https://doi.org/10.59893/abud.24(1).005

Acta Biol. Univ. Daugavp. 24(1) 2024
ISSN 1407 - 8953

GROWTH RATE AND PRODUCTIVITY OF NORWAY SPRUCE (*PICEA ABIES* (L.) H.KARST.) PLANTATIONS ON AGRICULTURAL AND FOREST LAND

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Daugaviete M., Zuševica A., Celma S., Vendiņa V., Makovskis K., Dūmiņš K., Štāls T.A. 2024. Growth rate and productivity of Norway spurce (*Picea abies* (L.) H. Karst.) plantations on agricultural and forest land. *Acta Biol. Univ. Daugavp., 2024(1): 47-65.*

Abstract
Norway spruce (*Picea abies* (L.) H.Karst.) as one of the fast-growing and highly productive forest tree species of the northern hemisphere has long been cultivated over vast areas especially in the boreal and hemi boreal forest zone. In Latvia, spruce-dominated stands account for 19% (623 000 ha) of the total forest area. In addition, spruce makes up 30%-40% of tree plantations established on abandoned agricultural lands. With due account for the high proportion of spruce forests and spruce plantation forests on abandoned agricultural lands, the Latvian forest researchers followed up their growth rate on a variety of soil types, comparing different planting densities and considering tending practices. Assessment of productivity in 40 spruce plantations aged 10-50 years on agricultural and forest land shows higher productivity in plantation forests established on agricultural land in terms of growing stock, whereas tree height and diameter does not differ significantly between the land use types. The variation in productivity partially depends on soil and land use type. In plantation forests established on agricultural land biomass partitioning was studied to evaluate potentially obtainable product types (timber and green branches) at different stand ages. On average at 13 years 54% of the trees total biomass consists of green branches and 41% is timber and in 29-year-old plantations timber accounts for up to 65% and green branches comprise 30 to 32% on average.

Keywords: plantation forest, forest stand, annual increment, growing stock, soil type, CO_2 equivalent

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INTRODUCTION

Global wood consumption is expected to grow up to 37% by 2050 due to the increased demand for substitution of non-renewable materials (FAO 2022). There are currently 131 million hectares of plantations of different tree species worldwide, of which conifer plantations account for one third, mainly in the northern hemisphere (FAO 2020). Norway spruce (*Picea abies* (L.) H.Karst.), as a relatively fast-growing tree species capable of producing significant amounts of biomass within a short time, is one of the most important sources of wood and green biomass in the Nordic countries (Jansone et al. 2020). Norway spruce has long been cultivated over large areas, especially in boreal and temperate forest zones. In Latvia, Norway spruce stands cover 19.6% of the forest area and produce about 16% of the total forest stock (CSP 2022). Given the current situation, in the presence of 368 900 ha of uncultivated agricultural land (RSS 2022), some of which has become partially afforested with low-value tree species (*Salix caprea* L., *Celtis occidentalis* L.) and shrubs (various species of willow (*Salix* L.)), there is a potential to establish high-quality plantations of various tree species, including spruce, as well as mixed plantations of spruce and other tree species in these areas. Such land can maintain its agricultural land status if these plantations are grown in the short term, or can be converted to forest land and be further managed as forest (Ministru Kabinets 2012).

In Latvia, studies on the establishment of Norway spruce plantations date back to the 1970s, when foresters responded to the government's call to ensure the balance of spruce pulpwood by supplying around 200 thousand m³ of wood annually. During the evaluation of the progress of spruce growth in plantations, it was established that the average diameter at breast height (DBH) in spruce plantations varies from 6–12 cm at 20 years, 10–15 cm at 30 years and 11–16 cm at 35 years (Jansons 2019).

While in the 1950s spruce was considered a shade-tolerant tree species requiring a cover plant for artificial regeneration, in the 1960s scientists concluded that spruce does well in plantation-type stands in open areas. In the 1960s and 1980s, the main purpose of short-rotation spruce plantations was pulp production. But already in the 1990s, this vision was broadened, and scientists of many countries considered spruce as the most suitable evergreen conifer species for the production of green aboveground biomass, while at the same time being an excellent tree species for carbon sequestration and storage (Mund et al. 2003).

In order to increase the productivity of spruce, extensive research work in the selection and propagation of the most productive and resistant spruce clones, as well as the development of technological schemes for the establishment of short-rotation spruce plantations has been carried out (Rone 1984, Rone 1985, Zeltiņš et al. 2016, Zeltiņš 2017, Zeltiņš et al. 2018). Fertilisation of the stand, selection of the most suitable site and planting density can increase the productivity of spruce plantations by 60%, the use of genetically selected planting material – by 17%, and prompt tending – thinning, stocking – by 8% (Evans 2000, Petrinovic et al. 2009, Man et al. 2013, Zeltiņš 2017, Cekstere et al. 2018, Katrevičs et al. 2018, Zeltińš et al. 2018, Adams et al. 2020, Baders et al. 2020).

