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Distribution, growth and productivity of *Larix decidua* Mill. plantations in the western Forest-Steppe of Ukraine

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Abstract

This study provides an analysis of the distribution of European larch in artificial forest stands in Ukraine. It was found that the potential area for the successful cultivation of this species can be not only the Western but also the Right-Bank and Left-Bank Forest-Steppe. The study has confirmed that European larch plantations, with the appropriate technology for planting and cultivation, are marked by rapid growth, high productivity and resistance. Under the forest site conditions of types C_2, D_2, and D_3, in which the largest number of larch stands were built, a tendency was revealed towards an increased volume of stemwood with an increasing share of larch in the stand composition. Constructed regression models formalize this dependence. With advancing age, the influence of larch on an increase in the growing stock of plantations is reduced. Productivity and growth character of larch plantations in different types of forest growth conditions are different. European larch can form steady-state and highly productive plantations not only in fresh, but also in moist types of forest growth conditions. Under conditions of a fresh fertile site type (D_2), as evidenced by the results of ANOVA, the share of larch in the composition of the stand has a significant impact on the main mensuration indices of the stand. The highest values for the average height are characteristic of larch with its significant share in the composition of plantations (6–10 units), and the highest values for the average stem diameter were observed with an average share of the species (3, 5–8 units). It is noted that the technology for the establishment and management of artificial larch plantations should be differentiated depending on the type of forest growth conditions by using optimal mixing and spacing schemes and appropriate silviculture regimes that regulate the share of larch in these stands.

Keywords: European larch, forest plantation, forest stand, type of site conditions, stand composition

Introduction

Larix decidua Mill. is characterized by a fragmented distribution within its natural range in the mountains of southern, central and eastern Europe – from southeast France and southwest Italy to eastern Poland and central Romania. It grows in a wide hypsometric range, forming plantations from 180 (Poland) to 2,500 m above sea level (the Central Alps, the Southwestern Alps). At high altitudes, larch occurs in small groups or single trees in protected areas (Ronch et al. 2016).

In Ukraine, *Larix decidua* is an indigenous species. However, to date, only a few of its natural micropopulations have survived in the Ukrainian Carpathians (Wagner et al. 2012). Most of the European larch stands both in the Carpathian region and in the adjacent plain territories were planted artificially.

Many years of practical experience in the cultivation of larch in Ukraine, numerous research studies have shown that if larch is artificially introduced in forest plantations, it grows better than local species, forming a growing stock at a young age which the main forest-forming species reach only at a maturity age. Under favourable conditions, European larch demonstrates good growth and high productivity both in pure and mixed stands (Debryniuk 2014, Belelia et al. 2017).

In the climatic and soil conditions of the Western region of Ukraine, larch stands are fast-growing and highly productive. Thus, at the age of 100 years, the standing volume of European larch plantations in the *Galileja* forest stand in the Ternopil region was estimated to be 835 m^3 ha^{-1} (Hayda et al. 2008). It shows good growth and high productivity in Polissia under conditions of moist and fairly fertile site type, the 180-year-old European larch plantations at the Horodnytskyi State Forestry Enterprise had a growing stock estimated at 790 m^3 ha^{-1} with an average tree diameter of 76 cm and an average height of 44 m (Tkachuk 2010).

The intensive spread of insect pests in some years can limit the rapid growth of trees and cause certain economic losses (Ronch et al. 2016). However, in Ukraine, European larch is a species that is virtually not susceptible to disease and pests even under conditions of climate change (Debryniuk 2010).

As mentioned above, European larch is a fast-growing high-yielding forest species, and therefore, its introduction in forest plantations significantly increases their overall productivity. However, many years' experience in growing larch plantations in Ukraine shows that not all of them are characterized by optimal growth rates and productivity indices. This can be explained using various technological schemes for establishment of larch plantations with a different proportion of European larch and associate species in the plantation, with different planting spacing and different silviculture regimes.

Until now, the question of the optimal composition of mixed stands with the inclusion of European larch remains unclear. Within the framework of this study, an attempt was made to assess the influence of the proportion of larch trees in the composition of the stand, as well as to find out the effect of stand density on the total growing stock within various types of forest growth conditions. Also important is the issue of determining the optimal geographical and forest typological areas for cultivation of European larch.

Materials and methods

The initial data for the analysis were obtained as a result of field forest inventory studies of a significant number of pure and mixed forest plantations with the inclusion of European larch within the forest growth conditions of C_2, D_2, D_3 types. The type of forest growth conditions (site type), as the main classification unit of forestry-ecological typology developed by P.S. Pogrebnyak and D.V. Vorobiov, unites lands that are homogeneous in soil and hydrological conditions, covered with forest vegetation or intended for growing forests. According to the Alekseev-Pogrebnyak edaphic grid, C_2 conditions are identified as fresh and fairly fertile site type, D_2 as fresh and fertile site type, and D_3 as moist and fertile site type (Pogrebnyak 1955).

