INTERDISCIPLINARY DOCTORAL SCHOOL

Faculty of Silviculture and Forest Engineering

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Management, growth and yield of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in European beech forests of Romania

SUMMARY

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Topic of the thesis

The doctoral thesis aims to analyze the behaviour of the green Douglas-fir in some European beech stands in the Forest District (F.D.) Călimănești, the Forestry Directorate (F.Di.) Vâlcea, to which is added a Norway spruce stand (F.S. Voineasa, F.Di. Vâlcea), respectively of mixtures (Local Public Directorate of Forests Săcele). From the need to compare the biometric performances of individual Douglas-fir trees and stands including Douglas-fir in their species composition, the works in F.D. Călimănești did not limit themselves to the results obtained in European beech trees, but extended both to lower altitudes (400 m), in a sessile oak stand, and higher (1,400 m), in a Norway spruce stand.

Disciplines in which it integrates

The PhD thesis is integrated into the field of Forestry (Forest Science) and includes various components on forest sites, natural forest vegetation, biology, ecology, growth, production and management of Douglas-fir stands.

Purpose of the thesis

The doctoral thesis, starting from the goal stated by the theme, aims to achieve four *objectives*.

1. Analysis of the location of pure and mixed stands of green Douglas-fir in the Călimănești and Voineasa Forest Districts, respectively in the Local Public Directorate of Forests Săcele.
2. Analysis of site and vegetation conditions in which green Douglas-fir was used in the Călimănești and Voineasa Forest Districts, respectively in the Local Public Directorate of Forests Săcele.
3. Analysis of the biometric performance of Douglas-fir (individual trees and stands) in various site and vegetation conditions.
4. Analysis of the need and the technical-economic justification of the application of artificial pruning to green Douglas-fir trees in young stands.

Structure/chapters of the thesis

The doctoral thesis shows the following structure/chapters:

Introduction: general considerations, purpose and objectives of research

Chapter 1. State-of-the-art regarding the range, ecology, growth, production and management of green Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco

Chapter 2. Location of research, material and research methods

Chapter 3. Results and Discussions

Chapter 4. Final conclusions. Personal contributions. Dissemination of results. Future research directions

Bibliography

Research metholdology

1. Field work and office processing related to biometric research

They were made in six stands belonging to F.D. Călimănești, from Management Unit I Muereasca (sub-compartment 129E), Management Unit III Căciulata (sub-compartments 25B, 45B and 45C) and Management Unit VI Berislăvești (sub-compartments 41B and 109B), considered representative for the use of green Douglas-fir in this forest district.

In addition to the six stands in F.D. Călimănești, it was chosen for research sub-compartment 92G from the Dobrun forest, part of the former Management Unit VIII Cataracte from the Voineasa F.D.

To the seven stands, from two forest districts administered within the Vâlcea Directorate of the National Forest Administration-Romsilva, was added the stand from sub-compartment 87E, Management Unit V Tesla, Local Public Authority of Forests Săcele.

During the field work, two rectangular sample plots (SP) with a size of 300-500 m^2 were installed in 2022 in each research stands in F.D. Călimănești. In sub-compartment 92G, a sample plot of 800 m^2 was installed in the same year. In sub-compartment 129E (both SPs) future/final crop trees were selected and painted based on the criteria of vigour (thickest and tallest) – quality (no forking, cankers, other defects) – spacing/distribution (as evenly as possible).

The field work in sub-compartment 87E were carried out in June 2023, the working material consisting of 71 future crop trees (20 Douglas-fir, 51 Norway spruce), chosen based on the criteria mentioned above (vigour-quality-spacing/distribution), painted and artificially pruned up to 4.5-5 m high in August 2010. Of these trees, in June 2023 there were still 19 individuals of green Douglas fir (one, heavily damaged by bear, was not re-inventoried) and 48 of Norway spruce (3 dead individuals).

In all sample plots in the seven stands, diameters at breast height (d) were measured in all trees. In sub-compartments 25B, 41B, 109B and 129E, four crown radii (r1,...,r4) were measured for all Douglas-fir trees, arranged at 90^{o} to each other, two of which on the line of greatest slope and two on the contour line. Total heights (h) were measured in numerous trees of various species, with as varied diameters at breast height as possible. The instruments used for the SP installation and the biometric measurements were: 5 m, 20 m and 50 m long tape measure, with a precision of 5 mm (ri), Haglof caliper, with a precision of 1 mm (diameter at breast height d), the Romanian hypsometer with a pendulum, with the precision of 50 cm (h).

In the u.a. 87E, the measurements made in August 2010 and June 2023 were limited - to the initial 71 future/final crop trees, respectively 66 future/final crop trees remaining in the year 2023 - to the diameters at breast height (d) and four radii of the crowns (r1, ..., r4), arranged at 90° between them, of which two on the line of greatest slope and two on the contour line. The instruments mentioned above were used for the measurements.

Based on the field data, the mean diameter of basal area (dg), the height corresponding to the mean diameter of basal area (hg), as well as the mean crown diameter (dmedcor = (r1+r2+r3+r4)/ 2) were calculated. In addition, the correlation between d and dmedcor, expressed graphically, was analyzed. Values of d were used to calculate the basal area by species and SP, and volume tables by species (Giurgiu et al. 1972, 2004) were used to calculate the volume of individual trees and stands.

2. Field work and office processing related to the intervention with artificial pruning

The research works were carried out in two stands (sub-compartments 41B and 109D) from the Management Unit VI Berislăvești, Călimănești Forest District.

In September and October 2022, in the two stands, after 104 Douglas-fir trees were selected, which were equipped with a serial number, T-mark at the height of 1.30 m and a paint ring at the height of 2.0 m, artificial pruning works were carried out on them, in which two separate teams of two people each (one pruner + one timer) participated, in the following manner:

a. Sub-compartment 41B (71 pruned trees): team no. 1 pruned 31 trees, all of them up to 2.0 m high, and 28 trees from 2.0 m to heights between 3.6 and 4.4 m. Team no. 2 pruned 40 trees, all up to a height of 2.0 m.

b. u.a. 109D (33 trees pruned): both teams pruned up to a height of 2.0 m, with 18 individuals (team no. 1) and 15 individuals (team no. 2), respectively.

The pruners from teams no. 1 of both sub-compartments were different, while in teams no. 2 activated the same pruner. Pruning was done from the ground, using hand saws model Silky Gomtaro 270-8, made in Japan, from 0.0 to 2.0 m high, respectively a hand saw with non-telescopic rod model Wolf Garten, made in Germany, from 2.0 m to the maximum height allowed. The diameter at breast height of the trees was measured with a Haglöf Mantax Blue 95 cm caliper to the nearest 1 mm.

Original results

1. Structure, growth and production of Douglas fir stands

a. Stocking and density of Douglas-fir stands

In the 13 sample areas, as the age of the stands is variable (from 25 years to 115 years; each stand is even-aged), their density (number of trees per hectare) is also variable (Table 1).