Besides potential gains, the decision to establish a plantation must be made considering possible drawbacks. The major concern regarding plantations is ensuring their sustainability (Worrell & Malcolm 1990, E. K. S. Nambiar 1996, Wenk & Vogel 1996, Spiecker 1999, Evans 2000, Mauer & Palátová 2010), since a number of risks exist that can negatively affect the long-term growth and development of monoplantations and/or spruce dominant stands in a certain locations: i.e., 1) climate change (Ciesla & Donaubauer 1994, Cannell et al. 1998, Broadmeadow 2000); 2) the possibility of soil degradation (Dyck et al. 1994, Powers et al. 1994, S.E.K. Nambiar 1996, S.E.K. Nambiar & Ferguson 2005); 3) changes in the agrochemical composition of soil (Rennie 1955, Binns 1962, Goor 1985, Lonsdale & Gibbs 1996); 4) accumulation of plant litter and residues which can lead to changes in soil agrochemical properties (Johansson 1995, Miller 1995, De Noronha et al. 2022); 5) changes in soil mechanical composition driven by different soil preparation practices (Lundmark-Thelin & Johansson 1997), that in turn affects both tree growth (Attiwill et al. 1985, Uotila et al. 2010, Dumins & Lazdina 2018) and understorey vegetation (Uotila & Kouki 2005, Zuševica et al. 2023); 6) potential competition due to the weed infestations (Tonteri et al. 2016); 7) potential of the spread of pests and diseases (Gibson & Jones 1977, Von Sydow 1997, Brūna et al. 2018); 8) damage from intensive plantation management – pruning, silvicultural mechanisms (Dyck et al. 1994, Baders et al. 2017); 9) fire and wind damage (Snepsts et al. 2019); 10) inability to predict plantation growth and development due to a lack of long-term studies (Evans 1984, Spiecker 1999).

In the period from 1975 to 1983, the specialists of the Research and Production Association "Silava" carried out extensive research on the productivity and vitality of spruce stands. Studies have shown that establishing short-rotation forests-spruce plantations is recommended in Latvian conditions, which can increase the harvestable volume by 50–150% at 35–40 years compared to a mature 100-year-old spruce forest stand. Establishing approximately 1,000 ha of short-rotation spruce forests every year was recommended to cover for the wood deficit (Jansons 2019). In 1983, the scientists of the Research and Production Association "Silava" – Rone V., Bisenieks J., Matuzānis J., Ģērķis G., Pelse B., Kariņš Z., Ozols, G., Eglīte A., Špalte E. developed instructions for the establishment of such plantations – short rotation forests (Rone 1982, Rone 1983).

Spruce plantations, which have been established on mineral soils in accordance to guidelines, are currently producing excellent yields. However, in the plantations established on peat soils, many of the requirements provided by the Technical Guidelines were not met, for instance, insufficient drainage of the areas, especially on peat soils, prolonged mineral deficiencies due to lack of fertilization, as well as severe droughts of 2005, 2006, 2007, which dramatically lowered the water table at the root level, and had a significant negative impact on the viability of these spruce plantations. Crown defoliation, yellowing of needles, high insect infestations (*Aphids* spp.) and death of plantations in risk areas were observed in spruce plantations that were established on peatlands.

A study was conducted in Latvia between 2014 and 2017 to investigate the current status of Norway spruce stands of similar age and to develop recommendations for the establishment, tending and obtaining of the product output from such plantations (Brūna et al. 2018, Donis et al. 2018, Jansons 2018, Katrevičs et al. 2018, Lazdiņa et al. 2018, Lībiete et al. 2018). Starting from the 1990s, Latvia began the afforestation of unused agricultural lands. Norway spruce was one of the most commonly planted tree species, which was planted in 42% of the cases (CSP 2022).

The objective of the Study is to assess the growth performance and productivity of intensively cultivated spruce plantations on agricultural and forest land, by carrying out inventory of dendrometric parameters of spruce trees (DBH, cm and tree height, m), as well as to evaluate the dynamic change of aboveground biomass in spruce plantations, carbon sequestration in the above-ground biomass of spruce under different growth conditions.

MATERIAL AND METHODS

Study sites

Spruce stands of more than 10 years of age established on former agricultural or forest lands were selected for the study. For each stand, the following data were recorded: the year of establishment, stand density, forest type and soil type.

Sixteen spruce plantations that were established on agricultural land were surveyed – spruce plantations were of different ages, plantation densities, soil preparation methods (in tranches or without soil preparation) and soil types varied. The plantation forest stands were located in the central part of Latvia (Tab. 1, Fig. 1).

Spruce stands established in five forest types – *Hylocomiosa*, *Myrtillosa*, *Oxalidosa*, *Mercurialiosa mel.*, *Myrtillosa mel.* (Liepa et al. 2014) were selected for this study. These forest types are the most common types for spruce stands according to forest database (Valsts meža dienests 2022). Some stands were of similar age to the Norway spruce plantations on agricultural lands and some were older (Tab. 1). Initial plantation density differed from 2380 up to 6700 trees ha^{-1}, and different planting site preparation methods were used (furrows, mounds, and organised plantations with different trailer route distances). Spruce stands are located in the central and western parts of Latvia (Tab. 1, Fig. 1). For each selected plantation, the following was recorded: year of establishment, area, forest type, planting density and tending operations performed to date.

