynthetic production we can get for the usage by trees. Tietema found canopy nitrogen concentration directly regulates photosynthetic carbon assimilation and canopy is strongly correlated with leaf photosynthetic capacity [34]. Ollinger revealed that both carbon assimilation and canopy nitrogen concentration are positively correlated with shortwave surface albedo [35]. This finding demonstrates Tietema's conclusion that canopy nitrogen concentration regulates carbon assimilation because if canopy nitrogen concentration regulates carbon assimilation, canopy nitrogen concentration must be correlated with carbon assimilation, and shortwave surface albedo are both correlated with canopy nitrogen concentration and carbon assimilation which means canopy nitrogen concentration is also correlated with carbon assimilation by Tietema. And their conclusions are corresponded with each other. Now the issue is albedo correlates with carbon assimilation which determines the level of photosynthesis, so we only need to detect the variation of albedo to study the variation of the level of photosynthesis. Besides, albedo also correlates with canopy nitrogen concentration which regulates carbon assimilation, it means albedo correlates with carbon assimilation again indirectly. As what we did before, we can ignore carbon assimilation as well as canopy nitrogen concentration to study the photosynthesis process. So based on Ollinger and Tietema's conclusion, we only need to detect shortwave surface albedo to study photosynthesis.

Nitrogen deposition is suggested to one of the factors that affect tree growth [41]. And soil nitrogen availability is also found one crucial factor limiting photosynthetic capacity directly and tree growth in boreal forests [42]. However, all the nitrogen deposited would come into soil and calculated with existent soil nitrogen as the total soil nitrogen amount. So only soil nitrogen concentration need to be taken into account as one of the detecting factors to photosynthesis.

2.2.2 Effect of temperature and relative humidity

Several affecting factors for growth of conifers have been studied. Lundmark studied the recovery of winter depression of Scots pine, Lodgepole and Norway spruce by means of chlorophyll fluorescence and gas exchange measurements [43]. The correlation between potential rate of recovery of variable fluorescence / maximum fluorescence was found at different temperatures in laboratory. Kirdyanov found early summer temperature and the date of snow melt are the most important factors that affect seasonal growth and tree ring structure by means of tree ring analysis [37]. When detecting seasonal changes in stem increment and xylem formation of Norway spruce by dendrometer combined with examination of small increment cores taken twice weekly, the rate of xylem formation was found significantly correlated with mean daily temperature [22], while other researchers included relative humidity into affecting factors [44]. For pine trees, the temperature influence on initial stem increment in May to June was found through micro-coring method by counting the number of xylem cell formation. Intra-annual variations in growth rate were related to relative humidity when detecting relationship between stem increment and intra-annual climate changes by point type dendrometer [39]. Another evidence is that Brooks found relative humidity negatively influencing the growing conditions of Jack pine at its southern boundary and lower temperature negatively influencing at its northern boundary. Contrarily, relative humidity and lower temperature influence positively the growth of Black spruce throughout its range. Besides the influence factors temperature and relative humidity, this finding also indicated us that different conifers may have species-specific response to an environmental factor, and we need to check the possible differences among different sample trees to the environmental factor in our research [45].

2.2.3 Usage of photosynthetic production

However, further proceeded photosynthesis doesn’t mean better tree growth, the photosynthetic production still need to be well absorbed by tree. Grace reported that it is the rate at which glucose can be utilized that limits growth but not carbon assimilation [40]. Besides, trees respond better to higher temperature because the warming can increase the rate of cell division and therefore the rate at which the assimilated carbon can be utilized. So it means that the factors that influence photosynthesis directly are not as important as that influence the ability of trees for using photosynthetic production. This is why the discussion on the relationship between temperature and values of albedo is necessary in this study.

But it doesn’t mean that temperature is the decisive factor and unnecessary to take into account albedo. Because the pre-assumption is that there is enough glucose produced can be utilized by tree. The exceptional case could be even when it has better temperature condition for further usage of glucose, the production of glucose by photosynthesis is limited which much lower than the usage capacity due to bad photosynthesis condition, high albedo and very limited soil nitrogen concentration for example.

Conifers in boreal forest are regarded to have lower albedo than other trees. Foley found that the winter albedo for conifers is low [46] while deciduous have twice albedo of conifers during winter [47]. In summer time, conifers also have the lowest albedo compared with deciduous and tundra [48]. So it is evident that conifers are more effective in converting incoming energy for photosynthesis than other vegetation because of its lowest albedo all year round in almost all the vegetation type.

What’s more, different conifers may have species-specific response to the same environmental factor. Scots pine is regarded to grow faster on sites with low availability of nutrients than Norway spruce [49-50]. In northern Sweden where availability of nutrients is low it was found that generally Scots pine grows faster than Norway spruce while in southern Sweden where nutrients is high Norway spruce grows faster than Scots pine [51]. As referred before in the part for effects of temperature and soil moisture, Brooks found Black spruce and Jack pine have contrary responses to temperature and soil moisture [45]. Based on these previous findings, the comparison of responses to various environmental factors from different coniferous species is necessary to be made.

3 MATERIALS AND METHODS

3.1 Study site

All the sample trees are located in Soontaga LKA (58° 01′ N 26° 04′ E), an Estonian nature conservation (Photo 1). It is located in the boreal forest in southern Estonia. The forest is dominated by 60-200 year old Scots pines (*Pinus sylvestrys* L.) with maximum height of 30 meters and it also exists Norway spruces (*Picea abies* L.).

Photo 1. Location of Soontaga Forest Station

3.2 Sampling method

The number of sample trees is 8. Samples were named from No.1 to No.8 respectively. The samples No.3, No.4 and No.8 are Norway spruces and the left are Scot pines. All the sample trees are monitored from the 9th of December in2014 to 3rd of September in 2015.

The band type dendrometers (Ecomatik, DC3) were installed on all the sample trees on March 2011. The thermal expansion coefficient of steel 1.2×10^{-5} °C^{-1} and it results in an expansion of the steel band 0.024 mm °C^{-1} for the length of 2 meters. The thermal expansion of the steel band will be corrected in the measurement. The output of the dendrometers were stored as 30 minutes intervals in the data logger. Based on these measurements, the daily mean value of stem circumferences of every 30 minutes are calculated later.

In this research, the dendrometer consists four elementary units: (1) a two meters long steel band encircling the tree for transmitting the circumference changes to the sensor. (2) the sensor reacting to movements of the steel band. (3) the rubber band with plug locks for fixing the sensor onto the tree. (4) one bag of plastic slides for reducing the friction between the steel wire and the measured tree stem. The steel band is pressed against potentiometer by a system of three reels using a constant force so that the band rotates the axle without sliding. The changes in tree circumference lead to the movements of steel band and the movements are transmitted to the axis of potentiometer. Resistance of potentiometer will be changed because of the movement transmitted to the axis of potentiometer. And then the voltage of potentiometer whose value can be shown in the voltmeter will be changed because of the changes of its resistance. So different stem circumferences correspond to different voltage shown in the voltmeter and we can apply the formula provided by the producer to the calculation on stem circumferences from the voltage value.[52]

Photo 2. Dendrometer on sample trees

Radiation was measured by Net Radiometer (Kipp and Zonen, CNR4 Net Radiometer with ventilation)and from there values of albedo were calculated, also the air temperature and air humitidy (Rotronic, HC2-S3) was measured after every 1 min and averaged for 30 min.

Photo 3. Observation tower for measurement on parameters

The CNR 4 is a 4 component net radiometer that measures the energy balance between incoming short-wave and long-wave Far Infrared (FIR) radiation versus surface-reflected short-wave and outgoing long-wave radiation. The CNR 4 net radiometer consists of a pyranometer pair, one facing upward, the other facing downward, and a pyrgeometer pair in a similar configuration. The pyranometer pair measures the short-wave radiation. And the pyrgeometer pair measures long-wave radiation. All 4 sensors are integrated directly into the instrument body, instead of separate modules mounted onto the housing. Each sensor is calibrated individually for optimal accuracy. [53]

Photo 4. Radiometer on observation tower

3.3 Statistical method

Statistical method mainly contains three parts: calculation of growth rate, calculation of albedo, and Check of Spearman's rank correlation coefficient by SPSS software for finding correlation or significant difference between two groups of data.

3.3.1 Calculation of growth rate

We calculate the daily pure growth as the growth rate with the following formula:

$$s = C_{i+1} - C_i$$

Where: s: the daily growth rate;

C_{i+1}: the circumference of tree in the number of day (i+1);

C_i: the circumference of tree in the number of day.

