

Paul N. Katjutin¹, Natalia I. Stavrova¹, Vadim V. Gorshkov^{1,2}, Andrew Yu. Lyanguzov³, Irina Ju. Bakkal¹ and Sergey A. Mikhailov¹

Radial growth of trees differing in their vitality in the middle-aged Scots pine forests in the Kola peninsula

Katjutin P.N., Stavrova N.I., Gorshkov V.V., Lyanguzov A.Yu., Bakkal I.Ju., Mikhailov S.A. (2020). Radial growth of trees differing in their vitality in the middle-aged Scots pine forests in the Kola peninsula. *Silva Fennica* vol. 54 no. 3 article id 10263. 10 p. <https://doi.org/10.14214/sf.10263>

Highlights

- Unmanaged middle-aged boreal Scots pine forests in the Kola peninsula are characterised by the prevalence of moderately and strongly weakened trees (65–70%).
- Radial increment and basal area increment differ greatly (70–75% and 85–90%, respectively) between Scots pine trees differing in their vitality.
- The trends of annual ring width in Scots pine trees aged from 15–35 to 65–85 years in green moss and green moss-lichen type pine forests are similar; the dynamics of basal area increment differs substantially in relation to forest site type.

Abstract

The research was carried out in unmanaged middle-aged (75–85 years) Northern taiga Scots pine (*Pinus sylvestris* L.) forests in the Kola peninsula. It was established that forests of green moss-lichen and green moss site types are characterised by a predominance (65–70% by stand volume) of moderately and strongly weakened trees. Trees of differing vitality have significant differences in annual increment. Healthy trees had a radial increment (RI) 70–75% greater than that of dying trees, and a basal area increment (BAI) 85–90% greater. The dynamics of the RI and BAI of Scots pine trees for the 70-year period (from 1945 to 2015) is different. The RI of all individuals in the communities studied decreases consistently. The decrease is expressed more strongly in green moss Scots pine forests (80–95% from 1945 to 2015) compared to green moss-lichen forests (60–80%); it manifests itself more in strongly weakened and dying individuals (75–95%) than in healthy and moderately weakened ones (60–80%). Annual basal area increment in green moss Scots pine forests increases by 45–65% from stand establishment until the trees are 25 to 35 years old and subsequently decreases by 50–80% to 70–80 years of age. In green moss-lichen pine forests the BAI of Scots pine remains rather stable in healthy and moderately weakened trees and decreases in strongly weakened and dying individuals by 45% and 75–80%, respectively throughout the studied period.

Keywords *Pinus sylvestris*; basal area increment; radial increment; Northern taiga

Addresses ¹Komarov Botanical Institute of the Russian Academy of Sciences, Professor Popov str. 2, 197376, Saint-Petersburg, Russia; ²Saint-Petersburg State Forest Technical University, letter U, 5, Institutsky per., 194021, Saint-Petersburg, Russia; ³Saint-Petersburg State University, 7/9 Universitetskaya Emb., 199034, Saint-Petersburg, Russia

E-mail paurussia@binran.ru

Received 24 October 2019 **Revised** 9 July 2020 **Accepted** 9 July 2020

1 Introduction

The research concerning the radial growth of trees primarily analyse climatic and anthropogenic factors external to the forest community (Vaganov et al. 2006; Juknys et al. 2014; Vacek et al. 2017). The radial increment of forest-forming conifer trees shows a high ($r=-0.5-0.8$) air pollution sensitivity (Juknys et al. 2014; Yarmishko 2015). Some studies have identified significant relationships ($r=|0.3-0.6|$) between annual ring width and weather in the growing season (Pichler and Oberhuber 2007; Hordo et al. 2011; Helama et al 2012; Vacek et al. 2017). Precipitation deficit and high temperature in spring-summer period result in lowered Scots pine (*Pinus sylvestris* L.) and *Picea abies* (L.) Karst. radial growth in Central Europe, while in Northern Europe the tree rings and the temperature correlate positively. Intra- and inter-specific competition between trees are also important resulting in the differentiation of individuals in terms of growth rate and vitality status (Demidko et al. 2010; Das 2012; Hereş et al. 2018). Several authors found a significant correlation between stem radial growth and main indicators of vitality status of conifer trees such as crown density (Demidko 2011; Cortini et al. 2016; Donnelly et al. 2017) and needle mass (Vanninen 2004). Using *Pinus sibirica* Du Tour as an example, Demidko et al. (2010) showed that the radial increment in strongly weakened individuals at the age of 60 and 140 years is 35% and 65% lower than in healthy ones. The study of the vitality state–radial growth relationships make it possible to predict the loss of tree productivity in relation to healthy trees based on visual assessment. However, this relationship may vary between species and regions. We are currently aware of very few studies, which have examined radial growth of trees differing in their vitality status.