The type of forest site conditions and the type of forest were determined by proven methods of typological research (Vorobiov 1967, Vorobiov et al. 1979, Ostapenko et al. 2002) using the works by Z. Herushynskyi (1996).

The study region covers areas from the Volyn Upland to the southern part of the Western Podillia, from the Carpathians and to the eastern border of the Western Forest-Steppe.

In general, data on 109 trial plots (TPs) were used, the plots were laid in artificial plantations of European larch aged from 18 to 160 years, with the share of European larch in the composition of the plantation ranging from 5 to 100%, with a density of 5 to 873 pcs. ha^{-1} (Table 1). The total density of the studied plantations varied within the following limits: within conditions D_3 over the range of 780–4,830 pcs ha^{-1}; within conditions D_2 over the range of 880–5,300 pcs ha^{-1}; and within conditions C_2 over the range of 840–5,950 pcs ha^{-1}.

All the studied plantations with the inclusion of European larch have an artificial origin. Along with larch, maple, sycamore maple, small-leaved linden, common ash, English oak, and Scots pine were introduced artificially. In addition to these artificially introduced tree species, most plantations include hornbeam, which is of exclusively natural origin. In plantations with larch in 7–10 units, it forms starting from 15–25 years of age the second tier of different densities, which depending on the type of forest conditions.

To determine the growth and productivity indices, the conventional methods of forest inventory were used (Hrom 2005). The trial plots comprised 100–200 trees, depending on the age of the plantation. The area of the sample plots ranged from 0.3 to 1.0 ha and their establishment

Table 1. Characteristics of trial plots in *Larix decidua* plantations

Distribution of TPs by types of forest site conditions			Distribution of TPs by age classes			Distribution of TPs by the share of larch trees in the plantation			Distribution of TPs by density of larch tree stand		
Type of forest site conditions	pcs	%	Age class, years	pcs	%	Share of trees, %	pcs	%	Density pcs ha^{-1}	pcs.	%
C_2	20	18	11–20	1	1	2–5	1	1	1–100	36	33
D_2	72	66	21–30	20	18	6–15	7	6	101–200	38	35
D_3	17	16	31–40	30	28	16–25	13	12	201–300	16	14
			41–50	10	9	26–35	11	10	301–400	4	4
			51–60	16	15	36–45	14	13	401–500	8	7
			61–70	11	10	46–55	15	14	501–600	4	4
			71–80	7	6	56–65	13	12	601–700	1	1
			81–90	5	5	66–75	10	9	701–800	1	1
			91–100	5	5	76–85	14	13	801–900	1	1
			101–110	1	1	86–95	7	6			
			121–130	1	1	96–100	4	4			
			151–160	1	1						

was carried out according to the corresponding standard of Ukraine (Ministry of Agrarian… 2006). The diameters of trees were measured with 1-centimeter steps at a height of 1.3 m in two mutually perpendicular directions. The heights were measured in 15–25 trees of each species according to the proportional distribution of these trees by degrees of thickness. The average diameter was determined based on the average value of the total basal areas.

The total volume of stemwood was determined from the formula:

$$M = GHF,$$

where:
M is the stand volume, $m^3\ ha^{-1}$,
G is the total basal area of the stand, $m^2\ ha^{-1}$,
H is the average height, m,
F is the form factor.

The age of the plantations was determined by counting annual rings in model trees either according to the "Book of Forest Cultures" or using the materials of the mensuration description of plantations. The plantations were grouped according to 10-year age classes, the density of groups of larch trees with a step of 100 pcs ha^{-1}, as well as by groups of larch share in the plantation (by growing stock) with a step of 10% (see Table 1).

The experimental materials were processed by the methods of regression analysis and ANOVA employing Microsoft Excel spreadsheet and R statistical software package (R Core Team 2020). For the single-step multiple comparison procedure, to find means that are significantly different from each other, Tukey's honest significance difference test was used (de Mendiburu 2020).

Results

The area of larch-dominated plantations (in Ukraine, there are no data in the context of individual species of larch) is 9,848 ha, and 94% of larch plantations are concentrated within the Lviv, Ternopil, Ivano-Frankivsk, Transcarpathian, Khmelnytskyi, Rivne, Volyn and Chernivtsi regions, that is, the greatest part of these plantations was built within the conditions of the Western Forest-steppe. The relative volumes of stemwood in the plantations of the first three regions are 49, 23, and 5% of the total standing volume of larch plantations in Ukraine, respectively. It is in the Lviv and Ternopil regions that the largest silvicultural experience in the cultivation of larch plantations has been accumulated.