3.3.2 Calculation of albedo

Albedo is reflection coefficient for sunlight radiation, ranging from zero to one. It characterizes the radio between outdoing radiation and incoming radiation in all wavelengths. Large values of albedo means little radiation absorption while small values of albedo mean large radiation absorption [54]. In this study we focus on the albedo for shortwave radiation. The meaning of studying this kind of albedo is for forest where almost only shortwave radiation can be absorbed and then utilized for photosynthesis. Most of the longwave radiation would be reflected and cannot be utilized for photosynthesis. The albedo for shortwave radiation is equal to outgoing shortwave radiation divided by incoming shortwave radiation, as the following formula shows:

$$albedo = \frac{OSR}{ISR}$$

Where: albedo: reflection coefficient;

OSR: outgoing shortwave radiation, W/m^2;

ISR: incoming shortwave radiation, W/m^2.

3.3.3 Significant difference checking among species

Spearman's rank correlation coefficient is a nonparametric measure of statistical dependence between two variables [55]. As a nonparametric measure, Spearman's rank correlation coefficient can be used as a distribution-free approach for checking statistical dependence between two variables [56-57]. This means it can be applied to both normally and non-normally distributed data. So Spearman's rank correlation coefficient by SPSS software is used in this study for finding whether there is statistical dependence between two groups of data.

4 RESULTS

In this part, daily growth rate of biomass of every sample tree is calculated. And then Spearman's rank correlation coefficient between daily growth rate and values of albedo, temperature as well as relative humidity are checked by software for finding correlation between daily growth rate and these factors respectively.

4.1 General growth trend on all sample trees

Generally, the measuring period started from 9th of December in 2014 to 3rd of September in 2015. The onset of growing season was the beginning of May and cessation of it was the beginning of July, which means that the growing season lasts two months. In the other time, biomass of all samples didn’t show growth trend (Figure 3). So the period which was from 1st of May to 30th of June is extracted as the studying period for biomass growth rate.

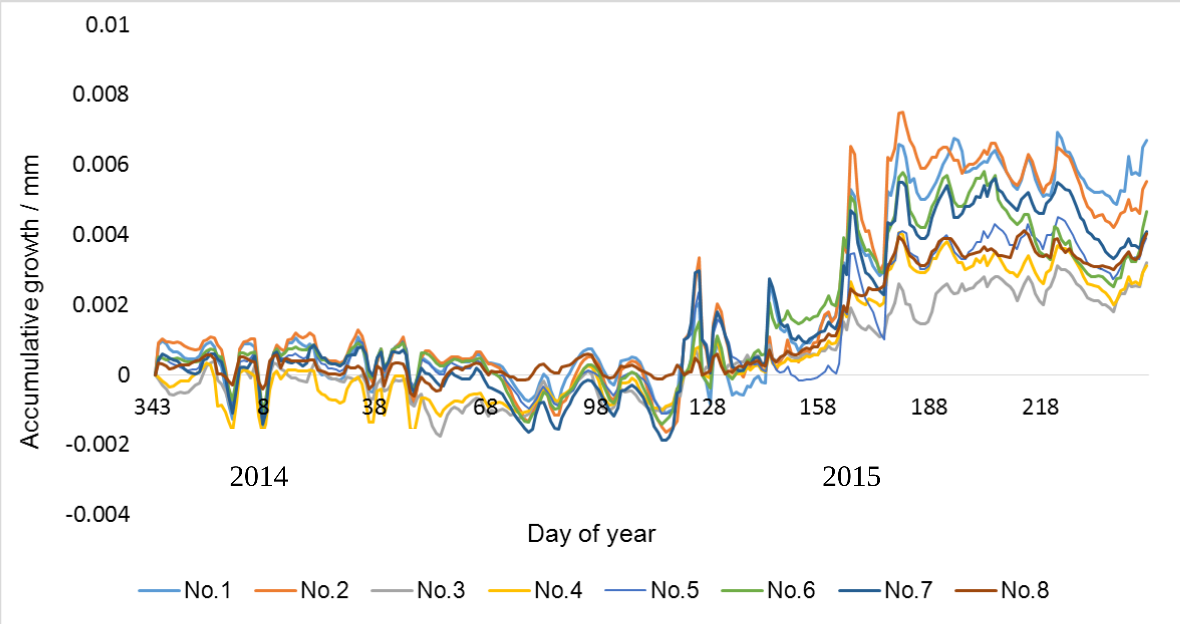

Figure 3. General biomass growth from 9th of December in 2014 to 3rd of September in 2015

Species comparison on growth in growing season:

It is observed that the trend of accumulative growth for Norway spruce in the growing season is flatter than Scots pine’s in the following figure (Figure 4), meaning Scots pine has higher growth rate than Norway spruce during the growing season.

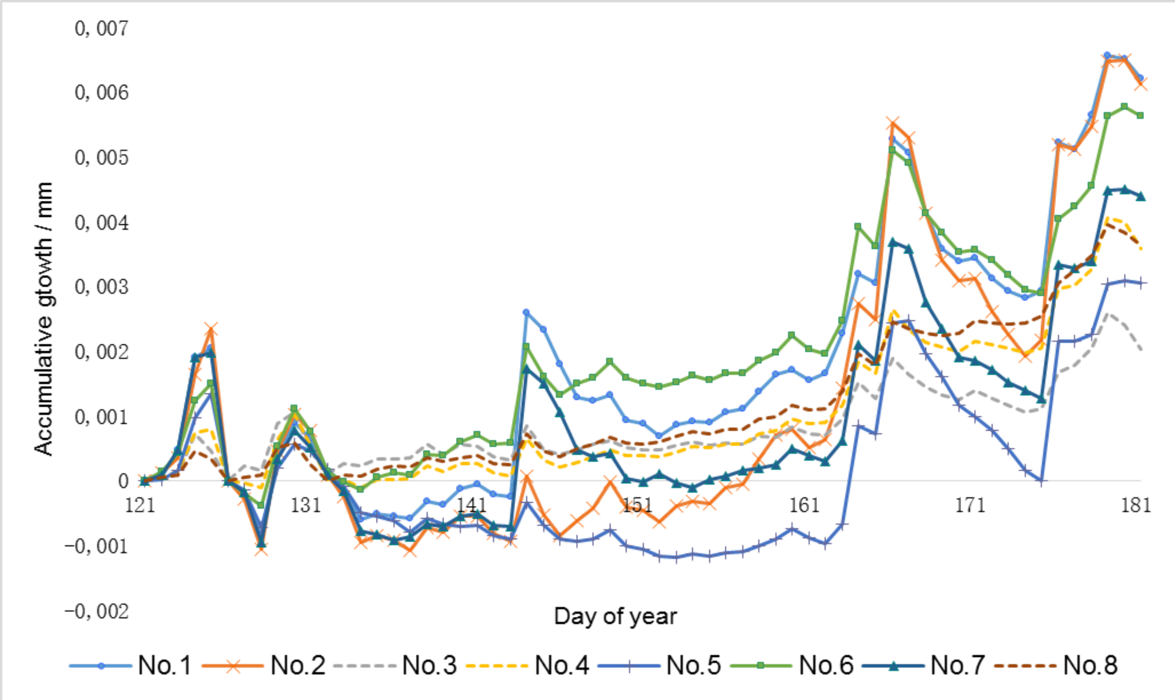

Figure 4. Accumulative growth of all samples from 1st of May to 30th of June in 2015

Spearman’s rank correlation coefficients are checked to find if there is any significant difference between each sample in Norway spruce species and each sample in Scots pine species (Table 1).

Table 1. Spearman's rank correlation coefficient between Norway spruce and Scots pine

	No.1	**No.4**	**No.9**	**No.10**	**No.11**
No.6	0.128	0.076	0.108	0.163	0.032
No.8	0.091	0.063	0.047	0.108	0.017
No.12	0.029	0.016	0.009	0.029	0.001

Spearman's rank correlation coefficients are also checked within the samples in Scots pine species to find if there is any significant difference (Table 2).

Table 2. Spearman's rank correlation coefficient within Scots pine species

	No.1	**No.4**	**No.9**	**No.10**	**No.11**
No.1		0.431	0.431	0.998	0.431
No.4	0.431		0.205	0.431	0.083
No.9	0.431	0.205		0.408	0.887
No.10	0.998	0.431	0.408		0.431
No.11	0.431	0.083	0.887	0.431	

Spearman's rank correlation coefficients are also checked within Norway spruce species to find if there is any significant difference (Table 3).

Table 3. Spearman's rank correlation coefficient within Norway spruce species

	No.6	No.8	No.12
No.6		0.983	0.922
No.8	0.983		0.808
No.12	0.922	0.808	

There is not any correlation found between tree growth rate and temperature as well as relative humidity when the Spearman's rank correlation coefficient are checked which are almost near 0. So the possibility that difference of growth rate between Scots pine and Norway spruce coming from temperature and relative moisture factors can be excluded.

However, Scots pine is more sensitive to albedo variance and this sensibility can be observed in the growing season because the actual growth of Scots pine is more responsive to the albedo variance than Norway spruce after the Spearman's rank correlation coefficient between values of albedo and growth rate of them are checked which will be shown later.