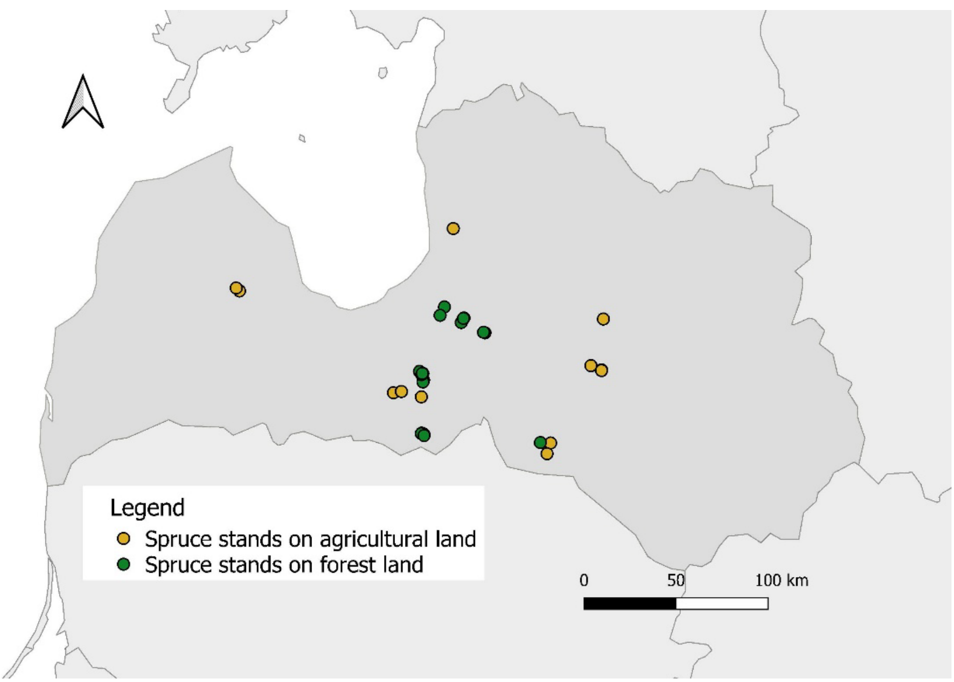

Figure 1. The location of spruce stand study sites across Latvia. Map author: T.A. Štāls.

Table 1. Study sites. The letter "A" in front of the site number represents sites on agricultural land and letter "F" – sites on forest land; soil classification in accordance with Karkliņš, 2008; forest type classification in accordance with Latvian forest typology (Liepa et al. 2014)).

Site no.	Soil type	Forest type	Stand age, years	Initial density, trees ha^{-1}	Current density, trees ha^{-1}
A1	Base-unsaturated brown soil		13	3300	2340
A2	Base-unsaturated brown soil		13	3300	3182
A3	Sod-podzolic soil		13	3300	2860
A4	Strongly altered by cultivation soil		14	2500	2190
A5	Sod-podzolic soil		15	3300	3100
A6	Alluvial sod-gley soil		15	3300	2650
A7	Strongly altered by cultivation soil		15	3500	2005
A8	Fen peat mucky-humus gley soil		24	5000	2590
A9	Fen peat mucky-humus gley soil		25	10000	2565
A10	Fen peat mucky-humus gley soil		26	10000	3475
A11	Sod-stagnogley soil		27	4400	1250
A12	Transitional mire mucky-humus gley soil		27	5000	1000
A13	Fen peat mucky-humus gley soil		27	1300	1965
A14	Fen peat mucky-humus gley soil		29	5000	1665
A15	Sod-podzolic gley soil		29	3300	2070
A16	Gleyic sod-podzolic soil		32	4000	605
F1	Sod podzolic soil	*Hylocomiosa*	10	2500	1595
F2	Gleyic sod-calcareous soil	*Mercurialiosa mel.*	12	2500	1575
F3	Sod-podzolic soil	*Oxalidosa*	13	2500	1855
F4	Sod-podzolic soil	*Oxalidosa*	13	3300	1430
F5	Gleyic sod-calcareous soil	*Mercurialiosa mel.*	14	3300	2064
F6	Gleyic sod-calcareous soil	*Mercurialiosa mel.*	17	5000	2650
F7	Sod podzolic soil	*Hylocomiosa*	18	4400	1630
F8	Sod podzolic soil	*Oxalidosa*	19	5000	1195
F9	Typic raised bog peat soil	*Mercurialiosa mel.*	20	5000	2290
F10	Sod-podzolic soil	*Oxalidosa*	20	3300	1765
F11	Typic podzol	*Myrtillosa*	24	3300	1230
F12	Sod podzolic soil	*Hylocomiosa*	25	3300	1190
F13	Gleyic sod-calcareous soil	*Mercurialiosa mel.*	26	6700	1080
F14	Gleyic sod-calcareous soil	*Mercurialiosa mel.*	27	5000	935
F15	Fen peat humic gley soil	*Myrtillosa mel.*	28	5000	1460
F16	Typic podzol	*Myrtillosa*	29	3300	1230
F17	Gleyic sod-calcareous soil	*Mercurialiosa mel.*	30	5000	2270
F18	Sod podzolic soil	*Hylocomiosa*	30	5000	610
F19	Sod-podzolic soil	*Oxalidosa*	31	5000	1400
F20	Sod podzolic soil	*Hylocomiosa*	32	3300	1560
F21	Sod-podzolic soil	*Oxalidosa*	37	5000	1280
F22	Sod-podzolic soil	*Oxalidosa*	41	5000	1195
F23	Gleyic sod-calcareous soil	*Mercurialiosa mel.*	42	5000	1160
F24	Gleyic sod-calcareous soil	*Mercurialiosa mel.*	50	2380	260

Establishment and surveying of sample plots

Four circular plots (500 m^2, R=12.62 m) were established in each plantation. If the geometry of the area did not allow for four plots to be placed, three plots were established, while in the afforested agricultural lands established in 1997 – all trees were measured. The sample plots were arranged by choosing the most characteristic locations.