Table 1 Stocking and density of stands in the 13 sample plots

Management unit	Sub-compartment	Mean age, years,	Plot no.	Density, no. of trees ha^{-1}	Stocking, m^2 ha^{-1}

I	129E	45	1	640	36.95
			2	460	44.09
III	25B	60	1	**360**	45.55
			2	520	62.84
III	45B	55	1	1,100	73.69
			2	980	64.19
III	45C	60	1	660	71.77
			2	779	70.14
VI	41B	25	1	**2,866**	39.56
			2	940	**28.15**
VI	109B	45	1	867	60.03
			2	783	64.59
VIII	92G	115	1	400	**90.70**

As expected, the highest density (2,866 trees ha^{-1}) was found in the youngest stand (25 years), while the minimum density (360 trees ha^{-1}) characterizes one of the oldest stands (60 years old). This value is similar to the one (400 tree ha^{-1}) found in the oldest stand, 115 years old. However, the density of all these stands is high (for example, approx. 800 trees ha^{-1} at 45 years; over 1,000 trees ha^{-1} at 55 years; approx. 700 trees ha^{-1} at 60 years) , regardless of the age and species composition of each u.a.

The stocking (m^2 ha^{-1}) is also very variable, with the minimum value (28.15 m^2 ha^{-1}) in the youngest stand (25 years), and the maximum (90.70 m^2 ha^{-1}) in the oldest stand older (115 years). As in the case of density, the stocking is very variable at all ages, regardless of the species composition of the stand, and reaches over 60 m^2 ha^{-1} at 45 years and over 70 m^2 ha^{-1} at 60 years.

b. The species composition of Douglas-fir stands

In even-aged stands of Douglas-fir, the species composition is highly variable, with the share of this species varying from 46% to 100% (species composition by number of trees) and between 69% and 100% (species composition by basal area) (Table 2).

Table 2 The species composition of research stands

Management unit	Sub-compartment	Plot no.	Species composition by no. of trees, %	Species composition by basal area, %
I	129E	1	47DU 16GO 37CA	83DU 11GO 6CA
		2	100DU	100DU
III	25B	1	50DU 22PAM 17LA 11FA	69DU 16LA 14PAM 1FA
		2	46DU 19PAM 16LA 19FA	76DU 11PAM 11LA 2FA
III	45B	1	60DU 33 (FA,CA,PAM, ULM,SAC) 7 (TE,CI)	84DU 8(FA,CA,PAM,ULM,SAC)

				8(TE,CI)
		2	47DU 37(CA,ME,PAM) 17(TE,FR)	69DU 11(HO,ME,PAM) 20(TE,FR)
III	45C	1	79DU 21(FA,CA,PAM)	91DU 9(FA,CA,PAM)
		2	78DU 22(FA,CA)	94DU 6(FA,CA)
VI	41B	1	94DU 3(MO,BR) 3PAM	92DU 7(MO,BR) 1PAM
		2	100DU	100DU
VI	109B	1	46DU 43FA(+CI,FR)	73DU 27FA(+CI,FR)
		2	56DU 33FA 11(CI,FR)	78DU 8FA 14(CI,FR)
VIII	92G	1	63DU 37MO	71DU 29MO

Conifers: DU Douglas-fir, MO Norway spruce, BR silver fir, LA European larch
Broadleaves: FA European beech, GO sessile oak, CA hornbeam, PAM sycamore, TE small-leaved linden, CI wild cherry, FR common ash, ULM mountain ash, SAC goat willow

As can be seen, the green Douglas-fir was associated with both conifer species (Norway spruce, silver fir, European larch) and broadleaves species such as European beech, sessile oak, sycamore, hornbeam, small-leaved linden, wild cherry, common ash, etc. Green Douglas-fir has only been regenerated artificially (planted), in intimate mixture or grouped, to fill the non-regenerated gaps in naturally established stands, especially with European beech dominance, or in small pure stands. If all the conifer species were planted, the broadleaved ones were regenerated naturally, from seeds. In almost all cases (except SP1 in sub-compartment 41B), because Douglas-fir diameters (and consequently basal areas), as shown below, were greater than those of associated species, its share in the composition by basal area is (much) higher than by number of trees.

c. Biometric performance of individual trees and Douglas-fir stands

c.1. The mean diameter of basal area and its corresponding height

The values of these biometric parameters in the 13 SPs are presented in Table 3.

Table 3 The mean diameter of basal area and its corresponding height in the seven stands studied

Management unit	Sub-compartment	Mean age, years	Plot no.	Mean diameter of basal area (d_g), cm	Height corresponding cu d_g (h_g), m
I	129E	45	1	**DU 36.03**; GO 22.28; CA 11.42	**DU 30.84**; GO 19.30; CA 14.40
			2	**34.93**	DU 29.58
III	25B	60	1	**DU 47.29**; PAM 33.97; LA 39.22; FA 12.10	**DU 32.97**; LA 30.50; PAM 25.80 FA 12.10
			2	**DU 50.38**; PAM 30.19; LA 33.57; FA 9.77	**DU 33.20**; PAM 24.70; LA 29.20; FA 11.15
III	45B	55	1	**DU 34.51**; (FA,CA,PAM,ULM,SAC)	**DU 30.29**; (FA,CA,PAM,ULM,SAC)

				14.57; (TE,CI) 30.80	17.90; (TE,CI) 22.70
			2	**DU 34.96**; (CA,ULM,PAM) 15.79; (TE,FR) 32.13	**DU 33.19**; (CA,ULM,PAM) 18.70; (TE,FR) 23.80
III	45C	60	1	**DU 39.88**; (FA,CA,PAM) 24.87	**DU 30.39**; (FA,CA,PAM) 24.70
			2	**DU 37.05**; (FA,CA) 17.54	**DU 30.13**; (FA,CA) 20.20
VI	41B	25	1	**DU 13.16**; (MO,BR) 19.20; PAM 6.86	**DU 13.28** (MO,BR) 16.30 PAM 8.20
			2	**DU 19.53**	**DU 15.04**
VI	109B	45	1	**DU 37.36**; FA(+CI,FR) 21.00	**DU 28.30**; FA(+CI,FR) 20.30
			2	**DU 38.49**; FA 15.90; (CI,FR) 35.87	**DU 29.10**; FA 18.80; (CI,FR) 24.30
VIII	92G	115	1	**DU 57.39**; MO 46.98	**DU 36.67**; MO 32.01

Conifers: DU Douglas-fir, MO Norway spruce, BR silver fir, LA European larch
Broadleaves: FA European beech, GO sessile oak, CA hornbeam, PAM sycamore, TE small-leaved linden, CI wild cherry, FR common ash, ULM mountain ash, SAC goat willow

Douglas-fir reached important values of dg in all stands: over 35 cm at 45 years, up to 50 cm at 60 years, and over 57 cm at 115 years. Except SP1 in sub-compartment 41B, where the dg of MO and BR are slightly higher, the dg of Douglas-fir is (much) higher, in all SPs, than that of all cohabitant conifer and broasleaved species.
The relationship between the mean diameter of basal area and the mean age of the stand is shown in Figure 1, where the close correlation between the two parameters is observed (correlation coefficient *r = 0.92*).