The main objectives of this research are (1) to characterize the vitality structure of middle-aged Northern taiga Scots pine stands; (2) to compare the radial increment and basal area increment in Scots pine trees of differing vitality; (3) to detect the difference in dynamics of radial increment and basal area increment in Scots pine forests in different site types.

2 Materials and methods

2.1 Study area

The research was carried out in the Kola peninsula in Scots pine forests of the green moss-lichen site type *Pinetum hylocomioso-cladinosum* and the green moss site type *Pinetum empetroso-myrtillosum* (Neshatayev and Neshatayeva 1993), corresponding to *Empetrum-Vaccinium* and *Hylocomium-Myrtillus* site types of the Finnish site type classification system (Cajander 1949). The forests were formed after stand-replacing fires between 1920 and 1930. There have been no forestry activities in the study area.

The green moss-lichen and green moss Scots pine forests grow on central and lower hill slopes and on the plains formed by sandy, glacial and aqueoglacial deposits. Typical soil type is Albic Rustic Podzol (Arenic) (World reference base... 2015).

In the study area, the tree stratum includes *Pinus sylvestris* and *Betula pubescens* Ehrh. of post-fire origin with a diameter over 4 cm at breast height (Table 1). The dwarf shrub herb layer is dominated by *Vaccinium vitis-idea* L., *Vaccinium myrtillus* L. and *Empetrum hermaphroditum* Hagerup. The green moss-lichen cover consists primarily of mosses *Pleurozium schreberi* (Brid.) Mitt. and *Dicranum polysetum* Sw., and lichens – *Cladonia stellaris* (Opiz) Pouzar & Vezda, *Cladonia rangiferina* (L.) F. H. Wigg. and *Cladonia mitis* Sandst.

Table 1. Stand characteristics on the permanent study areas (PSA) in the Kola peninsula.

PSA number	PSA size, ha	PSA coordinates	Species	Age, years	DBH, cm	H, m	N, ind. ha ⁻¹	S, m ² ha ⁻¹	V, m ³ ha ⁻¹
Green moss-lichen type									
1 (75)	0.10	67°51'N, 31°23'E	P	70	11.9	11.5	1156	12.9	74.2
			B	no data	7.9	7.7	478	2.3	8.9
2 (90)	0.20	67°51'N, 31°23'E	P	81	17.6	15.0	420	10.2	76.5
			B	no data	4.5	3.6	32	0.05	0.1
3 (91)	0.10	67°51'N, 31°25'E	P	69	15.9	12.0	655	13.1	78.6
			B	no data	7.7	8.2	273	1.3	5.3
Mean value			P	74	15.1	12.8	744	12.1	76.4
			B	no data	6.7	6.5	261	1.2	3.9
Green moss type									
4 (93)	0.20	67°49'N, 31°19'E	P	69	10.9	10.5	3100	29.0	152.3
			B	no data	5.3	6.1	120	0.26	0.8
5 (94)	0.10	67°49'N, 31°19'E	P	70	14.5	14.6	1480	24.6	179.6
			B	no data	6.1	8.4	140	0.41	1.7
6 (99)	0.20	67°49'N, 33°19'E	P	75	15.0	14.2	1420	25.1	178.2
			B	no data	7.3	7.9	320	1.3	5.1
Mean value			P	71	13.5	13.1	2000	26.3	172.3
			B	no data	6.2	7.5	193	0.66	2.5

P – Scots pine; B – pubescent birch; H – height; N – number of individuals; S – basal area; V – volume.