The centre of the sample plot was marked with a stake in the field;

In each sample plot:

- all trees were marked, except for 10 to 13-year-old stands with clearly visible planting rows;
- DBH (diameter at 130 cm height, accuracy - up to 1 cm) was measured for all trees, and the Kraft class of the trees was determined;
- tree height of 15 trees (5 in medium, 5 in small, and 5 in large diameter classes) was measured with Vertex III, (accuracy – 10 cm), and in 10 to 14-year-old stands, the trees were measured with measuring tape, accuracy – 0.2 cm;
- the number of fallen trees was recorded, where possible;
- 15 trees were bored at breast height using increment borer to obtain core samples and determine the exact age of the tree and to measure the width of the annual growth by using *WinDendro* software.

Collection of specimen trees in afforested agricultural land

Norway spruce plantations with different planting densities were analysed: 2,500 trees ha^{-1}, 3,300 trees ha^{-1}. Three specimen trees, one from Kraft class I and two from Kraft class II, were felled in each plantation to investigate the growth progress of the spruce: height and DBH, as well as the amount of above-ground biomass were measured. The trees were cut at the root collar, with the north direction registered before cutting. After felling, the height of the tree was measured with tape; the tree was limbed and cut into one-meter-long sections. Specimen trees were weighed on the spot by individually weighing:

- the timber of the trunk;
- dry branches;
- green branches.

Wood samples were collected from each tree and dried in the laboratory – one dry branch, three green branches (from different sections of the crown) and three trunk cross-section discs at different heights. For tree-ring analysis, discs from each tree were collected at 0 m and 1.3 m as well as at the middle of the meter height sections (0.5; 1.5; 2.5 m, etc.) and the north direction were marked on the bottom of each disc. The discs were analysed with *WinDendro 2007* software.

Collection of core samples in plots that were established on forest land

To determine the development of spruce height and average DBH in the forest land plantations, Pressler increment borings were carried out in 10 trees in each plot, selecting three trees from each of the most frequent diameter classes, and three to four trees from adjacent diameter classes. Core samples were analysed with *WinDendro 2007* software.

Methodology for chamber works

Based on the measurement data, the following indicators were calculated for each sample plot in accordance with mathematical formulas in Liepa 1996:

- Number of trees ha^{-1}:

$$N=N_s \cdot 20,$$

where N_s= number of trees in sample plot (500m^2)

- Cross-sectional area (g_{avg}):

$$g_{avg} = \frac{g_1 \cdot n_1 + g_2 \cdot n_2 + ... + g_n \cdot n_n}{n_1 + n_2 + ... + n_n},$$

where g = tree cross-sectional area, n = number of trees

- Average diameter at breast height (DBH_{avg}) of the stand:

$$DBH_{avg} = \sqrt{4 \cdot g_{avg}/\pi},$$

- Growing stock volume m^3 ha^{-1} (V):

$$V = \psi \cdot h^{\alpha} \cdot d^{\beta \cdot lg + \varphi},$$

where ψ, α, β, φ – capacity coefficient determined by tree species

- Current annual increment of DBH, cm a^{-1} (Z_{DBH}):

$$Z_{DBH} = 2iu,$$

where i = average 5-year period tree ring width (mm), u = bark thickness coefficient

- Current annual increment of the tree height, m a^{-1} (Z_H):

$$Z_H = \frac{2iH(aDBH+b)}{cDBH+100},$$

where H = average tree height (m), a=-0.0256, b=1.69, c=5.794

- Current annual growing stock volume m^3 ha^{-1} a^{-1} (Z_M):

$$Z_M = k \cdot g \left(\frac{2Z_{DBH}(H-2Z_H+4)}{10DBH+Z_{DBH}}\right) + Z_H,$$

Data analysis

Mathematical processing of data and calculation of reliability, calculation of means and standard errors were carried out in accordance with mathematical statistical methods using Microsoft Office Excel 2003 and SPSS software Arhipova & Bāliņa 2006). R and generalized linear models were used to determine factors (land use type, soil type, stand density, age) significantly affecting growth variables (DBH, height, growing stock, current annual increment (CAI) of DBH, CAI of height and CAI of growing stock) (Core Team 2021). Factor significance in the model was estimated by ANOVA and best models were determined based on AIC values.