4.2 Trend of albedo

The general trend of albedo from 9th of December in 2014 to 3rd of September in 2015 varied in different period. Values of albedo in winter time are generally higher than the other time. Values of albedo decrease after winter, however the beginning of such decrease didn’t correspond to the onset of biomass growth. The above finding means at least the onset of biomass growth is not due to the decrease of albedo.(Figure 5)

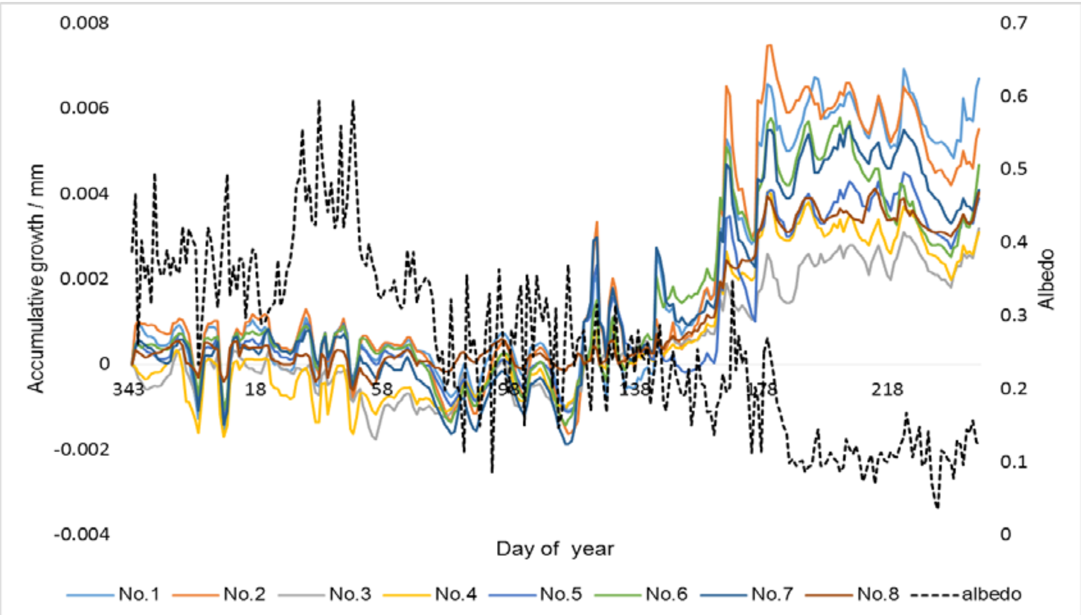

Figure 5. General comparison for values of albedo and accumulative growth from 9th of December in 2014 to 3rd of September in 2015

Relationship between biomass growth rate and the value of albedo：

When values of albedo began to decrease from the beginning of May, as the trend line shows, the accumulative growth began to increase, which also shows the value of albedo may have positive correlation to the growth rate of biomass for both species.

In the studying period, the responses of growth of Scots pine are higher than those of Norway spruce, which has already been demonstrated by checking Spearman's rank correlation coefficient. It is predicted that Scots pine is more sensitive to albedo than Norway spruce and this will be demonstrated by checking Spearman's rank correlation coefficient between values of albedo and biomass growth rate of each species later. (Figure 6)

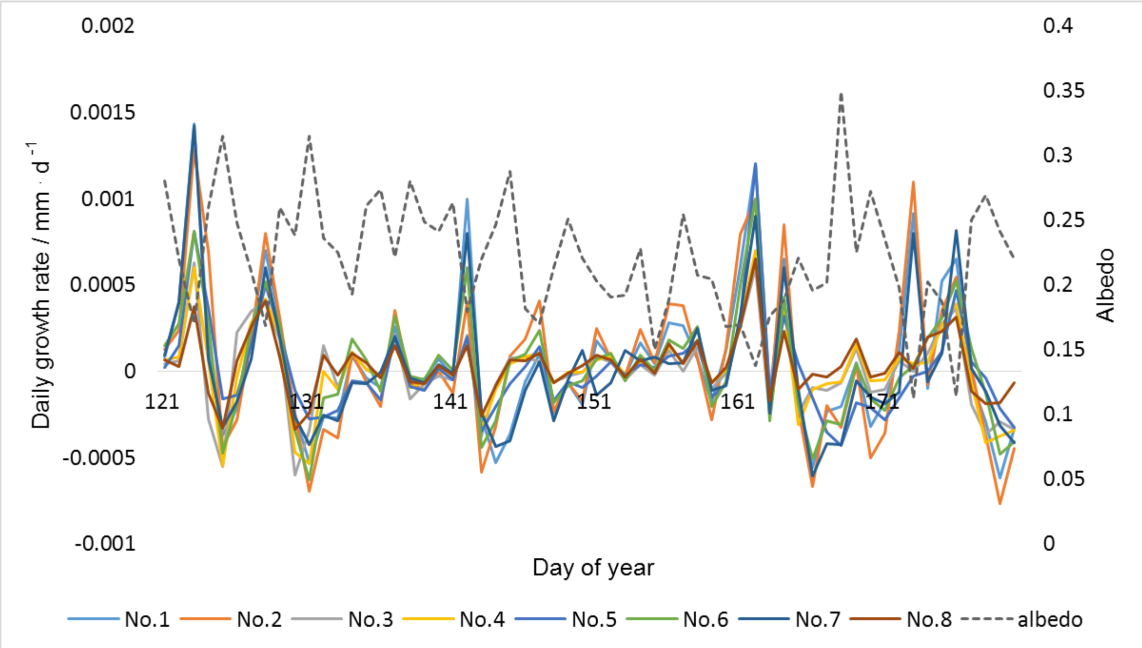

Figure 6. Comparison between daily growth rate and albedo

Some characteristic peaks of albedo are found correspond to valleys of growth rate. This means large values of albedo might be one of the reason that leads to negative growth and there must be other factors leading to negative growth because singly large albedo can only lead to small growth but not negative growth.

What’s more, characteristic valleys of albedo also correspond to peaks of growth rate and this means small values of albedo might be one of the reason that leads to large growth rate.

Whether there is correlation between the albedo and daily growth rate, the Spearman's rank correlation coefficient between them still need to be checked.

Table 4. Pearson coefficient between daily growth rate and albedo

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No.8
Spearman's coefficient	-0.49	- 0.46	- 0.20	- 0.40	- 0.48	-0.46	- 0.47	- 0.36

The Spearman's rank correlation coefficient is checked for finding correlation between the growth rate of each sample and albedo. As the absolute value of Spearman's rank correlation coefficient between -0.4 and -0.6 is thought correlated [58], the correlation is found between the growth rate and albedo for each Scots pine sample tree. For Norway spruce, only the sample No.3 just got the lower limit of the person coefficient range that can be considered as significant related with the value of -0.40. The other two Norway spruces don't show significant correlation between albedo and tree growth rate, with the value of Spearman's rank correlation coefficient -0.20 and -0.36 respectively. This finding means Scots pine is more sensitive to albedo effect compared with Norway spruce, which doesn't show significant growth effect by albedo.

4.3 Trend of temperature

It is noticed that the temperature increased gradually from the beginning of May with the onset of tree growth. The increasing trend of temperature just corresponds to the onset of biomass growth meaning temperature set its lower limit for biomass growth and once temperature surpass this lower limit biomass growth starts. However, whether temperature is correlated with biomass growth rate, the Spearman's rank correlation coefficient between them still need to be checked**. (**Figure 7**)**