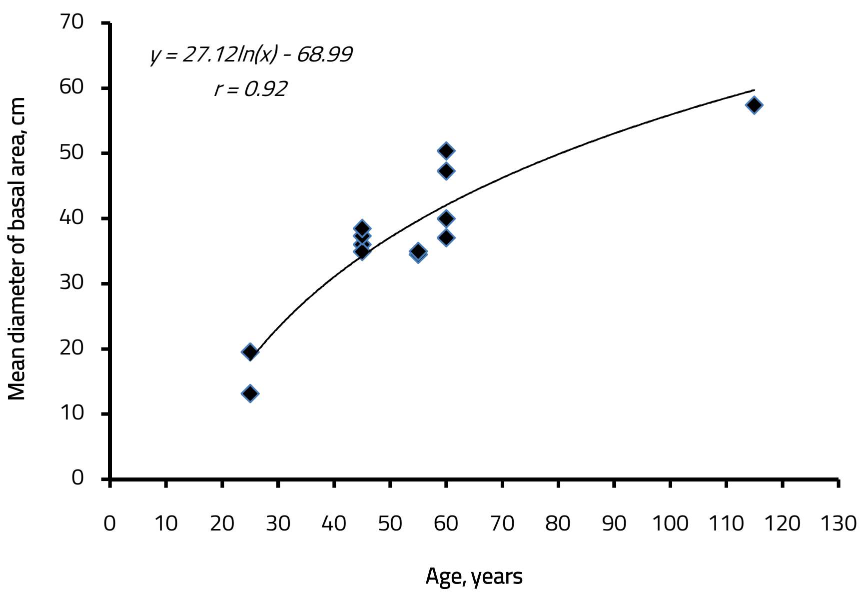


Figure 1 Variation of mean diameter of basal area of green Douglas-fir in relation to the mean age in the stands studied

In sub-compartment 87E, where the work was focused only on the future/final crop trees and did not take place in the sample plots, the values of d_g at the age of 45 years, in the year 2023, were 35.94 cm for Douglas-fir, respectively 32.33 cm for Norway spruce. These d_g values increased from 25.71 cm in Douglas-fir in 2010 (increase of 10.23 cm - 39.79% -, between 2010 and 2023), compared to 24.54 cm in Norway spruce (increase of 7 .79 cm, respectively 31.74%, between the same years).

The same conclusions, regarding d_g in the stands studied, are also valid in the case of h_g of the green Douglas fir, with values of 28-30 m at 45 years, 30-33 m at 60 years and over 36 m at 115 years (Figure 2).

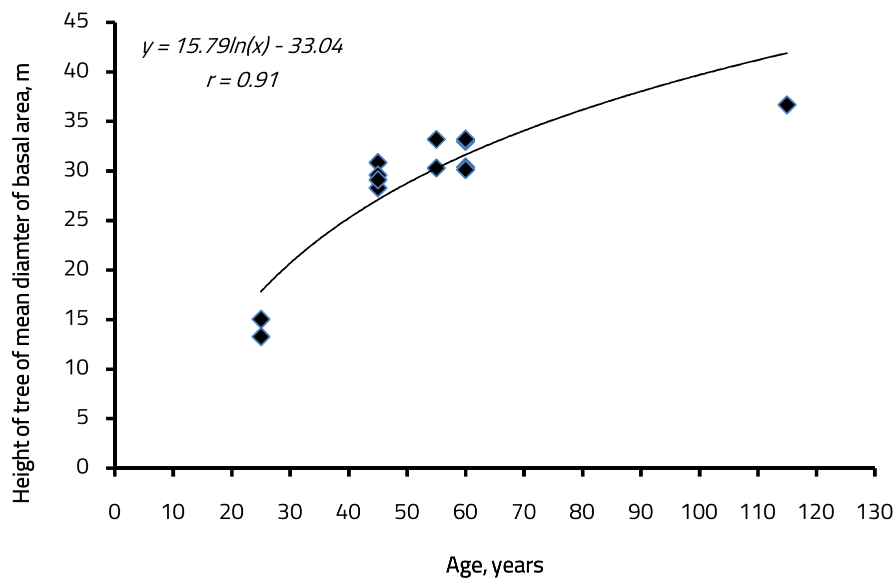


Figure 2 The variation of the height of tree of mean diameter of basal area in the green Douglas-fir species in relation to age in the stands studied

In all SPs, with one exception (SP1 of sub-compartment 41B), green Douglas-fir is much taller than the other conifer and broadleaved species with which it is associated. Three stands, due to the relevant differences in height between the green Douglas-fir and the species mixed with it, are slatted (irregular in the vertical structure), with the green Douglas fir forming the upper floor and the mixed species, mostly broadleaved (FA, CA, PAM), the lower floor.

The joint graphical expression of d_g and h_g values indicates the close relationship between these biometric parameters, with a correlation coefficient *$r = 0.95$* (Figure 3).

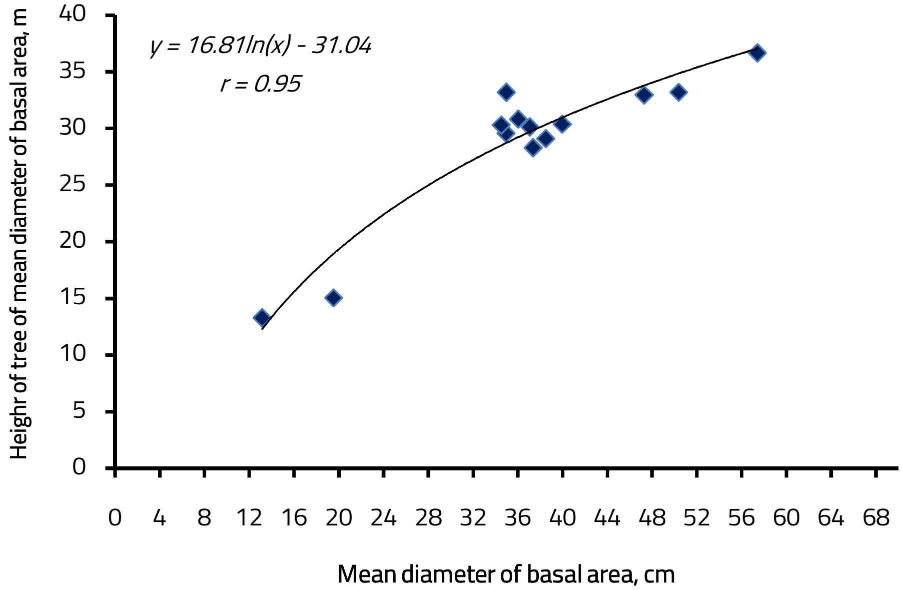


Figure 3 The variation of the biometric characteristics of the mean tree of the basal area in the Douglas-fir trees in the studied stands

c.2. Minimum and maximum diameter at breast height of different species

These values, in the seven trees investigated, are shown in Table 4.