RESULTS AND DISCUSSION

The results demonstrate that in young stands of the same age, DBH is higher on agricultural land compared to forest land, for instance in 13-year-old spruce plantations on agricultural land DBH = 9.1 cm (Tab. 2, Sites: A1; A2; A3), but on forest soil DBH = 4.9 cm (Tab. 2, site: F3 and F4.) (Fig. 2). Whereas in 14-year-old stands these differences are minor. In older stands, the mean DBH of spruce on agricultural land and forest land does not differ so drastically, mainly due to higher variation among forest stands. When comparing the slopes of regression lines for DBH of stands grown on forest land and agricultural land, there is no significant difference. Yet the high variation in forest stands suggests that establishing a plantation forest on agricultural land leads to more predictable yields.

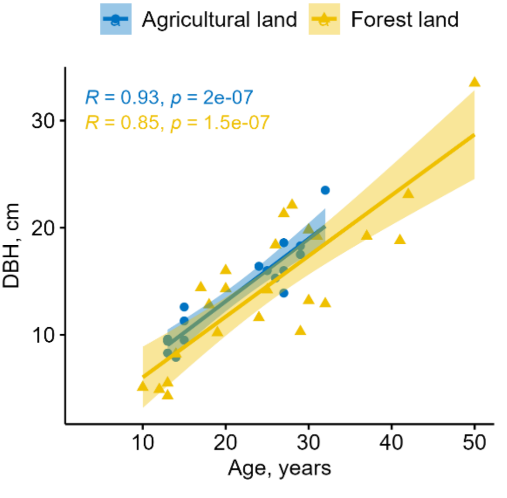

Figure 2. Average diameter at breast height (DBH) depending on stand age in spruce stands on agricultural land and forest land.

Table 2. Growth parameters of the studied sites. Site numbers with "A" are sites on agricultural land, and with "F" – on forest land. SPG – Sod-podzolic gley soil, SAC – Strongly altered by cultivation soil, BNB – Base-unsaturated brown soil, FPMHG – Fen peat mucky-humus gley soil, SP – Sod-podzolic soil, ASG – Alluvial sod-gley soil, SSG – Sod-stagnogley soil, TMHG – Transitional mire mucky-humus gley soil, GSP – Gleyic sod-podzolic soil, GSC – Gleyic sod-calcareous soil, TRBP – Typic raised bog peat soil, TP – Typic podzol; CAI– current annual increment.

Site no.	Soil type	Stand age, years	DBH, cm	Average tree height, m	Growing stock, m^3 ha^{-1}	CAI of DBH, mm	CAI of the tree height, m	CAI of growing stock volume, m^3 ha^{-1} a^{-1}
A1	BNB	13	9.4	7.4	53.0	18.4	1.22	7.76
A2	BNB	13	8.3	6.4	42.8	16.74	1.06	5.51
A3	SP	13	9.6	9.1	82.6	6.94	0.58	7.42
A4	SAC	14	7.9	7.4	42.9	12.34	0.91	10.27
A5	SP	15	9.5	7.4	97.0	9.12	0.60	20.98
A6	ASG	15	12.6	7.7	87.4	7.68	0.45	15.76
A7	SAC	15	11.3	10.0	82.6	15.9	1.26	13.04
A8	FPMHG	24	16.4	16.5	386.9	5.27	0.54	17.84
A9	FPMHG	25	16.0	14.5	274.7	7.74	0.71	19.21
A10	FPMHG	26	15.3	14.6	286.5	9.62	0.93	24.90
A11	SSG	27	13.9	12.8	117.3	7.04	0.71	17.32
A12	TMHG	27	16.0	14.8	142.6	6.0	0.68	18.97
A13	FPMHG	27	18.6	16.5	306.2	8.16	0.75	20.64
A14	FPMHG	29	17.5	17.2	328.5	6.69	0.68	22.53
A15	SPG	29	18.3	17.3	369.7	5.23	0.51	18.33
A16	GSP	32	23.5	20.2	259.0	5.15	0.46	15.82
F1	SP	10	5.1	4.8	10.2	6.84	0.39	2.57
F2	GSC	12	4.9	4.2	9.8	6.66	0.33	2.41
F3	SP	13	4.3	4.0	7.5	5.53	0.27	1.59
F4	SP	13	5.5	4.6	11.4	6.91	0.36	2.76
F5	GSC	14	8.2	6.6	37.3	8.41	0.53	8.32
F6	GSC	17	14.4	11.6	203.2	5.58	0.45	18.28
F7	SP	18	12.8	12.8	111.8	3.74	0.36	8.06
F8	SP	19	10.2	6.5	39.3	3.02	0.17	2.92
F9	TRBP	20	14.3	13.0	209.6	7.20	0.65	23.66
F10	SP	20	16.0	13.8	219.9	6.91	0.61	15.40
F11	TP	24	11.6	10.1	55.0	4.47	0.36	5.26
F12	SP	25	14.2	13.3	123.2	4.37	0.40	9.72
F13	GSC	26	18.4	15.4	213.8	4.74	0.41	15.18
F14	GSC	27	21.3	18.4	287.3	6.73	0.60	23.94
F15	FPMHG	28	22.1	20.3	421.8	3.41	0.33	17.79
F16	TP	29	10.3	8.8	44.9	3.65	0.27	3.97