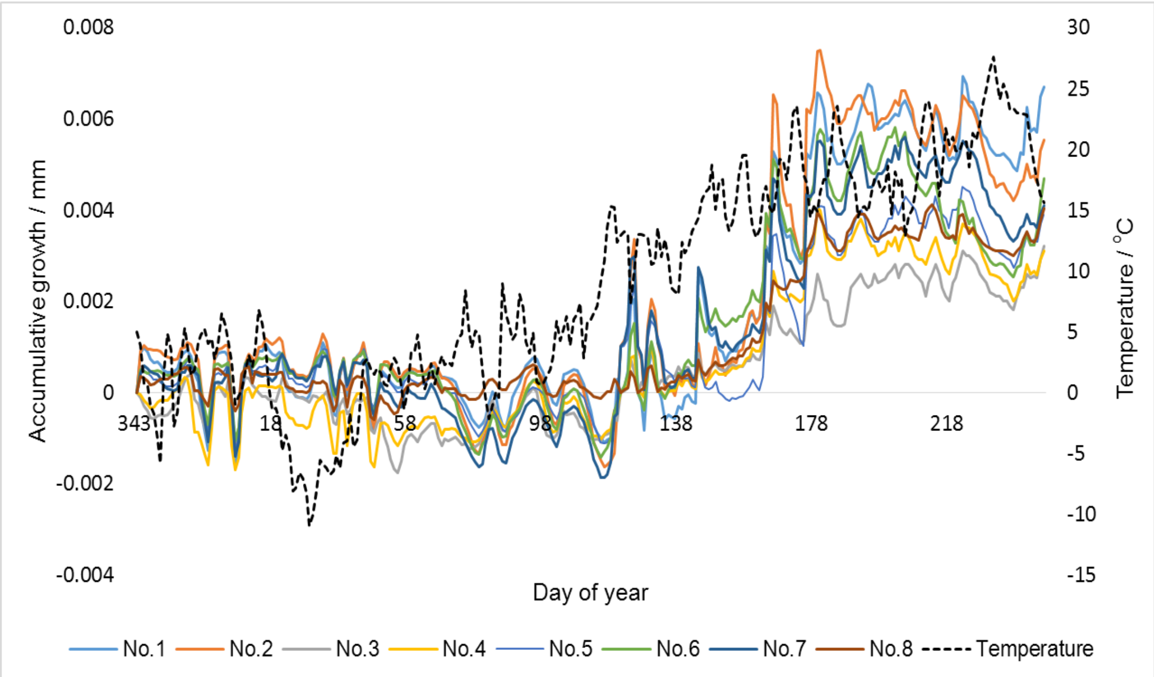

Figure 7. General comparison for temperature with accumulative growth from 9th of December in 2014 to 3rd of September in 2015

Relationship between biomass growth rate and temperature:

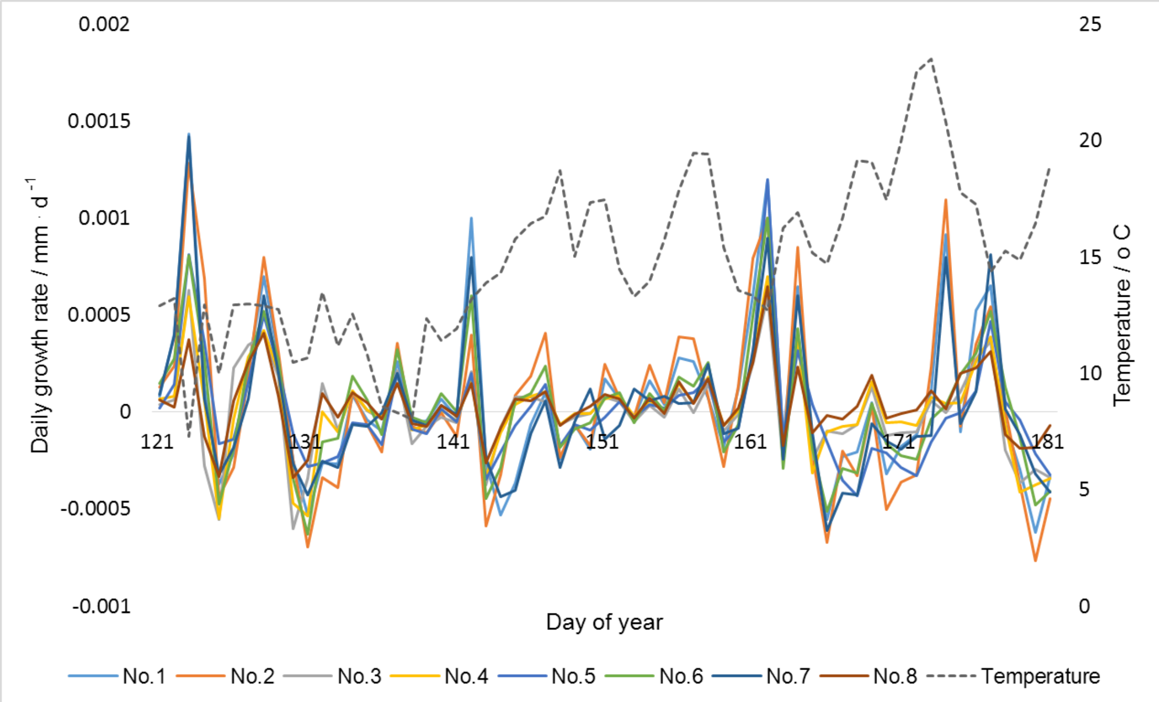

Figure 8. Comparison between daily growth rate and temperature

Similarly, some characteristic peaks of albedo are found correspond to valleys of growth rate. This means high temperature might be one of the reason that lead to negative growth together with large albedo referred before.

What's more, characteristic valleys of temperature also correspond to peaks of growth rate and this means relatively low temperature might be one of the reason lead to large growth rate.

So some extreme temperatures can affect biomass growth rate. (Figure 8)

And then the Spearman's rank correlation coefficient are checked between growth rate and their corresponding temperatures:

Table 5. Pearson coefficient between daily growth rate and temperature

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No.8
Spearman's coefficient	0.00	0.05	0.13	0.04	0.05	0.11	0.04	0.02

The Spearman's rank correlation coefficient between daily growth rate and temperature are all almost zero which shows temperature doesn't have correlation with biomass growth rate.

Based on this checking of Spearman's rank correlation coefficient and general temperature trend from 9th of December in 2014 to 3rd of September in 2015 as well as the graph correspondence between temperature and growth rate, it is assumed that (1) there is no relationship between relative humidity and biomass growth rate generally, (2) but temperature sets the lower limit for biomass growth, (3) what's more, high or low temperature may still affect biomass growth rate.

4.4 Trend of relative humidity

General trend of relative humidity doesn't show significant changes during different period in monitoring period, so relative humidity is not thought as the factor that lead to the onset of biomass growth. However, the correspondences of valleys of relative humidity with valleys of accumulative growth are noticed during the period of late summer (Figure 9).

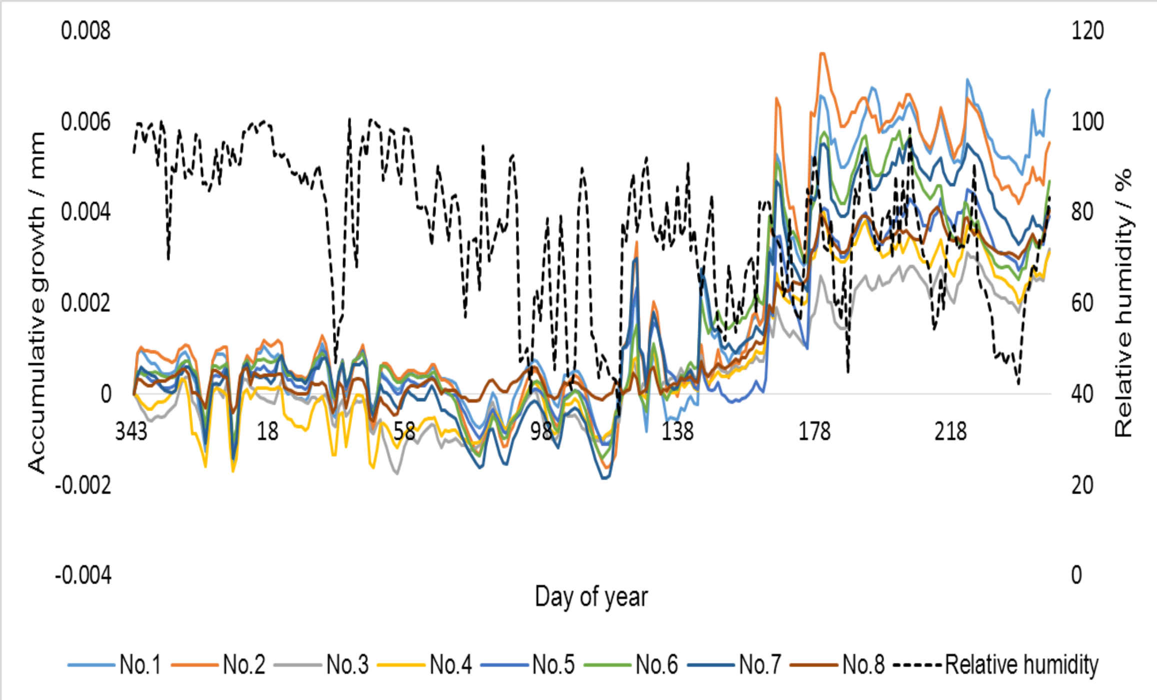

Figure 9. General comparison for relative humidity with accumulative growth from 9th of December in 2014 to 3rd of September in 2015

Relationship between biomass growth rate and relative humidity:

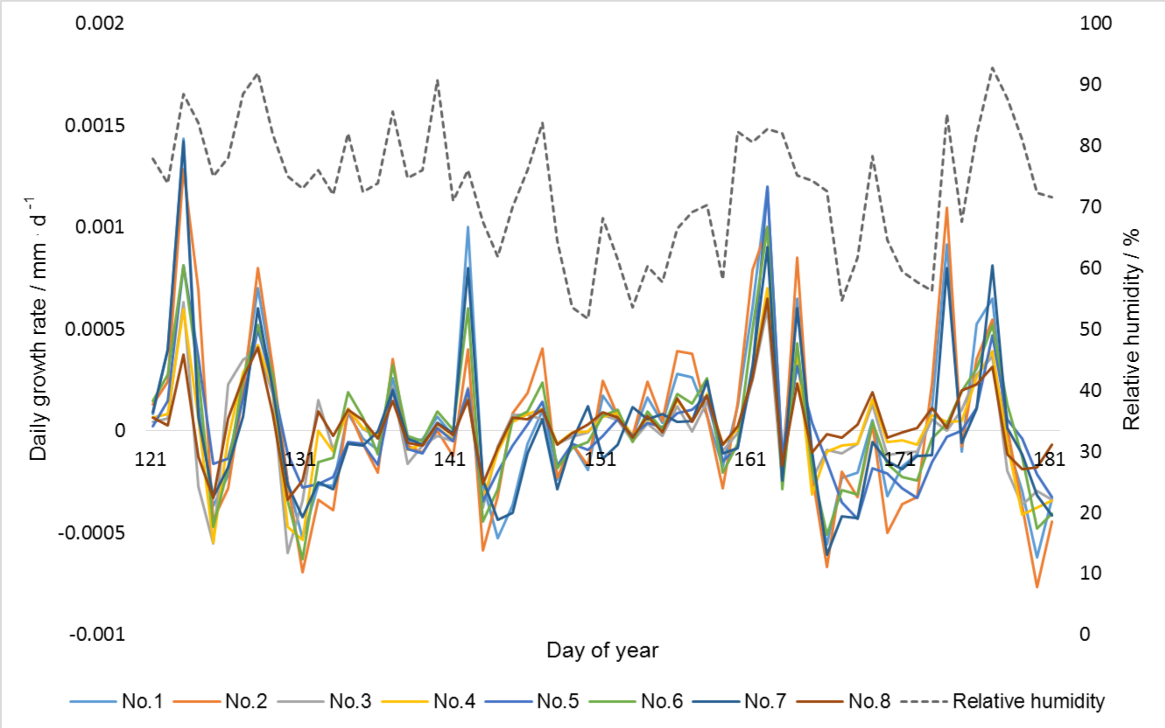

Figure 10. Comparison between daily growth rate and relative air humidity in growing season

Similarly, some characteristic valleys of relative humidity are found correspond to valleys of growth rate. This means low relative humidity might also be one of the reason that lead to negative growth together with large albedo and high temperature referred before.

What's more, characteristic peaks of relative humidity also correspond to peaks of growth rate and this means relatively high relative humidity might also be one of the reason lead to large growth rate.

So some extreme relative humidity can affect biomass growth rate (Figure 10).

Table 6. Pearson coefficient between daily growth rate and relative humidity

	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8
Spearman's Coefficient	0.07	0.08	0.12	0.08	0.20	0.14	0.16	0.18

There is not any correlation found between tree growth rate and relative humidity after checking the Spearman's rank correlation coefficient between daily growth rate and relative humidity.

Based on previous checking for Spearman's rank correlation coefficient and the graph correspondence, it is assumed that there is no relationship between relative humidity and biomass growth rate generally, but high or low relative humidity may still affect biomass growth rate.

5 DISCUSSION

The relationship between albedo which characterizes the quantity of radiation absorption and temperature is critical because it decides whether the glucose produced in photosynthesis can be fully used for biomass growth. The direct effect of temperature on biomass growth rate could be excluded as the Pearson coefficient shown before, so the temperature effect on biomass growth could be attributed as the usage of glucose from temperature variations, and the usage of glucose will lead to the changes on tree growth. When the photosynthetic production is limited and the elevated temperature cannot increase the usage of photosynthetic production anymore. So if stem circumference doesn’t increase with the increase of temperature, it means radiation absorption is relatively unsaturated for temperature. However, if stem circumference increases with the increase of temperature, it means temperature is relatively unsaturated for radiation absorption.

Affecting mechanism would be established. Before that, the effect of relative humidity to biomass growth rate would be discussed. As before found some extreme temperatures may also correspond to lower biomass growth rate and temperature is one of the affecting factor to relative humidity, the correlation between temperature and relative humidity would also be checked. The aim to do this is try to find whether some extreme relative humidity would have effect on biomass growth rate and whether those extreme temperatures affect the biomass growth by leading to extreme relative humidity.

Species-specific difference is another topic discussed in this part. As the Spearman's rank correlation test taken before, the difference of growth rate response between Norway spruce and Scots pine was found and the reason for that would be discussed and revealed.

5.1 Model on relationship between albedo and temperature

The albedo affect the level of photosynthesis and the amount of photosynthetic production and the temperature affect the usage of photosynthetic production. However, the quantitative relationship among them is still not clear. There could be the following two cases:

(1) The value of albedo is relatively low compared with temperature, meaning sunlight radiation is abundant and the photosynthetic production is enough. It cannot fully used by tree. So if temperature doesn’t change, the usage of photosynthetic production keeps the same; and the usage of photosynthetic production will increase if the temperature increases. (Figure 11)

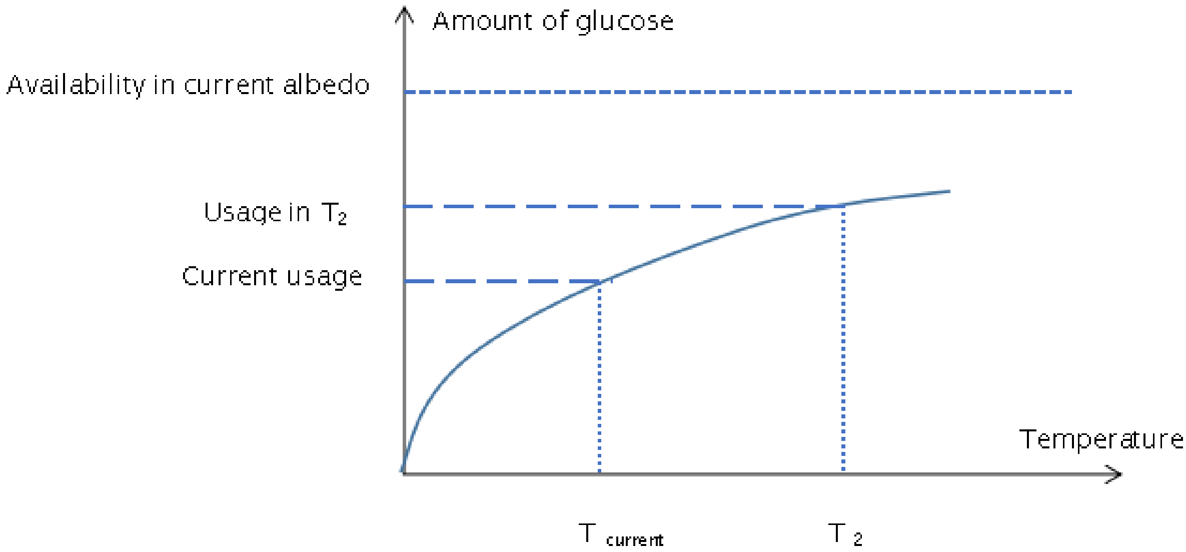

Figure 11. Relationship between actual usage of glucose and temperature in case 1

(2) The value of albedo is relatively high compared with temperature. The photosynthetic production is not enough and it can be fully used by tree. In such a condition, if albedo doesn't change, the increase of temperature is doesn't do any help for more usage of photosynthetic production because the photosynthetic production is fully used and it won't increase when albedo keeps constant. So the higher capacity of using photosynthetic production caused by increased temperature won't lead to more usage of photosynthetic production. (Figure 12)

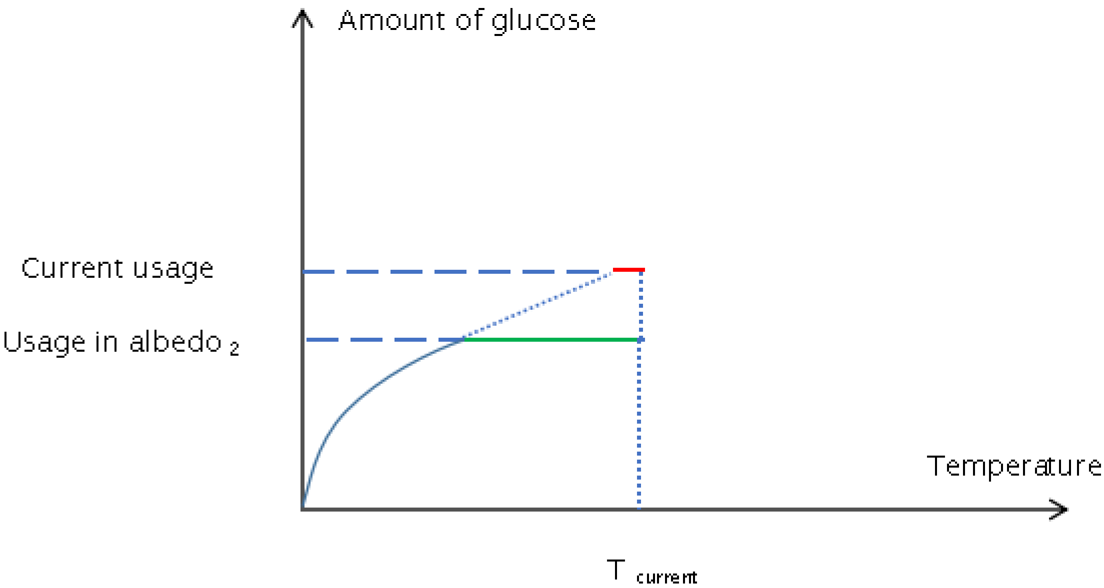

Figure 12. Relationship between usage of glucose and temperature in case 2; albedo2 – the albedo higher than the current albedo

Actually, the existence of the above three cases depends on the correlation between albedo and temperature condition. (1) When albedo is quite high and temperature is relatively low, the first case exists. (2) When albedo is quite low and temperature is relatively high, the second case exists.