2.2 Measurements

The research was carried out in 6 permanent study areas (PSA), 0.10–0.20 ha of size (3 PSA in the green moss-lichen pine forest and 3 PSA in the green moss pine forest). Core samples were selected from 30–100 Scots pine trees aged 50–85 years (several post-fire generations that form the basis of the stand) at the height of 1.3 m using a Pressler increment borer. Radial increment was measured following standard techniques using a MBS-10 microscope and a semi-automated unit LINTAB-6 accurate to 0.01 mm.

The vitality status of the Scots pine trees was determined in according to recommended practices (Alexeyev 1989; Yarmishko et al. 2003), based on the comparison of crown density with a reference individual assigned the value of 100%. The reference individual is an unsuppressed tree growing under equivalent ecological conditions. The crown density was estimated visually. The final grade was the average of the two definitions. Tree vitality state was evaluated using 5 categories: I – healthy (non-oppressed) trees – relative crown density (CD) >75–100%; II – moderately weakened (moderately oppressed) trees – CD >50–75%; III – strongly weakened (strongly oppressed) trees – CD >25–50%; IV – dying trees – CD >0–25%; V – dry trees.

Vitality distributions of Scots pine were calculated, both by the number of trees and by volume. The volume proportion (%) of trees of any vitality state (P_v) was estimated using the equations:

$$P_v = V_i / V \times 100, \quad (1)$$

$$V = fSH, \quad (2)$$

where V_i is the volume of trees of any vitality state; V is stand volume, $\text{m}^3 \text{ha}^{-1}$; S is stand basal area, $\text{m}^2 \text{ha}^{-1}$; H is average height, m ; f is the coefficient equal to 0.5.

Mean values for radial increment (RI) and basal area increment (BAI) in live *P. sylvestris* trees were calculated according to the method developed by the authors (Lyanguzov et al. 2017), on the basis of the measured values of tree ring widths.

The sequence of annual RI of every tree was presented by a numerical series $P_1 \dots P_n$ (mm) for the period starting from the conditional first year (the first radius R_1) up to the last year. The radii (R) of the rings were calculated by consecutive summarisation $R_1 = P_1$, $R_2 = R_1 + P_2$, $R_3 = R_2 + P_3$, ..., $R_n = R_{n-1} + P_n$ (or a reverse procedure of subtraction from the full radius of the trunk $R_{n-1} = R_n - P_n$...). The area of the circles was calculated consecutively using the formula:

$$S_i = \pi R_i^2 . \quad (3)$$

To calculate the BAI value (dS_i), the smaller circle area was consistently subtracted from the larger circle area:

$$dS_i = S_i - S_{i-1} . \quad (4)$$

For processing and presentation of the results, a script developed by the authors on the basis of free programming language R (R Core Team 2013...) was used. The script handled the following objectives: data presorting; calculation of BAI values of individual trees; grouping of values by the vitality status of trees and time intervals; estimation of parameters for distribution of characteristics with the help of the bootstrap method and construction of graphs.

The dynamics of the radial growth of trees for the 70-year period from 1945 to 2015 was analysed. To reveal the main patterns of change of the explored variables, the dataset values were split to six time intervals (1945–1966–1976–1986–1996–2006–2015). To analyse the results, the bootstrap method was used to estimate the median (nonparametric mean) value of the variable (RI and BAI) and percentiles (2.5, 17, 83, 97.5) in every group. The obtained values were presented graphically in the “box-and-whisker” form. The significance of differences in the variables was evaluated for different groups using the median test (Gibbons and Chakraborti 2011).