Table 4 The minimum and maximum diameter at breast height of the different species in the seven research stands

Management unit	Sub-compartment	Mean age, years	Plot no.	Minimum diameter at breast height, cm		Maximum diameter at breast height, cm	
				DU	Other species	DU	Other species
I	129E	45	1	23.1	GO 9.8; CA 7.3	47.7	GO 27.5; CA 16.3
			2	22.7	-	46.5	-
III	25B	60	1	36.0	LA 33.8; PAM 24.4	61.8	LA 41.9; PAM 38.0
			2	37.3	LA 23.2; PAM 22.9	60.7	LA 43.4; PAM 34.7; FA 13.8
III	45B	55	1	14.2	(FA,CA,PAM,ULM,SAC) 8.1; (TE,CI) 10.8	69.4	(FA,CA,PAM,ULM,SAC) 24.2; (TE,CI) 40.4
			2	10.8	(CA,ULM,PAM) 6.9; (TE,FR) 26.0	62.2	(CA,ULM,PAM) 31.2; (TE,FR) 37.1
III	45C	60	1	21.4	(FA,CA,PAM) 10.3	60.0	(FA,CA,PAM) 38.3
			2	12.3	(FA,CA) 6.9	62.1	(FA,CA) 41.5
VI	41B	25	1	5.1	PAM 5.0; (MO,BR) 11.3	29.3	PAM 8,8; (MO,BR) 24.9
			2	13.9	-	25.7	-
VI	109B	45	1	23.3	FA(+CI,FR) 8.5	55.8	FA(+CI,FR) 33.9

			2	16.5	FA 13.0; (CI,FR) 32.3	66.8	FA 22.7; (CI,FR) 39.2
VIII	92G	115	1	20.2	MO 17.9	83.2	MO 54.0
V	87E	45	-	24.3	MO 20.8	46.0	MO 43.0

Conifers: DU Douglas-fir, MO Norway spruce, BR silver fir, LA European larch

Broadleaves: FA European beech, GO sessile oak, CA hornbeam, PAM sycamore, TE small-leaved linden, CI wild cherry, FR common ash, ULM mountain ash, SAC goat willow

As with mean diamater of basal area, Douglas-fir trees are thicker (except above) than companion species—conifers and broadleaves—for minimum and maximum diameters. Although all the stands are even-aged, the differences between these diameter values are very relevant and reach 20, even 30 cm, in the case of the maximum diameters.

The individual Douglas-fir trees reached important diameters (over 46 cm at 45 years – over 60 cm at 60 years), the thickest individual showing a diameter at breast heightof over 83 cm.

The fact that the stands are even-aged is confirmed by the values of the diameter variation coefficients in the case of Douglas-fir trees: in almost all SPs (except sub-compartment 45B, both SPs), this parameter ranges from 30 to 45%, values specific to regular stands /even-aged stands (Giurgiu 1969).

c.3. Standing volume, mean annual increment and mean tree volume

In all stands and SPs, the standing volume reaches high values, from over 200 m^3 ha^{-1} at 25 years to over 1,160 m^3 ha^{-1} at 115 years (Table 5).

Table 5 Standing volume and mean annual increment in the research stands

Management unit	Sub-compartment	Mean age, years	Plot no.	Standing volume, m^3 ha^{-1}	Mean annual increment, m^3 an^{-1} ha^{-1}
I	129E	45	1	462.8	10.28
			2	566.0	12.58
III	25B	60	1	588.2	9.80
			2	772.3	12.87
III	45B	55	1	913.3	***16.61***
			2	832.0	15.13
III	45C	60	1	847.1	14.12
			2	869.7	14.50
VI	41B	25	1	283.0	11.32
			2	206.5	8.26
VI	109B	45	1	644.5	14.32
			2	703.5	15.63
VIII	92G	115	1	***1167.1***	10.15

Standing volumes above 550 m^3 ha^{-1} were reached at age 45, while volumes above 800 m^3 ha^{-1} at 55-60 years exist in five out of six SPs.

Under these conditions, the mean annual increment at different ages is high and varies between 8.26 m^3 yr^{-1} ha^{-1} and 16.61 m^3 yr^{-1} ha^{-1} (Table 5). However, in 11 out of 13 SPs, this increase exceeds 10 m^3 yr^{-1} ha^{-1}, values of 13-15 m^3 yr^{-1} ha^{-1} being the most frequent.

Mean tree volume of basal area was determined using the values of d_g and h_g shown previously in Table 3, as well as the Douglas-fir volume tables in Giurgiu et al. (2004). Consequently, the graph was constructed that correlates the mean age of Douglas-fir with the mean tree volume of basal area in the 13 sample areas (Figure 4).

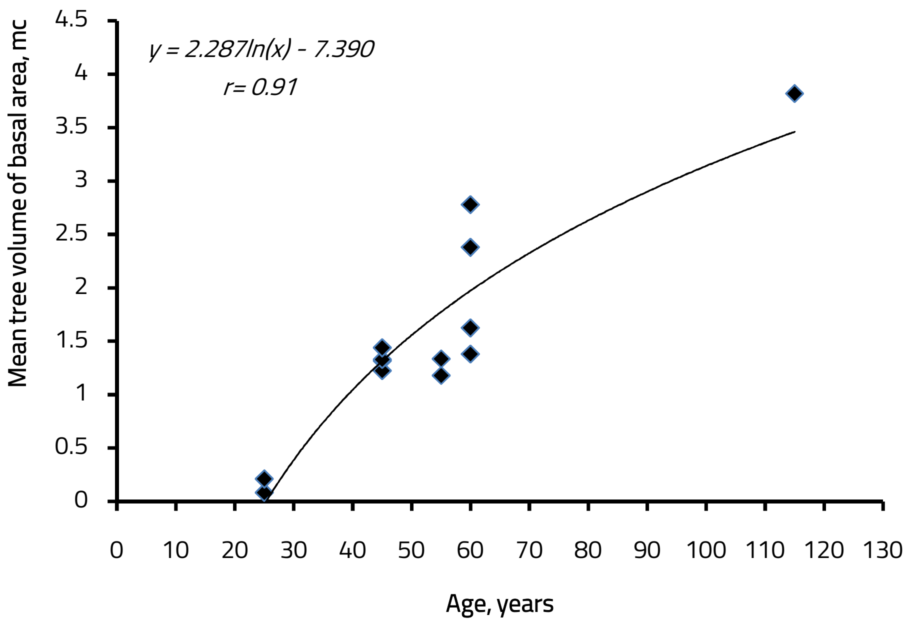
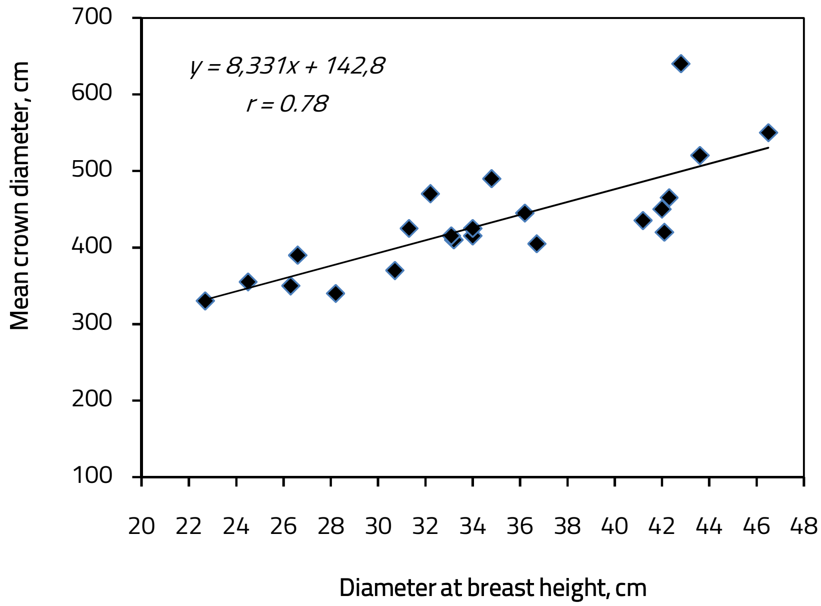