F17	GSC	30	13.2	12.7	175.6	3.72	0.35	12.12
F18	SP	30	19.8	18.1	154.4	3.69	0.31	4.53
F19	SP	31	19.2	19.4	346.3	3.64	0.38	15.77
F20	SP	32	12.9	11.2	110.8	2.84	0.47	7.79
F21	SP	37	19.2	18.1	277.7	3.42	0.34	13.33
F22	SP	41	18.8	19.3	352.0	2.96	0.32	14.43
F23	GSC	42	23.1	24.5	563.0	2.62	0.29	14.43
F24	GSC	50	33.5	27.3	262.73	4.04	0.30	7.21

The tree height is tightly related to DBH and thus also demonstrate similar tendencies. Age was the only significant factor affecting height (P <0.01) and DBH (P <0.01). Land use type, soil type and stand density did not have a clear significant effect. Our results are similar to those of previous studies, where average tree height depended on the site index and varied between 6–11 m at 20 years, 10–16 m at 30 years and 11–17 m at 35 years (Bisenieks 1976, Rone 1982).

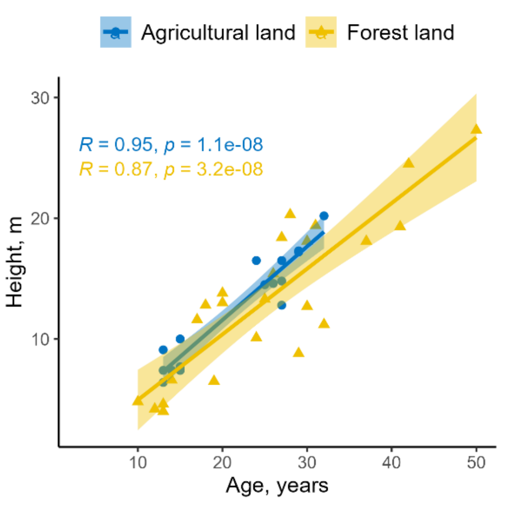

Figure 3. Average tree height depending on stand age in spruce stands on agricultural land and forest land.

The DBH and height were measured for trees in Kraft classes I, II and III, which could contribute to the lack of clear difference in these parameters between land use types, however, the growing stock was calculated including trees from all five Kraft classes. There is a trend of bigger growing stock in stands established on agricultural land, but the difference is not significant during the 32 years of growth. Yet in glm models growing stock was best explained by age and soil type, where only age had a significant (P <0.01) effect on the growing stock. Stand age as the determining factor of growing stock as well as tree height and DBH is expected. Stands on fen peat mucky-humus gley soil (FPMHG) and sod-podzolic gley soil (SPG) had the highest growing stock (Tab. 2.).

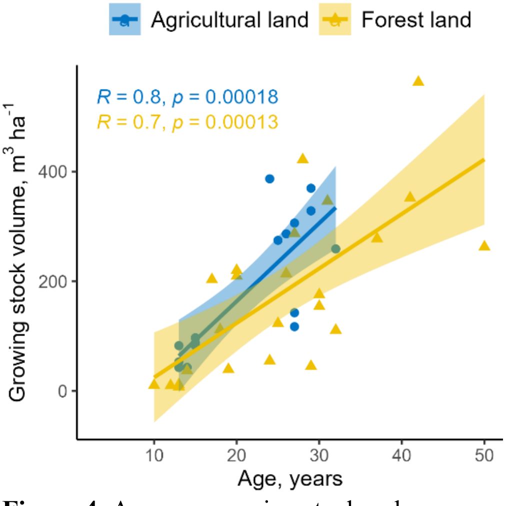

Figure 4. Average growing stock volume depending on stand age in spruce stands on agricultural land and forest land.

However, if current annual increments are considered, there is a clearer difference between plantations on agricultural land and stands on forest land. CAI of DBH depended on soil type, stand age (P<0.01) and was significantly lower in on forest land than on agricultural land ($P<0.01$). CAI of height depended on soil type and on land use type ($P<0.01$). CAI of growing stock was affected by age ($P<0.01$) and land use type ($P=0.01$) as well as land use type and current density interaction ($P=0.02$). There was a weak positive association between CAI of growing stock and current stand density in stand on forest land, yet there was no association between CAI of growing stock and current stand density on agricultural land. Stands on agricultural land had significantly higher CAI of growing stock. Promoted growth on agricultural land is confirmed by studies of other researchers as well (Donis et al. 2018, Jansons 2018, Katrevičs et al. 2018, Lībiete et al. 2018, Jansone et al. 2020). However, it should be noted that in spruce plantations growing on forest soils, stock thinning has been carried out up to the age of 30 years, therefore, this current growing stock volume may decrease.

According to results CAI of DBH and height were higher on strongly altered by cultivation soil (SAC), typic raised bog peat soil (TRBP) and base-unsaturated brown soil (BNB). However, the limitations of the study design need to be considered, as the representation and adequate coverage of all soil types and all ages is not attainable. Spruce plantation forests on agricultural land have the potential to produce high stock and thus it has high economic efficiency as soon as it reaches 20 to 30-year age (Fig. 5). Trials have shown that spruce plantations on agricultural land can produce the first stock as early as at the age of 24 years – up to 386.9 m^3 ha^{-1}, with current annual increment of growing stock volume of up to 17.8 m^3 ha^{-1} a^{-1} (Tab. 2). Spruce stands on forest soils show high growing stock volume in 27- and 28-year-old stands on gley-sod carbonate soil – 287.3 m^3 ha^{-1} and 421.8m^3 ha^{-1}, while the current annual increment of growing stock volume is – 23.9 m^3 ha^{-1} a^{-1} and 17.8 m^3 ha^{-1} a^{-1} (Tab. 2).