3 Results

3.1 The vitality structure of forest stands

In the green moss-lichen and green moss Scots pine forests moderately and strongly weakened individuals predominate by number of stems and volume; the share of strongly weakened trees (38 and 31% by number in green moss-lichen and green moss sites, respectively) is somewhat higher than those of moderately weakened ones (30 and 22%) (Fig. 1). In green moss-lichen forests the proportion of moderately weakened trees in terms of volume (47%) is twice as high as the strongly weakened ones. In the green moss pine forests, most of the stand volume (65%) is equally distributed between moderately and strongly weakened trees. The share of healthy trees in both community types does not exceed 10% by number of stems, but is twice as high in terms of volume. The contribution of dying and dry individuals is 2–2.5 times higher in the green moss Scots pine forests than in the green moss-lichen sites.

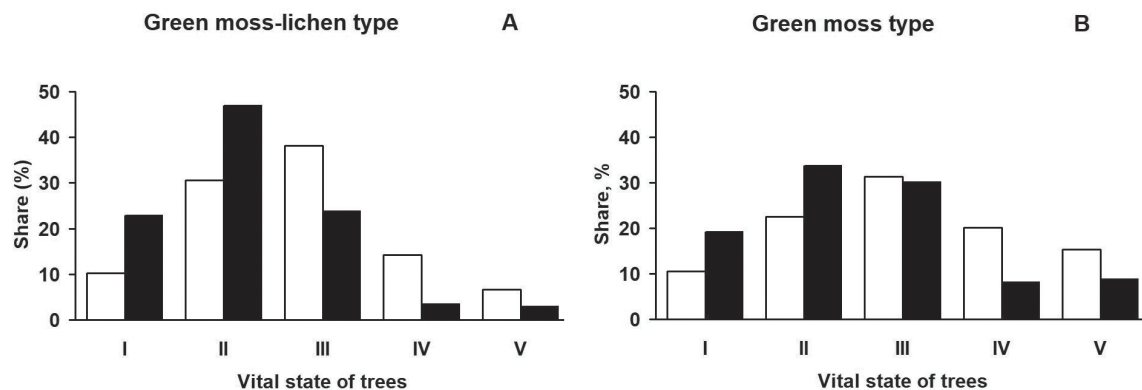


Fig. 1. The vitality distribution of Scots pine trees in the studied communities in the Kola peninsula. White bars – by the number of individuals, black bars – by volume. I – non-oppressed (healthy) trees; II – moderately oppressed (moderately weakened) trees; III – strongly oppressed (strongly weakened) trees; IV – dying trees; V – dry trees.

3.2 Radial increment

In the green moss-lichen forests, the RI of trees of different vitality did not differ significantly, averaging $1.80 \text{ mm year}^{-1}$ (Fig. 2A) at the beginning of the study period. From 1976 to 1986, two groups were distinctly different: the age group 35–55 years consisted of healthy and weakened trees and the group 20–45 years consisted of strongly weakened and dying trees. Subsequently, the difference increased due to the decrease in the RI of weakened trees compared to healthy ones, and after the 2000s, because of differences in the RI of strongly weakened and dying trees.