Figure 4 The variation of the mean tree volume of basal area in the Douglas-fir trees in the studied stands

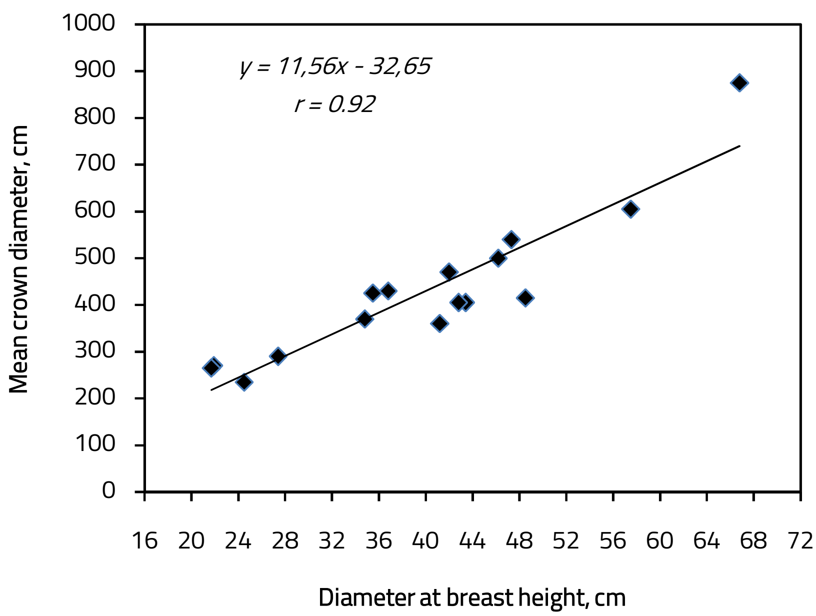
The graph shows the close correlation between the age of the studied stands and the mean tree volume of basal area, with a correlation coefficient *r = 0.91*. The graph also shows the particular influence of stand stocking and density on the mean tree volume: in subp-compartment 25B, where the stand stocking and density are much lower than in sub-compartment 45C at the same age (60 years), the mean tree volume is much bigger, up to 50%. The points above the correlation line indicate the mean tree volume values of basal area in sub-compartment 25B, and those below it for sub-compartment 45C.

c.4. The relationship between the diameter at breast height and the mean crown diameter

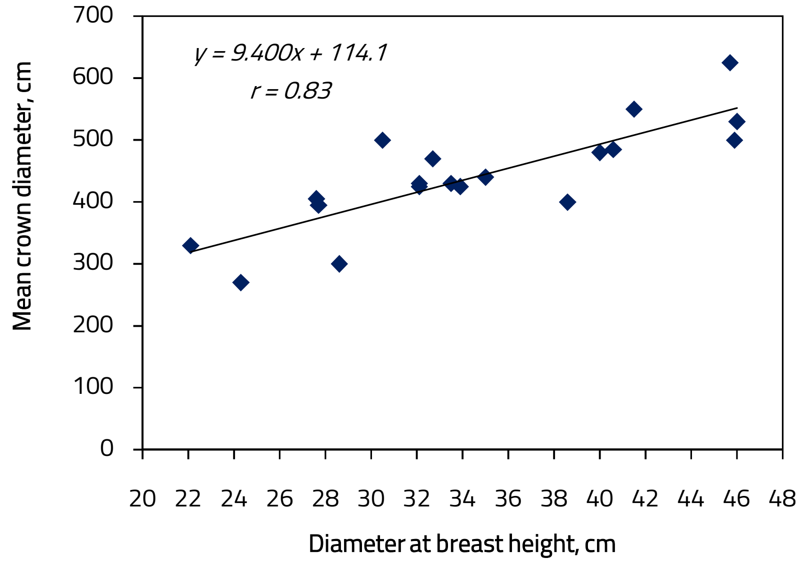
In green Douglas-fir trees of SPs, diameter at breast height and mean crown diameter show a close relationship, with a correlation coefficient (r) ranging from above 0.75 to above 0.90, as seen in Figures 5a, 5b and 5c.


y = 8,331x + 142,8
r = 0.78
Mean crown diameter, cm
Diameter at breast height, cm
700
600
500
400
300
200
100
20 22 24 26 28 30 32 34 36 38 40 42 44 46 48

(a)


y = 11,56x - 32,65
r = 0.92
Mean crown diameter, cm
Diameter at breast height, cm
1000
900
800
700
600
500
400
300
200
100
0
16 20 24 28 32 36 40 44 48 52 56 60 64 68 72

(b)



(c)

Figure 5 Correlation between diameter at breast height and mean crown diameter in individual Douglas-fir trees in sub-compartments 129E, SP2 (a), 109E, SP2 (b) and 87B (c)

The close correlation between the two parameters is used in the "crop-tree silviculture" of Douglas-fir: the future/final crop trees are chosen at the beginning of the pole stage (mean diameter 12-15 cm) among the thickest individuals, with large and symmetrical crowns, and the thinnings the following are mixed in character (but predominantly from above), around these vigorous trees (in addition, of the best quality and as evenly spaced as possible).

c.5. Correlation between initial diameter and diameter growth in future trees from u.a. 87E

The measurements made on the diameter at breast height of the future Douglas-fir and Norway spruce trees, respectively, in the years 2010 and 2023, are relevant for two different situations in the case of the two species:

1. In Douglas-fir, the correlation between initial diameter (in 2010) and its growth between 2010 and 2023 is relatively strong (correlation coefficient $r = 0.51$ – Figure 6), with a concentrated spread of relative values.

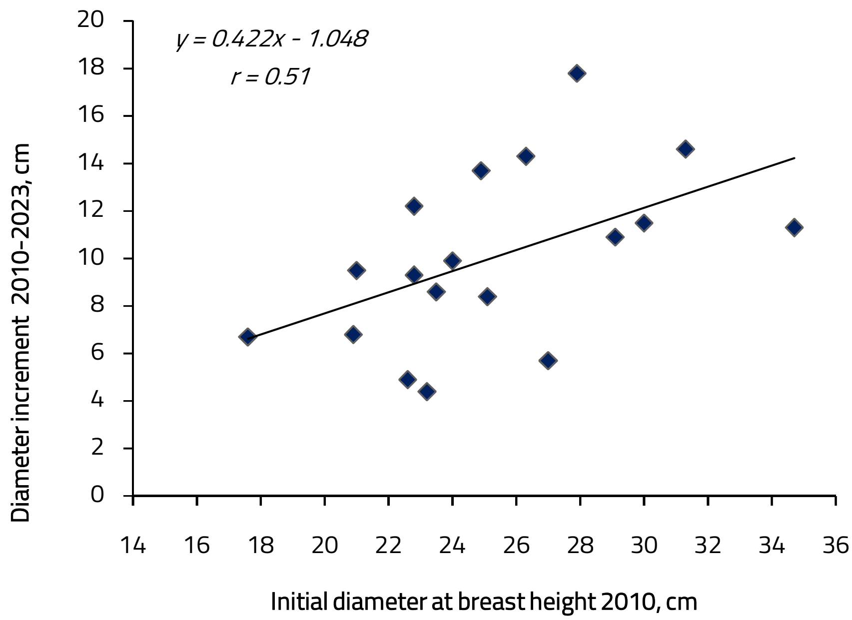


Figure 6 Correlation between the initial diameter at breast height (2010) and diameter increment between 2010 and 2023 in future/final crop Douglas-fir trees in the sub-compartment 87B