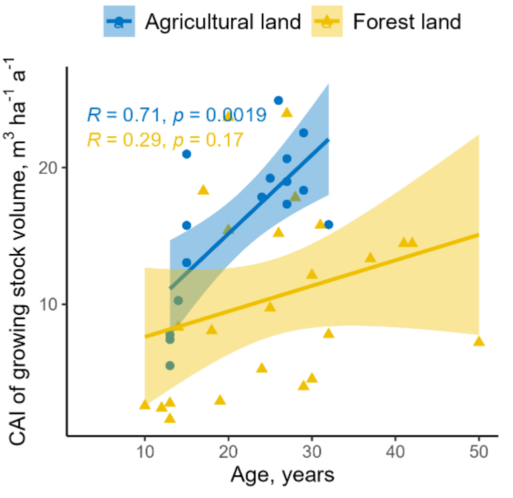

Figure 5. Current annual increment of growing stock volume depending on stand age in spruce stands on agricultural land and forest land.

Besides overall stand productivity, the evaluation of produced biomass type was one of the aims of the study. The results demonstrate that on average in a 13-year-old spruce plantation forest 54% of the total biomass are green branches and 41% is stem wood (timber), while in 29-year-old plantation forest timber accounts for up to 65% of the total biomass and green branches for 30 to 32% on average (Fig. 6). This ratio is expected to increase with stand age. Total biomass production was extrapolated based on three to seven well grown (Kraft class I and II) trees per each age group, therefore it must be taken critically, as it considerably exceeds the growing stock estimates based on tree height and density (Tab. 2.), where five Kraft classes were considered (Fig. 4.).

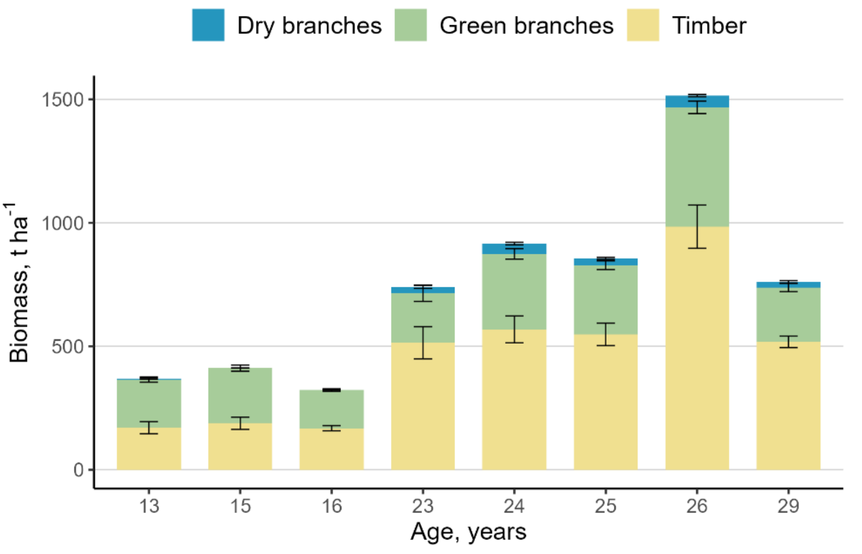

Figure 6. Spruce plantation biomass depending on age of plantation.

Studies of previous years have led to the conclusion that spruce plantation forests can play a significant role in CO_2 sequestration and production of green biomass and timber, thus, having the potential to increase both economic and environmental benefits of areas that are not used for agriculture (Kreismane 2015, Daugaviete et al. 2017, Daugaviete et al. 2020). In a sustainably managed forest, carbon accumulation never stops as new trees replace those that are cut down: the carbon is fixed in the felled tree–like in a carbon "store" – but young stands are highly productive in sequestering CO_2 (Lundmark et al. 2016, Pukkala 2017). In the 1.59 million ha of forests managed by Latvian State Forests (LVM 2024), 4.1 million tonnes of carbon, or 15 million tonnes of CO_2 equivalent, are sequestered annually as the forest grows, while the total accumulation in living biomass, of all forests managed by LVM, is 123 million tonnes of carbon, or 450 million tonnes of CO_2 equivalent (the conversion factor from carbon to carbon dioxide is 3.67) (Lazdiņš 2012). The scientist of Latvian State Forest Research Institute (LSFRI) "Silava", conducted an extensive literature analysis, evaluating the results of 31 research studies on carbon content changes between different regions worldwide, in coniferous and deciduous groups of trees, and concluded that regardless of climatic region, the carbon content in the timber of conifers (50.8 ± 0.7%) is significantly higher than in the timber of deciduous trees (47.7 ± 0.3%) (Liepiņš 2020). Upon the evaluation of data, it was suggested that, since there is still no conclusive information on the wood carbon content that should be used in the hemiboreal forest zone, the mean values of carbon content in coniferous and deciduous trees are 50.8 ± 0.6% and 48.8 ± 0.6%, respectively, which were recommended by S. Thomas and A.R. Martin for the temperate and boreal zones, respectively (Thomas & Martin 2012).