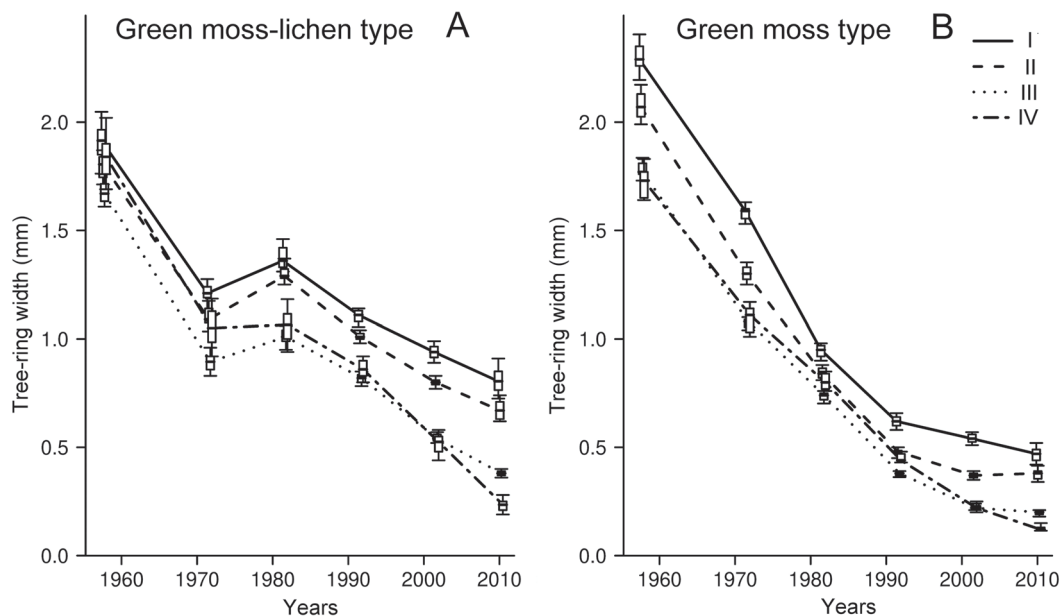


Fig. 2. Dynamics of radial increment (mm year^{-1}) in Scots pine trees of differing-vitality state (I–IV) in green moss-lichen (A) and green moss site type (B) pine forest in the Kola peninsula. I – non-oppressed (healthy) trees; II – moderately oppressed (moderately weakened) trees; III – strongly oppressed (strongly weakened) trees; IV – dying trees. A horizontal line is the median; a box is the interval between 17th and 83th percentiles; whiskers represent the interval from 2.5th to 97.5th percentiles.

During the whole period, RI decreased by 58% (from 1.9 to 0.8 mm year⁻¹) in the trees with no signs of suppression; in the moderately weakened trees, it decreased by 61% (from 1.8 to 0.7 mm year⁻¹), in the strongly weakened ones by 77% (from 1.7 to 0.4 mm year⁻¹). The greatest reduction in RI (ca. 90%, from 1.8 to 0.2 mm year⁻¹) was observed in the dying trees. In the period 2006–2015, the annual RI of dying Scots pine trees aged 50 to 85 years was estimated to be about 70% lower than in healthy trees.

The difference in RI of Scots pine trees of differing vitality in the green moss Scots pine forest was detected from the age of 15–25 years (1955–1966) onwards. Three groups of trees were singled out (Fig. 2B). Significant differences in RI in strongly weakened and dying individuals began to appear only at the very end of the study period. The RI values in healthy and moderately weakened Scots pine trees within that time period decreased by ca. 80% (from 2.0–2.3 to 0.35–0.4 mm year⁻¹); in strongly weakened and dying trees it decreased by an average of 90% (from 1.65 to 0.12–0.2 mm year⁻¹). At the beginning of the observation period, the difference in the annual RI in healthy and dying pine individuals was about 30% and by the end of the period under review it had increased up to about 70%.

The comparison of RI of healthy and moderately weakened Scots pine trees in different forest types has demonstrated that at the beginning of the study period, the values were slightly higher in the green moss Scots pine forests (2.0–2.3 mm year⁻¹) compared to the green moss-lichen ones (1.8–1.9 mm year⁻¹). Strongly weakened and dying trees showed similar values (1.65–1.85 mm year⁻¹). The RI of Scots pine trees decreased more rapidly in the green moss forests being about 50% lower than in the green moss-lichen communities by the end of the study period (Fig. 2).

3.3 Basal area increment

In green moss-lichen forests, the basal area increment (BAI) in healthy, moderately weakened and dying Scots pine trees did not differ at the beginning of the study period and averaged 3.0 cm² year⁻¹. Within the following decade, its value decreased considerably in strongly weakened and dying trees (by 50–60%) and two groups of individuals were singled out (Fig. 3A). Healthy and moderately weakened trees were characterized by an increase of BAI (ca. 20–25%) in the interval between 1965 and 1985 (from 35–40 to 55–60 years), which was followed by a stabilisation period with an average level of 3.5±0.1 cm² year⁻¹. The above-mentioned vitality classes of Scots pine trees showed significant differences in BAI only at the age of 75–85 years (Fig. 3A).

The strongly weakened and dying trees had a stable BAI for the period from 1965 to 1995, averaging 1.2±0.1 cm² year⁻¹. This variable decreased during the subsequent 20 years, more pronounced in the dying individuals compared to the strongly weakened ones (by 60 and 25%, respectively).