5.2 Affecting mechanism by environmental factors

It is found the existence of negative growth in growing season. The growth shouldn't be negative value even the albedo is high and few photosynthetic production was produced for absorption of tree. It surely had evaporation on sapwood water due to relatively high temperature with high values of albedo.

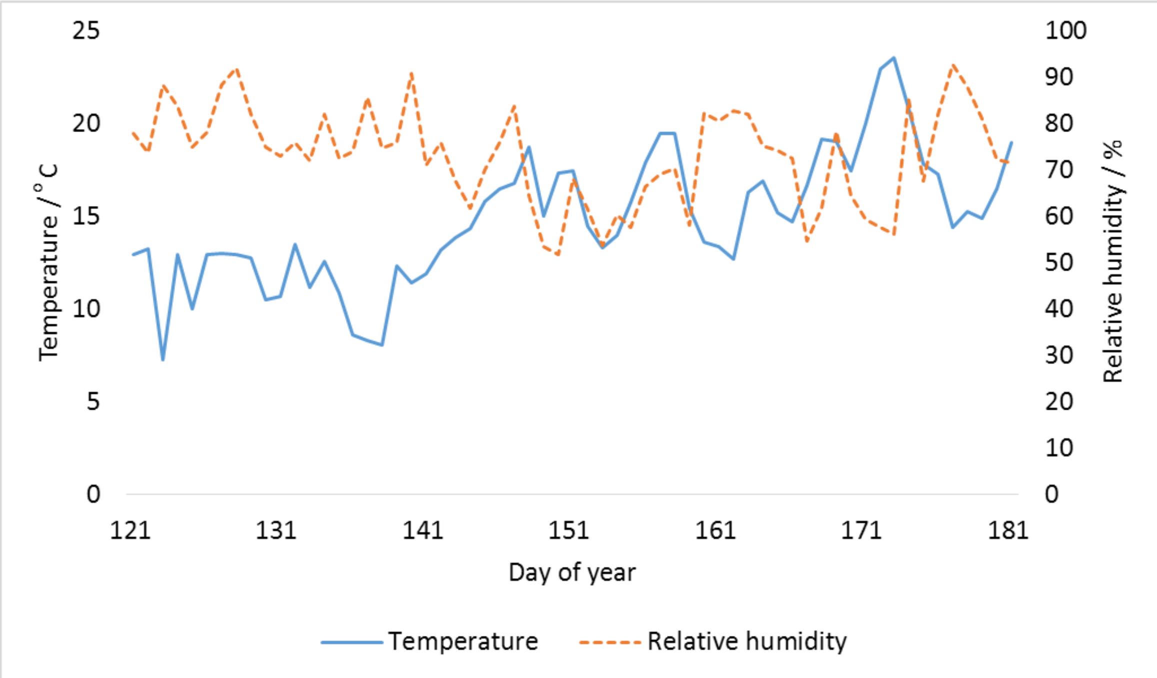

Figure 13. Comparison between temperature and relative humidity

As the above figure shows, relative humidity may have negative correlation with temperature. The Pearson rank correlation coefficient between temperature and relative humidity during the studying period is checked with the value -0.52, meaning relative humidity is negatively correlated with temperature. So once low relative humidity can be attributed as one of the reason that lead to negative growth, high temperature can also be attributed as the reason.

The average value of albedo during studying period is 0.22, the average value of temperature during studying period is 14.79 and the average value of relative humidity is 73.81. It is noticed that, for most of the days with negative growth, their albedo and temperature are beyond average value respectively together with relative humidity which is lower than average value (Table 7) .

Contrarily, for those days with large growth, their values of albedo and temperature are lower than average value respectively while humidity is higher than average value (Table 8).

Table 7. Environmental factors of those days with negative growth

	125	126	130	131	132	133	135	136	138
albedo	0.32	0.25	0.24	0.31	0.24	0.23	0.26	0.27	0.28
temperature	9.98	12.93	10.48	10.66	13.49	11.18	10.84	8.59	8.04
relative humidity	75.87	78.73	75.38	73.63	76.94	71.95	72.39	73.89	74.76
	139	141	143	144	145	148	149	150	153
albedo	0.25	0.26	0.22	0.25	0.29	0.21	0.25	0.22	0.19
temperature	12.35	11.92	14.88	14.33	15.78	18.72	15.02	17.34	13.30
relative humidity	76.47	71.73	67.58	61.77	70.18	64.33	54.70	53.57	61.38
	159	165	167	168	170	171	172	179	181
albedo	0.21	0.27	0.26	0.35	0.27	0.24	0.25	0.25	0.22
temperature	15.42	15.19	16.66	19.14	17.46	19.98	22.95	16.44	17.48
relative humidity	70.20	75.17	**72.50**	61.67	78.31	**59.33**	57.60	72.29	71.52

Table 8. Environmental factors of those days with large growth

	123	128	161	164	174	176	177
albedo	0.17	0.16	0.17	0.18	0.11	0.18	0.11
temperature	12.96	12.91	12.70	16.90	20.80	17.25	14.34
relative humidity	83.74	91.94	82.27	81.96	67.48	81.91	92.72

5.3 Species comparison for response on environmental factors

When checking the Pearson coefficient for ensuring the relationship between the growth rate and albedo, all the Scots pines show the significant relationship with the value of albedo for growth rate while the growth rate of Norway spruces are not significantly correlated with albedo except the No.4 which just get the lower limit that can be considered as significantly correlated. The above finding shows the difference on sensibility of two species to the effect of albedo.

As it was referred before, Scots pine is regarded to have better performance on growth on sites with low availability of nutrient which is related to temperature than Norway spruce [49-50]. And in this study, the temperature is saturated which means it still has space to use more photosynthetic production in this temperature condition, but the problem is the limited absorption of shortwave radiation limits the amount of photosynthetic production. So in this condition, as the second case applied, the availability of nutrients can be thought as 'low'**.** In such a condition where the availability of nutrients is low, Scots pines do behave better than Norway spruces on tree growth rate in growing season, which are significant differences between Scots pines and Norway spruces on growth rate found by checking Spearman's rank correlation coefficient. The finding is in accordance with conclusion made by Heskanen, Makitalo and Berg.

What's more, the initial reason was found for different responses to glucose availability from this research. That is the different sensibilities to albedo of Scots pine and Norway spruce. In the second case applied, all the photosynthetic production produced will be used by tree in that temperature condition. So that explains why the availability of photosynthetic production decides the tree growth rate of different species as Heskanen et al concluded. Furthermore, in the second case, the availability of photosynthetic production is negatively correlated with the value of albedo, the variance trend of albedo can well represent the effect of other factors that may affect the availability of photosynthetic production, which have been well explained in the introduction part. So it is concluded that albedo is the factor that control the availability of nutrient. And the overall logic is: the value of albedo control the availability of nutrient, then the availability of nutrient decides the tree growth rate in the second case where the temperature is 'saturated' for using all nutrient, that's the way tree growth rate is affected by albedo**.** Besides, for different species, Scots pine and Norway spruce for example, have different sensibility to the variance of albedo and albedo affect them differently. In the same environment, the albedo is same for Scots pine and Norway spruce but they are affected by albedo differently and the photosynthetic production is also produced as different amount. The different amount of photosynthetic production produced by Scots pine and Norway spruce are both fully used. So the different usage of photosynthetic production lead to the different growth rate of these two species. Norway spruce is more sensitive to albedo and more photosynthetic production be produced in Scots pine under the same albedo. The more photosynthetic production is used by Scots pine and it shows that tree growth rate is higher for Scots pine than Norway spruce. So it is concluded that the difference of sensibility on albedo of Norway spruce and Scots pine is the reason for the species-specific difference on growth rate in growing season (Figure 14).