2. In Norway spruce, this is much less obvious (*r = 0.26*), and the spread of values is much wider (Figure 7).

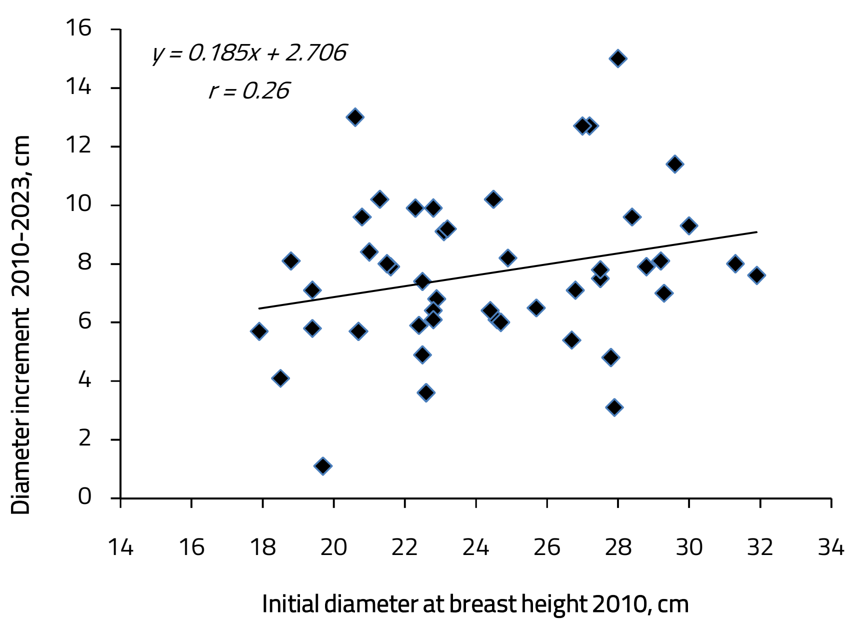


Figure 7 The correlation between the initial diameter at breast height in 2010 and its increment between 2010 and 2023 in future/final crop Norway spruce trees in the sub-compartment 87B

d. Natural pruning of Douglas-fir

In all SPs and stands studied, natural pruning of Douglas-fir trees, regardless of age, stocking, density or stand species composition, was imperfect, as its branches are persistent and their shedding is very slow. Under these conditions, their artificial pruning is a must, if the goal is to produce knot-free wood for superior uses.

In this context, it should be mentioned that, although the resource of green Douglas fir on the local market is reduced, its wood, from trees that are not naturally or artificially pruned and harvested predominantly from middle-aged stands through thinning works, is used locally for roofs/coverings, ceilings, panelling, small furniture pieces.

e. Miscellaneous

As a complement to the aspects presented above, two important aspects should be mentioned in relation to the green Douglas-fir in the Călimănești F.D.:

- the species showed a high resistance to diseases and pests and was not damaged by snow or wind, regardless of the location, age or species composition of the stands.

- in open areas adjacent to Douglas-fir stands, as well as under sparse canopies, the species was able to regenerate naturally from seed.

Anyway, the green Douglas-fir does not behave in the conditions of the stands studied or in their proximity as an invasive species, but in a normal competition with the native broadleaved and conifer species alongside which it was cultivated. This fact confirms the conclusions of the European specialists cited in paragraph *1.2.4. The potential for natural regeneration from the seed*.

f. Discussion of the structure, growth and production of Douglas-fir stands

All the research stands showed high stockings and densities due to (i) the high initial density of the green Douglas-fir plantations and (ii) the relatively low intensity of tending operations (cleaning and thinning), imposed by Romanian technical norms for a long time. Regarding the first aspect, this was (MS 1987) and still is (MMAP 2022a), 4,400 seedlings ha^{-1} (1.5 x 1.5 m) when Douglas-fir is planted on bare land, and 2,500 seedlings ha^{-1} (2.0 x 2.0 m), when the species is used to fill gaps in natural regenerations. Such high initial densities are not greatly reduced by the application of cleaning (moderate, with the intensity of a maximum of 15% of the basal area and reducing the canopy cover to a minimum of 0.8) and thinnings (MMAP 2022b). In the case of thinnings, the volume intensity of the mixed interventions is also moderate: 16% at the age of 21-30 years, respectively 12% at the age of 31-40 years. The thinnings aim to reduce the density of stands to 500-550 future crop trees ha^{-1}, in high-quality sites, and 550-700 future crop trees ha^{-1} in medium-quality ones, at the age of 50 (MMAP 2022b).

The species composition of the green Douglas-fir stands in the Călimăneşti F.D. is very diverse, including many conifer and broadleaved species, as recommended in the past and currently by the Technical Norms (MS 1987, MAPPM 2000a) and the Good Practice Guidelines (MMAP2022a). This situation is similar to that in other European countries, where the species is mixed with European beech (Czech Republic, France, Germany, Switzerland), Norway spruce (Bulgaria, Czech Republic, Germany, Slovenia), silver fir (Czech Republic, France, Slovenia), European larch (Bulgaria, Great Britain) (Čokl 1965, Petkova 1989, Alexandrov et al. 2000, MAPPM 2000a, Horgan et al. 2003, Wilson and Cameron 2015, Petkova et al. 2017, Keane et al. 2018, Novák et al. 2018, COFORD 2020, Nicolescu et al. 2021, Royal Forestry Society 2021). An interesting situation encountered in the Călimănești F.D. is the use of green Douglas-fir mixed with sessile oak and hornbeam, in the vegetation layer of sessile oak. The use of Douglas-fir in mixed hardwood stands dominated by sessile oak has never been recommended by the Technical Standards and Good Practice Guidelines (MS 1987, MAPPM 2000a, MMAP 2022a), but this type of stand has achieved relatively high yields and growth.

In all research stands, green Douglas-fir demonstrated important increases in diameter and height at all ages, being, in almost all cases, the species with the thickest and tallest trees compared to the mixed species. This growth potential led to high volumes, like 600-700 m^3 ha^{-1} at 45 years, similar to green Douglas-fir stands of the same age in Slovenia (Smolnikar et al. 2021) or Italy (La Marca et al. 2016), but lower than those reached in the Czech Republic at the age of 100 years (750 m^3 ha^{-1} – Remeš and Zeidler 2014). The maximum standing volume (over 1,000 m^3 ha^{-1}, at 115 years) from sub-compartment 92G was also reached in Slovenia (1,154 m^3 ha^{-1} - Čokl 1965) and Bulgaria (1,166 m^3 ha^{-1} - Popov 2006, 2009), but in younger stands, of (60) 70-80 years.

The mean volume increment confirms the high productive potential of the species, similar to that achieved in green Douglas-fir stands in Slovenia (7.8-15.9 m^3 yr^{-1} ha^{-1} - Čokl 1965), Croatia (8.3-18.5 m^3 yr^{-1} ha^{-1} – Klepac 1962), France (14.8 m^3 yr^{-1} ha^{-1} - Kohnle et al. 2019) or Italy (15 m^3 yr^{-1} ha^{-1} – La Marca et al. 2016).