By the end of the study period healthy trees demonstrated the maximum BAI (3.9 cm² year⁻¹), which was 30%, 70% and ca. 90% higher than that of moderately weakened (2.8 cm² year⁻¹), strongly weakened (1.1 cm² year⁻¹) and dying individuals (0.5 cm² year⁻¹), respectively (Fig. 3A). Within the study period, a significant reduction of BAI was registered only in the strongly weakened (by 45%) and dying (ca. 85%) trees.

In the green moss forests, Scots pine trees differing in their vitality demonstrated a uniform trend in BAI. This trend consisted of an increase by 45–65% in the first 30 years of the study period, followed by a significant decrease by ca. 45% in the healthy and the moderately weakened trees and by 65–75% in the strongly weakened and the dying ones (Fig. 3B). For most of the study period, BAI was significantly dependent on the vitality state of Scots pine individuals. The BAI in the healthy trees was 65–85% higher than in the dying trees. By the end of the study period, BAI in the Scots pine trees in the green moss pine forest was 35–45% lower than in the green moss-lichen forests.

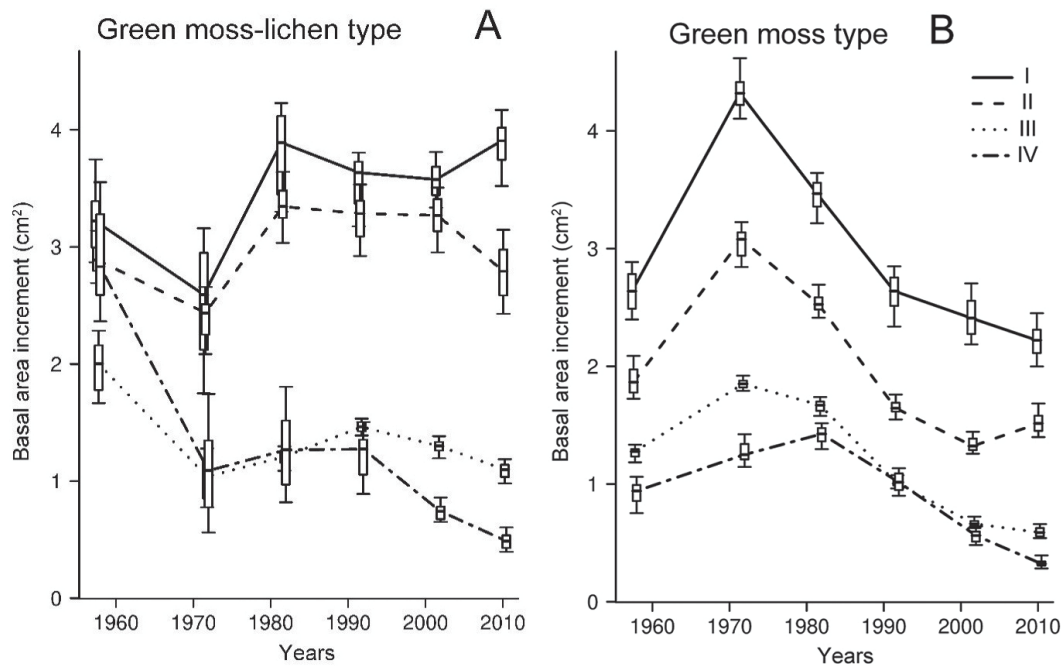


Fig. 3. Dynamics of basal area increment ($\text{cm}^2 \text{ year}^{-1}$) in Scots pine trees of differing-vitality state (I–IV) in green moss-lichen (A) and green moss site type (B) pine forest in the Kola peninsula. I – non-oppressed (healthy) trees; II – moderately oppressed (moderately weakened) trees; III – strongly oppressed (strongly weakened) trees; IV – dying trees. A horizontal line is the median; a box is the interval between 17th and 83th percentiles; whiskers represent the interval from 2.5th to 97.5th percentiles.