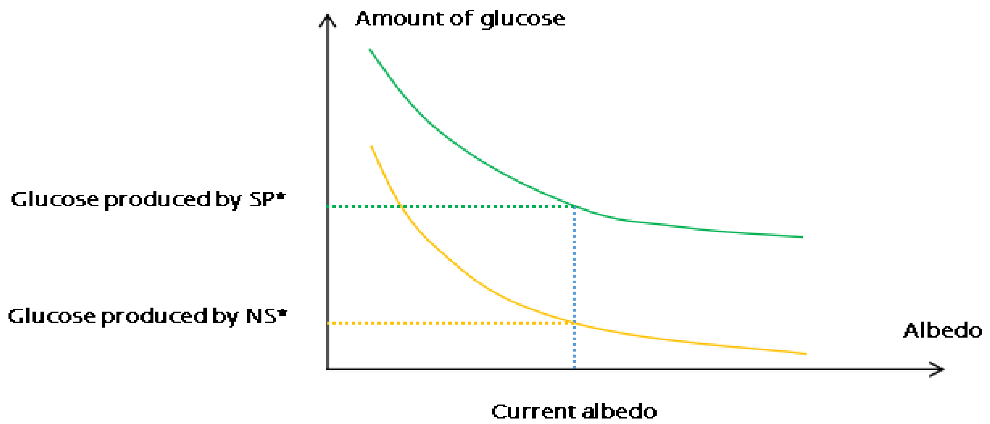

Figure 14. Sensitivity difference on albedo between Scots pine and Norway spruce；SP*-Scots Pine, NS*-Norway spruce

6 SUMMARY

In this study, the affecting mechanism of environmental factors to the growth rate of boreal forests is revealed.

Absorption of shortwave radiation which is characterized by albedo is found as the dominant affecting factor to biomass growth of Scots pine and Norway spruce. Meanwhile, extreme temperature and relative humidity can also affect growth: negative variation can be attributed to large albedo, high temperature together with low relative humidity. Contrarily, large growth can be attributed to small albedo, optimal temperature together with high relative humidity.

The model on the relationship between the values of albedo and temperature for using photosynthetic production in the process of biomass growth is established.

The difference on sensitivity to albedo variance of two tree species, Norway spruce and Scots pine, is found. It can be used for explaining the difference on their growth rate. Scots pine is more sensitive to the shortwave radiation for growth rate. Specifically, for each affecting factor we researched: (1) Albedo dominates the growth rate of biomass. (2) Temperature sets the lower limit for the growth of biomass. It affects the evaporation of sapwood water indirectly by affecting relative humidity. It doesn’t affect the efficiency of absorption to photosynthetic production in this case. (3) Relative humidity directly affects the evaporation of sapwood water which affects the growth rate of biomass temporarily.

Prospects of the research: It is still difficult to distinguish the evaporation of sapwood water from the actual biomass growth and the sampling sites could be increased widely. Besides, how to apply the biomass growth observation into practical air pollution monitoring could be the next research direction.

7 KOKKUVÕTE

Keskkonnaparameetrite ja maapealse biomassi kasvu vahelised seosed boreaalses metsas

Käesolevas uurimustöös uuriti keskkonnategurite nagu õhutemperatuur, õhuniiskus ja albeedo mõju boreaalsete metsade puude kasvule ja tüve ümbermõõdule.

Uuringust selgus, et hariliku männi ja hariliku kuuse biomassi kasvu mõjutab enim albeedo ning temperatuuril ja õhuniiskusel on väiksem mõju boreaalsete metsadele nende vegetatsiooniperioodil. Uurimustöös koostati mudel puude kasvuperioodil toimuva fotosünteesi ja albeedo ning temperatuuri vahel.

Tulemustest ilmnes, et harilik mänd ja harilik kuusk on erineva tundlikkusega albeedo osas. Selle aspektiga on võimalik selgitada nende kasvu erinevust. Harilik mänd on vegetatsiooniperioodil palju tundlikum lühilainelise kiirguse suhtes. Kokkuvõtvalt öeldes: (1) albeedo domineerib biomassi kasvu puhul; (2) biomassi kasvuks on vajalik täita temperatuuri alampiir; (3) Suhteline õhuniiskus mõjutab otseselt maltspuidu vee aurustumist, mis mõjutab biomassi kasvu.

Uuringu väljavaated: on keeruline eristada maltspuidu vee aurustumist tegelikust biomassi kasvust, mistõttu võiks proovivõtukohtade arvu suurendada oluliselt. Kuidas rakendada biomassi kasvu vaatlust praktilise õhusaaste jälgimise osas, võiks olla järgmine uuringu suund.

8 REFERENCES

1. Kruys, N., Fries, C., Jonsson, B.G., Lamas, T. & Stahl, G. 1998. Wood-inhabiting cryptogams on dead Norway spruce (Picea abies) trees in managed Swedish boreal forests. *Canadian Journal of Forest Research* 29(2): 178-186.

2. Aamlid, D., Torseth, K., Venn, K., Stuanes, A.O., Solberg, S., Hylen, G., Christopherson, N., Framstad, E. 2000. Changes of forest health in Norweigian boreal forests during 15 years. *Forest Ecology and Management* 127: 103-118.

3. Burton, P.J., Messier, C., Smith, D.W., Adamowicz, W.L. 2003. Towards Sustainable Management of the Boreal Forest. Ottawa: NRC Research Press. ISBN 978-0-660-18762-4.

4. Pensa, M., Sepp, M., Jalkanen, R. 2006. Connections between climatic variables and the growth and needle dynamics of Scots pine (Pinus sylvestris L.) in Estonia and Lapland. *International Journal of Biometeorol* 50: 205-214.

5. Hordo, M., Metslaid, S. & Kiviste, A. 2009. Response of Scots pine (Pinus sylvestris L.) radial growth to climate factors in Estonia. *Baltic Forestry* 15(2): 195-205.

6. Shorohova, E., Kuuluvainen, T., Kangur, A., Jogiste, K. 2009. Natural stand structures, disturbance regimes and successional dynamics in the Erasian boreal forests: a review with special reference to Russian studies. *Annals of Forest Science* 66: 201p1-201p20.

7. Esseen, P-A., Ehnstrom, B., Ericson, L., Sjoberg, K. 1997. Boreal forests. *Ecological Bulletins* 46: 16-47.

8. Dullinger, S., Dirnbock, T., Kock, R., Hochbichler, E., Englisch,T., Sauberer, N. & Grabherr, G.. 2005. Interactions among tree-line conifers: different effects of pine on spruce and larch. *Journal of Ecology* 93: 948-957.

9. Schmitt, U., Jalkanen, R. & Eckstein, D. 2004. Cambium Dynamics of Pinus sylvestris and Betula spp. in the northern boreal forest in Finland. *Silva Fennica* 38(2): 167-178.

10. Seo, J-W., Eckstein, D., Jalkanen, R., Schmitt, U. 2011. Climate control of intra- and inter-annual wood-formation dynamics of Scots pine in northern Finland. *Environmental and Experimental Botany* 72: 422-431.

11. Rushforth, K. 1987. Conifers. London: Christopher Helm. ISBN 0-7470-2801-X.

12. Rushforth, K. 1986. Bäume. Bern: Hallwag AG. ISBN 3-444-70130-6.

13. Farjon, A. 2005. Pines Drawings and Descriptions of the Genus Pinus. Leiden: Brill. ISBN 90-04-13916-8.

14. James, J.C., Grace, J., Hoad, S.P. 1994. Growth and photosynthesis of Pinus sylvestris At its altitudinal limit in Scotland. *Journal of Ecology* 92: 297-306.

15. Mitchell, A.F. 1974. A field guide to trees in Britain and Northern Europe. New York:

Collins. ISBN 0-00-212035-6.

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

17. Pesonen, E., Mielikainen, K. & Makinen, H. 2004. A new girth band for measuring stem diameter changes. *Forestry* 77: 431-439.

18. Wolter, K.E. 1968. Notes: a new method for marking xylem growth. *Forest Science* 14: 102-104.

19. Yoshimura, K., Itoh, T., Shimaji, K. 1981. Studies on improvement of pinning method for marking xylem growth. II. Pursuit of the time sequence of abnormal tissue formation in loblolly pine. *Mokuzai Gakkaishi* 27: 755-760.

20. Kuroda, K. 1986. Wound effects on cytodifferentiation in the secondary xylem of woody plants. *Bulletin of Wood Research Institute Kyoto University* 72: 67-118.

21. Schmitt, U., Moller, R., Eckstein, D. 2000. Seasonal wood formation dynamic of beech (Fagus sylvatica L.) and black locust (Robinia pseudoacacia L.) as determined by ‘pinning’ technique. *Angewandte Botanik* 74: 10-16.