Finally, the mean tree volume of basal area, with increasing values as the age of the trees increases, can reach important values, over 2 m^3/tree at 60 years, respectively approximately 4 m^3/tree at 115 years. Its values in stands of the same age, but with very different stockings and densities, confirm the very strong influence of these two parameters on the biometric performances of the stands: the higher the stocking and density, the greater the mean diameter of basal area, respectively the volume of the mean tree of diameter of basal area, are smaller.

2. Artificial pruning of Douglas-fir

The artificial pruning of Douglas-fir trees was applied in compliance with the known recommendations: the smooth cut, on the outside of the swelling at the base of the branches, perpendicular to them, without leaving any stub.

The 104 pruned trees showed very different diameters at breast height, ranging from 9.1 cm to 25.7 cm in sub-compartment 41B, respectively from 10.2 cm to 31.2 cm in sub-compartment 109D. Only 22 individuals to prune (21.15%) had diameters at breast height of a maximum of 15 cm.

The applied pruning has the following characteristics regarding its duration, in correlation with the type and height of pruning:

a. Low (access) pruning, up to 2.0 m height

It showed an average duration per tree from 1'31" (team no. 2, in both subplots) to 2'10" (team no. 1, in sub-compartment 109D) (Table 6).

Table 6 The main characteristics of the artificial pruning work up to 2.0 m height

Sub-compartment	Team no.	Mean arithmetic diameter of pruned trees, cm	Coeficient of variation of diameter of pruned trees, %	Mean duration of pruning up to 2 m height, min' and sec"			Coeficient of variation of duration of pruning, %	Duration of pruning per m, min' and sec"
				Mean	Min	Max		
41B	1	18.06 (9.1...19.3)	22.44	*1'49"*	0'51"	2'58"	29.68	*0'55"*
	2	18.88 (13.2-25.7)	16.44	*1'31"*	0'45"	2'31"	24.41	*0'46"*
109D	1	16.21 (10.2-31.2)	19.32	*2'10"*	1'16"	3'10"	26.33	*1'5"*
	2	16.19 (10.2-21.2)	20.97	*1'31"*	1'3"	2'7"	20.19	*0'46"*

The minimum duration of artificial pruning on the tree was slightly variable among the four teams (31", from 0'45" for team no. 2 in sub-compartment 41B to 1'16" for team no. 1 in sub-compartment 109D), in while the variation of the maximum duration of pruning was much wider, of 1'3" (2'7" in team no. 2 from sub-compartment 109D, respectively 3'10" in the case of team no. 1 from the same sub-compartment).

A relatively high amplitude, of almost 10% (from 20.19% to 29.68%), is also found in the case of the coefficient of variation of the duration of pruning, with a similar variation in the case of both teams marked with 1, respectively 2, in the two sub-compartments.

Per meter of stem pruned, the duration of artificial pruning varies from 0'46" (team no. 2 in both sub-compartments) and 1'5" (team no. 1 in sub-compartment 109D).

b. High pruning, up to heights of over 2.0 m

Of the 28 green Douglas-fir trees pruned to a height between 3.6 m and 4.4 m, 21 (75%) had at least 4.0 m of dead and green branches removed.

The average duration of artificial pruning from 2.0 m height to the one mentioned above was 2'46", with a variation from 1'16" to 4'13"" (coefficient of variation of time consumption of 26.58%).

The average time consumption per meter pruned from 2.0 height up on the stem was 1'36", with a variation of 1'22" to 2'3" (coefficient of variation of pruning time of 9.69%).

Finally, corroborating the data from the low pruning (pruning height 0.0-2.0 m) with those from the high pruning (pruning height over 2.0 m, reaching a maximum of 4.4 m), it resulted an average pruning duration of 4'38" (range 2'31"-6'33").

Per linear meter of trunk, the average time consumption of the artificial pruning work from the height of 0.0 m to the maximum height of 4.4 m, in the case of the 28 trees pruned, was 1'9" (variation 0'39"-1'35", coefficient of variation of pruning duration of 23.35%).

Discussions on artificial pruning of Douglas-fir

Artificial pruning of green Douglas-fir is, from a technical point of view, an easy operation, with an average duration per meter pruned of a maximum of 1 minute up to a height of 2.0 m and about 1.5 minutes at heights above 2.0 m.

As the average time per meter laid at the maximum working height of 4.4 m was 1'9", and the average time consumption per meter laid at heights higher than the maximum measured (4.4 m) will have specific values for heights above 2.0 m, it follows that it will reach values of at least 7'30"-8' when pruning up to 6 m high.

The average durations of artificial pruning of Douglas-fir on pruned sections, resulting from the mentioned research, are similar to those mentioned in the profile literature for this species, as for Norway spruce, in Germany: 3-5' (from 0 to 3 m height) , respectively 5-7' (from 3 to 6 m), when applied in two interventions. If pruning involves a single intervention from 0 to 6 m height, the time consumption per tree is 5-9' (Burschel and Huss 1997).

Unfortunately, in Romania there are no time and production standards for the artificial pruning of green Douglas-fir, but only for Norway spruce, pines and hybrid poplars.

In the case of Norway spruce, with which we have assimilated green Douglas-fir, the Unified Time and Production Norms for Forestry Works (Anonymous 2014) include a time norm (100 trees 8 hours^{-1}), when pruning dry branches from the ground, of 1,25 (on 2.00 m), respectively 0.63 (on 4.00 m). Similar standards in 1997 (MAPPM/RNP 1997) also included pruning of dry Norway spruce branches from the ground up to 6.00 m with a time standard of 0.39. This last value is consistent with the data from the French literature on the profile, for which the yield of artificial pruning for Douglas-fir, up to a height of about 6 m, is 30-50 trees worker^{-1} day^{-1} (CRPF 2015a), respectively 40 -60 trees worker^{-1} day^{-1} (CRPF 2002).

In the case of Norway spruce, according to the same time and production norms from 2014, the work formation for artificial pruning consists of a qualified worker (forester), paid with the 4th grading scale, which means, for the National Forest Administration-Romsilva, a rate of 19.00 lei per hour in the current year (RNP-Romsilva 2022). This leads to a gross salary of the pruner of 152 lei per day, respectively to a pruning cost of 1.216 lei per tree^{-1}, for pruning up to 2 m high, and 2.413 lei per tree^{-1}, for up to 4 m height. The cost of artificial pruning goes up to 3.897 lei tree^{-1} for pruning up to 6 m. The mentioned cost values, at an exchange rate of 4.9297 lei euro^{-1} on December 2, 2022, are 0.25 euro tree^{-1} (pruning up to 2.0 m), 0.49 euro tree^{-1} (pruning up to 4.0 m), respectively 0.79 euro tree^{-1} (pruning up to 6.0 m), significantly lower than those mentioned for the artificial pruning of Douglas-fir in France:

0.80-1.10 euro tree^{-1} (up to 2 m high), respectively 3.40-5.00 euro tree^{-1} (from 0 to 6 m) (CNPF 2017).
In the situation of pruning 360 trees ha^{-1}, the maximum number proposed by Liubimirescu (1973), one of the most experienced Romanian specialists in Douglas-fir forestry, the total cost per hectare of the work up to a height of 6 m would be approximately 1400 lei (284 euros), which we believe is fully justified if the goal is to obtain quality wood with superior uses.
Unfortunately, artificial pruning is applied on a small scale in European forests because it suffers from what economists call the "prisoner's dilemma" (Price 1989):
- little quality wood is produced because buyers do not offer any premium/pay extra for superior quality;
- buyers do not offer premium because an insufficient/low volume of felled wood is put on the market.
This is also the case of our country, where artificial pruning, applied in the pre-1989 period, mainly in Norway spruce and pine forests, on areas of the order of tens of thousands of hectares (Nicolescu 2016), is currently used on much reduced areas, of the order of thousands of hectares (2021: 1,585 ha, in young stands from the forestland owned by the state, managed by the National Forest Administration-Romsilva, with a national program of only 1,100 ha in the current year) (www.rosilva.ro/articole/ tree_care_works_ tinere_p_172.htm).