Data obtained in this study fits well with previously obtained knowledge that average tree height depends on the site index and varies between 6–11 m at 20 years, 10–16 m at 30 years and 11–17 m at 35 years. Yet the estimated stock in spruce plantations varies and by other authors has been estimated to be 170 m^3 ha^{-1} (60–170 m^3 ha^{-1}) at 20 years, 290 m^3 ha^{-1} (150–290 m^3 ha^{-1}) at 30 years and 320 m^3 ha^{-1} (190–320 m^3 ha^{-1}) at 35 years (Bisenieks 1976, Rone 1982). Studies have demonstrated that the growth rate of spruce plantations established on agricultural land at the age of a young stand corresponds to the parameters of site index rating (Ia) and covers an area of 18,046 ha over 10 years (2013-2022) (CSP 2022). This means that the timber stock from existing plantations could increase from 3.07 million m^3 at the age of 20 to 6.68 million. m^3 at the age of 50 years (Tab. 3), which could lead to an economic increase from 224 million EUR to 487 million EUR, if the average price of spruce sawlogs reaches 73 EUR m^3 (56-90 EUR m^3); ('Inčukalns Timber' n.d.). Additionally, the projected carbon sequestered in spruce plantation forests established in the period from 2013 to 2022 at the wood stock of 6.68 million m^3 (Tab. 3) amounts to 3.39 million t of CO_2.

Table 3. Potential wood stock from spruce plantation forests (Bisenieks 1976, Rone 1982).

Growing stock, $m^3 ha^{-1}$/thou m^3 (m^3 area^{-1})	
During 20 years	170/3068
During 30 years	250//4511
During 40 years	300/5414
During 50 years	370/6677

In forecasting the sustainable development of plantation forests and the benefits to the Latvian economy, both the surveys of the first 20 years performed at the research sites and the current research results, as well as the current regulations governing forest valuation in the Republic of Latvia have been considered (Zālītis & Jansons 2009, Daugaviete et al. 2017, Zālītis et al. 2017, Jansons et al. 2019, Donis & Šņepsts 2019, Donis et al. 2019, Lazdiņa et al. 2019, Lībiete et al. 2019).
One of the benefits of plantation forests is the use of non-wood products, i.e., the conversion of coniferous forest green mass into new products (Daugavietis et al. 2012, Daugavietis 2013, Polis & Spalvis 2013). Studies on the volume of green biomass from conifers demonstrate that 100±20 kg of spruce litter and 80±10 kg of pine litter can be obtained per 1 m^3 of wood (Daugavietis 2013, Spalvis et al. 2014), which, if utilized and processed into valuable ecological products, could contribute significantly to the national economy, accounting for 58 to 89 million EUR (Tab. 4). One-hectare spruce plantation forest (40–50 years old) can yield 24–37 t ha^{-1} of spruce green mass, respectively.

Table 4. Projected revenue from the use of coniferous green biomass (greens) in spruce plantation forests established in Latvia during 2022.

Parameters	
Area of spruce plantations established in 2022, ha	2642
Estimated wood stock, (at 40-50-years), m^3 ha^{-1}	300-370
Green foliage from 1 m^3 timber, kg	80-100
Green foliage from 1 ha spruce plantation, t	24.0-37.0

CONCLUSION

1. Overall data dispersion was higher in forest stands, suggesting that plantation forests established on agricultural land are a more controlled environment, thus, possibly more predictable in terms of productivity.
2. The running stock growth of spruce plantations established on agricultural land is higher than that of spruce stands on forest land in the respective age group by an average of 30–38%, i.e., if the average running stock growth of 10 to 15-year-old plantations on agricultural land reaches 7 m^3 ha^{-1} a^{-1}, then on forest land 4.3 m^3 ha^{-1} a^{-1}. In older plantations (30 years old) the growth rate of spruce on agricultural land reaches up to 22.5 m^3 ha^{-1} a^{-1}, while on forest land 15.8 m^3 ha^{-1} a^{-1}.
3. Plantation forests can make a significant contribution to the economy if planted in areas that are fertile but remain unused for agriculture. The yield from 1 ha of plantation forest depends on the management objective: extraction of roundwood (pulpwood, sawn-wood, veneer logs, containerboard) and carbon storage in products or extraction of

locally sourced energy-intensive biomass (energy timber).

ACKNOWLEDGEMENTS

Research work and data collection had been funded by Latvian State Forest funded research programmes "Working methods and technologies for restoration, planting, care and protection of forest stands" project No 5-5.9.1_007o_101_21_77; "Carbon turnover in forest ecosystem" project No 5-5.9.1_0081_101_21_87 and European Regional Development fund project "Climate change mitigation potential of trees in shelter belts of drainage ditches in cropland and grassland" agreement No. 1.1.1.1/21/A/030. Thanks to two anonymous reviewers for helping to improve this article.

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Received: 30.06.2024.
Accepted: 08.08.2024.