4 Discussion

The results of this research will help to fill the information gap on the age dynamics of Scots pine radial growth for this region (Alekshev and Soroka 2002; Yarmishko 2015; Yarmishko et al. 2017).

Scots pine trees of different vitality classes showed significant differences in RI, which increased during the course of the stand development. This fact may be interpreted as an effect of competitive interactions between the individuals. The increased competition results in a prevalence of weakened and strongly weakened individuals in unmanaged Scots pine stands. An analogous phenomenon was observed in other forest-forming species – *Larix sukaczewii* Dylis and *L. sibirica* Ledeb. (Fedorkov 2014), *Pinus sibirica* Du Tour (Demidko 2010), *Picea obovata* Ledeb. and *B. pubescens* (Stavrova et al. 2016).

According to our results, the 60% difference in crown density in non-oppressed and strongly oppressed individuals in Scots pine forests aged 75–85 years led to the 50–60% difference in RI. An analogous result (60–70% difference) was obtained for similar-age Scots pine stands in the upland forests of the Alps (Pichler and Oberhuber 2007). The difference in BAI of non-oppressed and strongly oppressed *Pseudotsuga menziesii* (Mirb.) Franco individuals aged 30–40 years was not so evident (about 30%) (Waring et al. 1980), when compared to Scots pine of the same age in this study (45% on average). The 50% difference in RI for healthy and weakened *Quercus robur* L. individuals in stands aged 30 years (Tulik and Bijak 2016) appeared to be much higher than that of *P. sylvestris* trees of the same age (5–15%). These results give evidence to the view that the ratio between the crown density and stem radial growth has regional characteristics and may depend on the species.

The research has shown the importance of comparing BAI with RI, evidenced not only by the contrast of values, but also by the possibility of revealing differences in temporal dynamics.

A quantitative assessment of the influence of stand density on the radial growth of individuals is of great interest. The differentiation in the RI of Scots pine trees of different vitality status in green moss pine forests appeared approximately 20 years earlier than in the green moss-lichen forests where stand density is 60–65% lower on average. The RI of Scots pine was 45–60% lower in the middle-aged green moss pine forests than in the green moss-lichen communities. Experimental data obtained for Scots pine stands in northern Finland (Varmola et al. 2004) have shown that in the poorer and dryer habitat type analogous, approximately 45–65% RI change takes place across a more considerable (70–90%) range in stand density.

5 Conclusions

Middle-aged Scots pine stands in unmanaged boreal forests are characterised by the prevalence of moderately and strongly weakened trees (65–70%). The proportion of dying and dry trees is higher in the denser green moss Scots pine forests compared to the green moss-lichen communities (respectively 36 and 20%).

Differences in RI and BAI for Scots pine trees of different vitality status in green moss pine forest occur 20 years earlier compared to the green moss-lichen forests. The difference in the RI of healthy and dying 75–85-year-old Scots pine trees is less pronounced (70–75%) than in the BAI (85–90%).

In the two studied forest types, the annual RI of Scots pine trees aged from 15–35 to 75–85 years demonstrates gradual decrease, which is more pronounced in green moss forests (80–90%) compared to green moss-lichen forests (60–85%). The RI reduction is more significant in the strongly weakened and dying trees (by 75–95%) than in the healthy and moderately weakened trees (60–80%).

In contrast to RI, BAI trend is differed in the two forest types studied. In green moss-lichen forests BAI of the healthy and moderately weakened trees increases till the age of 45–65 years (by 20–25%) and thereafter stabilizes; in the strongly weakened and dying trees BAI decreases throughout the studied period (by 45 and 85%). In green moss forests BAI of all Scots pine individuals increases until the age of 45–65 years (by 45–65%) and then decreases by 45–75%.

Acknowledgments

The authors are grateful to anonymous reviewers for their valuable comments and suggestions that helped to improve the manuscript. The work was carried out within the framework of the state task of the Komarov Botanical Institute of the Russian Academy of Sciences (the planned theme №AAAA-A19-119030690058-2) with the involvement of resource RC “Observatory of environmental safety” Saint-Petersburg state University.

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