Conclusions

From the analysis of the aspects presented in the doctoral thesis, some important conclusions emerge:
a. The favorability of site and vegetation conditions in the studied areas for green Douglas-fir culture
In general, in the stands studied, green Douglas-fir benefits from at least medium favorable conditions for its culture, because:
- all stands, except sub-compartment 129E (altitude 400 m, hill climate specific to sessile oak) and sub-compartment 92G (altitude 1400, Norway spruce mountain climate), are located at altitudes specific to high hills and lower mountains (from 500 to 850 m), therefore favourable for the cultivation of green Douglas-fir.
- the climate of the cultivation areas is favourable for the species, in terms of mean annual temperature, mean annual precipitation, winds, aridity, and climatic province. Exception (a lower degree of favorability) presents the same stands from sub-compartments 129E and 92G, where the climates are warmer (129E) and colder (92G), but with mean annual precipitation of at least 700 mm, than in the sites with at least average favorability for green Douglas-fir culture.
- the soil found in almost all the stands is the typical Eutricambosol, of high fertility for various natural forest formations, from sessile oak, European beech, sessile oak-European

beech, hill specific to European beech and conifer mixtures - this is also the case with green Douglas-fir. Only in sub-compartment 92G, the existing soil (typical podzol, strongly acid) shows only medium fertility for Douglas-fir.

- except sub-compartment 129E (sessile oak site) and u.a. 92G (Norway spruce site), in all the stands studied, the sites encountered are hilly or mountain-premontane, with medium or higher potential, therefore favourable for the cultivation of green Douglas-fir.

- from the point of view of the typology of natural vegetation, the studied Douglas-fir stands are installed in hills and mountain ridges, of high and medium productivity. The exceptions are the same: sub-compartment 129E [natural vegetation Sessile oak with grasses (m)], respectively 92G [Norway spruce with *Vaccinium myrtillus* (m)].

b. Species composition, structure, growth and production of Douglas-fir stands

- the species composition of the green Douglas-fir stands in the Călimănești F.D. is very diverse, including many conifer and broadleaved species. This situation is similar to that in other European countries, where the species is mixed with European beech, Nprway spruce, silver fir, European larch. An interesting situation encountered in the Călimănești F.D. is the use of green Douglas-fir mixed with sessile oak and hornbeam, in the vegetation layer of sessile oak. In the two stands studied at the Voineasa F.D., respectively at the Local Public Authority of Forests Săcele, the association of the green Douglas-fir with Norway spruce led to spectacular biometric results, the North American species being superior to the Norway spruce in terms of the diameters achieved.

- all the research stands showed high stocking and densities due to (i) the high initial density of the green Douglas-fir plantations and (ii) the relatively low intensity of tending operations (cleaning and thinning), imposed by Romanian technical norms for a long time.

- in all the research stands, the green Douglas-fir demonstrated important increases in diameter and height at all ages, being, in almost all cases, the species with the thickest and tallest trees compared to the mixed species. This growth potential led to high standing volumes, like 600-700 m^3 ha^{-1} at 45 years, similar to green Douglas-fir stands of the same age in Slovenia or Italy, but lower than those achieved in the Czech Republic at the age of 100 years (750 m^3 ha^{-1}). The maximum standing volume (over 1,000 m^3 ha^{-1}, at 115 years) from sub-compartment 92G was also reached in Slovenia and Bulgaria, but in younger stands, (60) 70-80 years old. The average increase in volume confirms the high productive potential of the species, similar to that achieved in green Douglas-fir stands in Slovenia, Croatia, France or Italy.

c. Artificial pruning of Douglas-fir

- the artificial pruning of green Douglas fir is, from a technical point of view, an easy operation, with an average duration per meter pruned of a maximum of 1 minute up to a height of 2.0 m and approx. 1.5 minutes at heights above 2.0 m.

- the average durations of the artificial pruning of Douglas-fir on pruned sections, results from the mentioned research, are similar to those mentioned in the profile literature for this species, as for Norway spruce, in Germany: 3-5' (from 0 to 3 m height), respectively 5-7' (from 3 to 6 m), when applied in two interventions. If pruning involves a single intervention from 0 to 6 m high, the time consumption per tree is 5-9'.

- in the situation of pruning 360 trees ha^{-1}, the total cost per hectare of the work up to a height of 6 m is approximately 1400 lei (284 euros), which is fully justified if the goal is to obtain quality green Douglas-fir wood and with superior uses.

In conclusion, under the conditions of the Călimănești and Voineasa F.D.s, respectively of the Local Public Administration of Forests Săcele, the introduction and use of Douglas-fir in various site conditions and in stands including native conifer and broadleaved species has proven to be a success, a valuable and promising option in similar conditions in our country.

Contribution to the field

The main personal contributions in the scientific field of the author of the paper consisted of:

- the identification of all stands of green Douglas-fir within the radius of the Călimănești and Voineasa F.D.s and the analysis of the data from the forestry facilities to establish whether they meet the minimum conditions necessary to achieve the objectives proposed by the doctoral thesis.
- active participation, by measuring the diameters at breats height, total heights, crown radii, as well as by pruning Douglas-fir trees, in collecting the field data necessary for the preparation of the two research reports, for the preparation and publication of the three scientific articles, as well as for the elaboration of the doctoral thesis.
- the rigorous processing and analysis of field data, their synthesis and, by joining bibliographical information and taken from the forestry facilities, the preparation of the doctoral thesis.

Relevance of doctoral thesis

The doctoral thesis presents an important scientific relevance, through the contributions to the issue of growth and production of Douglas-fir in stands of the European beech forest formation, as well as how to apply artificial pruning works to young Douglas-fir trees.

In this context, taking into account the growing importance of the green Douglas-fir at the European level in the conditions of anticipated climate changes, the scientific opening achieved by the doctoral thesis could be continued through future research works, concerned with:

- the identification of all green Douglas-fir stanfs established in Romania and their study at least from an ecological and productive point of view;
- identification of green Douglas fir stands in Romania and mapping+research of those that meet the conditions to be declared certified seed source stands, from which seeds are to be harvested;
- the installation of Douglas-fir plantations at higher distances and planting schemes than the current ones, in order to expand the species in cultivation where site conditions allow it,

considering its high capacity to adapt to climate changes and to provide timber of very good quality;

- carrying out research for the preparation of time and production norms for the artificial pruning of Douglas-fir, specific and applicable in Romanian forests.