22. Mäkinen, H., Nojd, P. & Saranpaa, P. 2003. Seasonal changes in stem radius and production of new tracheids in Norway spruce. *Tree Physiology* 23: 959-968.

23. Baucker, E., Bues, C-H. & Vogel, M. 1993. Radial growth dynamics of spruce (Picea abies L.) measured by micro-cores. *IAWA Journal* 19: 301-309.

24. Neher, H.V. 1993. Effects of pressure inside Monterey pine trees. Trees 8: 9-17.

25. Keeland, B.D., Sharitz, R.R. 1993. Accuracy of tree growth measurements using dendrometer bands. *Canadian Journal of Forest Research* 23: 2454-2457.

26. Kozlowski, T.T., Pallardy, S.D. 1997. Growth Control in Woody Plants. San Diego: Academic Press. ISBN 0-12-424210-3.

27. Irvine, J., Grace, J. 1997. Continuous measurements of water tensions in the xylem of trees based on the elastic properties of wood. *Planta* 202: 455-461.

28. Downes, G.M., Hudson, I.L., Raymond, C.A., Dean. G.H, Michell, A.j., Schimleck, L.R., Evans, R.& Muneri, A. 1999. Sampling Plantation Eucalypts for Wood and Fibre Properties. Collingwood: Criso Publishing. ISBN 0-643-06284-X.

29. Abe, H., Nakai, T. 1999. Effects of water status within a tree on tracheid morphogenesis in Cryptomeria japonica D. Don. *Trees* 14: 124-129.

30. Deslauriers, A., Rossi, S., Anfodillo, T. 2006. Dendrometer and intra-annual tree growth: What kind of information can be inferred. *Dendrochronologia* 25: 113-124.

31. Partanen, J., Koski, V. & Hanninen, H. 1998. Effects of photoperiod and temperature on the timing of bud burst in Norway spruce (Picea abies). *Tree Physiology* 18: 811-816.

32. Betts, R.A. 2000. Offset of potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* 408: 187-190.

33. Kirschbaum, M.U.F., Whitehead, D., Deam, S.M., Beets, P.M., Shepherd, J.D. & Ausseil, A.-G.E. 2011. Implications of albedo changes following afforestation on the benefits of forests as carbon sinks. *Biogeosciences* 8: 3687-3696.

34. Tietema, A., Wessel, W.W. 1992. Gross nitrogen transformations in organic layer of acid forest ecosystems subjected to increased atmospheric nitrogen input. *Soil Biology and Biochemistry* 24: 943-950.

35. Olliger, S.V., Richardson, A.D., Martin, M.E., Hollinger, D.Y., Frolking, S.E., Reich, P.B., Plourde, L.C., Katul, G.G., Munger, J.W., Oren, R., Smith, M.-L., Paw U, K.T., Bolstad, P.V., Cook, B.D., Day, M.C., Martin, T.A., Monson, R.K., Schmid, H.P. 2008. Canopy nitrogen, carbon assimilation, and albedo in temperate and boreal forests: Functional relations and potential climate feedbacks. *PNAS* 105: 19336-19341.

36. Seo, J-K., Eckstein, D., Jalkanen, R., Rickebusch, S., Schmitt, U. 2008. Estimating the onset of cambial cativity in Scots pine in northern Finland by means of the heat-sum approach. *Tree Physiology* 28: 105-112.

37. Kirdyanov, A., Hughes, M., Vaganov, E., Schweingruber, F., Silkin, P. 2003. The importance of early summer temperature and date of snow melt for tree growth in the Siberian Subarctic. *Trees* 17: 61-69.

38. Fritts, H.C. 1987. Tree Rings and Climate. New York: Academic Press. ISBN 0 12 268450-8.

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

40. Grace, J., Berninger, F., Nagy, L. 2002. Impacts of climate change on the tree line. *Annals of Botany* 90: 537-544.

41. Harri, P., Arovaara, H. 1988. Detecting CO2 induced enhancement in the radial increment of trees. Evidence from northern timber line. *Scandinavian Journal of Forest Research* 3: 67-74.

42. Luo, Y., Su B., Currie, W.S., Dukes, J.S., Finzi, A., Hartwig, U., Hungate, B., McMurtrie, R.E., Oren, R., Parton, W.J., Pataki, D.E., Shaw, M.R., Zak, D.R.& Field, C.B. 2004. Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide. *BioScience* 54: 730-739.

43. Lundmark, T., Heden, J., Hallfren, J-E. 1988. Recovery from winter depression of photosynthesis in pine and spruce. *Trees* 2: 110-114.

44. Turcotte A., Morin, H., Krause, C., Deslauriers, A., Thibeault-Martel, M. 2009. The timing of spring rehydration and its relation with the onset of wood formation in black spruce. *Agricultural and Forest Meteorology* 149: 1403-1409.

45. Brooks, J.R., Flanagan, L.B. & Ehleringer, J.R. 1998. *Canadian Journal of Forest Research* 28: 524-533.

46. Foley, J., Kutzbach, J., Coe, M. & Levis, S. 1994. Feedback between climate and boreal

forests during Holocene epoch. *Nature* 371: 52-54.

47. Chapin, F.S., McGuire, A.D., Randerson, J., Pielke Sr, R., Baldocchi, D., Hobbie, S.E., Roulet, N., Eugster, W., Kasischke, E., Rastetter, E.B., Zimov, S.A., Running,S.W. 2000. Response of subarctic vegetation to transient climaticchange on Seward Peninsula in north-west Alaska. *Global Change Biology* 6: 211-223.

48. Eugster, W., Rouse, W., Pielke Sr, R., McFadden, J., Baldocchi, D., Kittel, T.F., Chapin, F., Liston, G., Vidale, P.L., Vaganov, P., Chambers, S. Land-atmosphere energy exchange in Arctic tundra and boreal forest: available data and feedbacks to climate. *Global Change Biology* 6: 84-115.

49. Heiskanen, J., Mäkitalo, K. 2002. Soil water-retention characteristics of Scots pine and Norway spruce forest sites in Finnish Lapland. *Forest Ecology and Management* 162: 137-152.

50. Berg, B., Davey, M.P., De Marco, A., Emmett, B., Faituri, M., Hobbie, S.E., Johansson, M.B., Liu, C., McClaugherty, C., Norell, L., Rutigliano, F.A., Vesterdal, L., Virzo De Santo, A. 2010. Factors influencing limit values for pine needle litter decomposition: a synthesis for boreal and temperate pine forest systems. *Biogeochemistry* 100: 57-73.

51. Nilsson, U., Elfving , B., Karlsson, K. 2012. Productivity of Norway spruce compared to Scots pine in interior of northern Sweden. *Silva Fennica* 46(2): 197-209.

52. Ecomatik.2014. Circumference Dendrometer (Type DC3). Retrieved May 27, 2016 from Internet: http://www.ecomatik.de/en/circumference_dendrometer2.php

53. Kipp & Zonen B.V. 2014. CNR4 Net Radiometer. Retrieved May 27, 2016 from Internet: http://www.kippzonen.com/Product/85/CNR4-Net-Radiometer#.V0tu2NR97Dc

54. Wiscombe, W. J., Warren, S.G. 1980. A model for the spectral albedo of snow. I: pure snow. *Journal of the Atmospheric Sciences* 37: 2712-2733.

55. Mayers, J.L., Well, A.D. 2003. Research Design and Statistical Analysis (2nd edition). New Jersey: Lawrence Erlbaum. ISBN 0-8058-4037-0.

56. Gibbons, J.D., Chakraborti, S. 2011. Nonparametric Statistical Inference. Berlin: Springer. ISBN 978-3-642-04897-5.

57. Iman, R.L., Conover, W.J. 1982. A distribution-free approach to inducing rank correlation among input variables. *Communications in Statistics – Simulation and Computation* 11: 311-334.

58. Jerrold, H.Z. 1972. Significance testing of the Spearman's rank correlation coefficient. *Journal of the American Statistical Association* 67: 578-580.

Non-exclusive licence to reproduce thesis and make thesis public

I, Xiaozhou Ye,

(author's name)

1. herewith grant the University of Tartu a free permit (non-exclusive licence) to:

1.1. reproduce, for the purpose of preservation and making available to the public, including for addition to the DSpace digital archives until expiry of the term of validity of the copyright, and

1.2. make available to the public via the web environment of the University of Tartu, including via the DSpace digital archives until expiry of the term of validity of the copyright,

Relationships between Environmental Factors and the Growth of Above-Ground Biomass in Boreal Forest

(title of thesis)

supervised by PhD Kaido Soosaar and PhD Alar Läänelaid

(supervisor's name)

2. I am aware of the fact that the author retains these rights.

3. I certify that granting the non-exclusive licence does not infringe the intellectual property rights or rights arising from the Personal Data Protection Act.

Tartu, **01.06.2016**