The distribution of plantations by year classes shows that in Ukraine, prevailing, in terms of area and volume of stemwood, are maturing larch plantations (28.7 and 36.5%, respectively), mature stands (25.3 and 30.5%, respectively), and middle-aged larch plantations (18.6 and 19.1%, respectively). The smallest areas in Ukraine are covered by overmature and young (I class of age) larch plantations – 5.5 and 9.8%, respectively. The legal age threshold for felling larch is 81 years in Ukraine. The selection of trial plots was carried out considering the age structure of larch plantations in the study region (see Table 1).

A regression analysis of the data set, which covers larch stands of all age classes and types of forest growth conditions, showed a direct linear relationship between the dependent variable – the total standing volume (*SV*) and individual regressors – the age of larch (*A*), the density of larch tree groups (quantity of larch trees per ha) (*QL*), the share of larch in the stand (*ShL*) and the total volume of larch stemwood (*SVL*) (Table 2). All obtained regression models are adequate, and their parameters are highly significant ($p < 0.0001$).

The results of multivariate analysis of variance, in which the types of forest growth conditions, age classes and the density of larch tree groups were used as categorical independent variables, showed a significant influence of all three factors on the total stemwood volume in the larch plantations (Table 3).

Based on the results of ANOVA, we continued the analysis of plant growth and productivity of the stands with the inclusion of European larch in context of types of forest site conditions and age classes.

It turned out that within the conditions of the fresh and fairly fertile site type (C_2) with an increased share of larch in the stand composition, the total standing volume increases within all age classes (Figure 1). High intensity of larch growth practically throughout the entire period of forest cultivation was indicated.

Under conditions of the fresh and fertile site type (D_2), in the stands aged 21–60 years, there is also a tendency towards an increase the total standing volume in the plan-

Table 2. Simple regression models (the dependent variable is total standing volume (*SV*), independent variables are age (*A*), quantity of larch trees per ha (*QL*), the share of larch in the stand (*ShL*) and the total volume of larch stemwood (*SVL*)

No. of model	Model	R^2	F	$F_{critical}$	p
1	$SV = 75.84 + 5.14A$	0.615	168.1	3.93	< 0.0001
2	$SV = 259.09 + 0.38QL$	0.181	23.24	3.93	< 0.0001
3	$SV = 180.18 + 29.7ShL$	0.260	37.0	3.93	< 0.0001
4	$SV = 182.84 + 0.81SVL$	0.650	195.1	3.93	< 0.0001

Table 3. Factorial ANOVA (the dependent variable is total standing volume (*SV*), categorical factors are site indices (Site), age groups (*AGr*) and groups concerning the quantity of larch tree per ha (*QGr*)

	DF	*SS*	*MS*	*F*	*p*
Site	2	122,687	61,344	16.98	< 0.0001 ***
AGr	9	1,297,390	144,154	39.91	< 0.0001 ***
QGr	8	494,915	61,864	17.13	< 0.0001 ***
Site : *AGr*	13	95,565	7,351	2.04	0.035 *
Site : *QGr*	6	17,309	2,885	0.80	0.575
AGr : *QGr*	13	18,503	1,423	0.39	0.966
Site : *AGr* : *QGr*	1	5,135	5,135	1.42	0.238
Residuals	54	195,063	3,612		

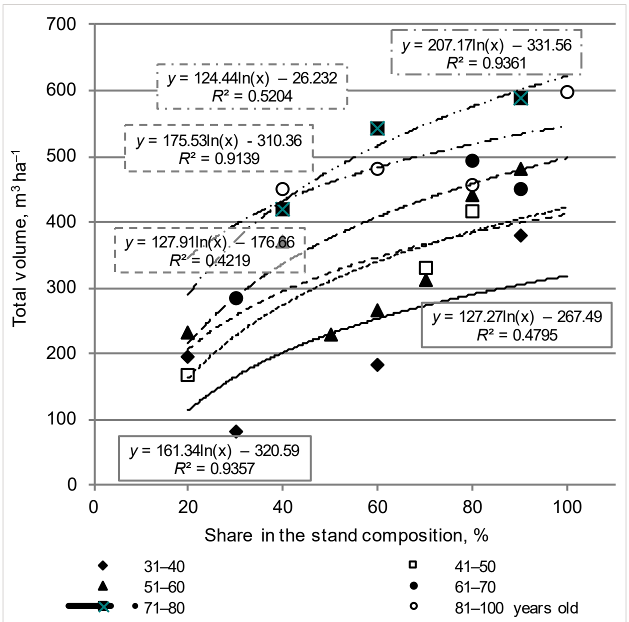

Figure 1. Relation between the total stemwood volume and the share of European larch in the composition of plantations of different age classes under C_2 forest site conditions

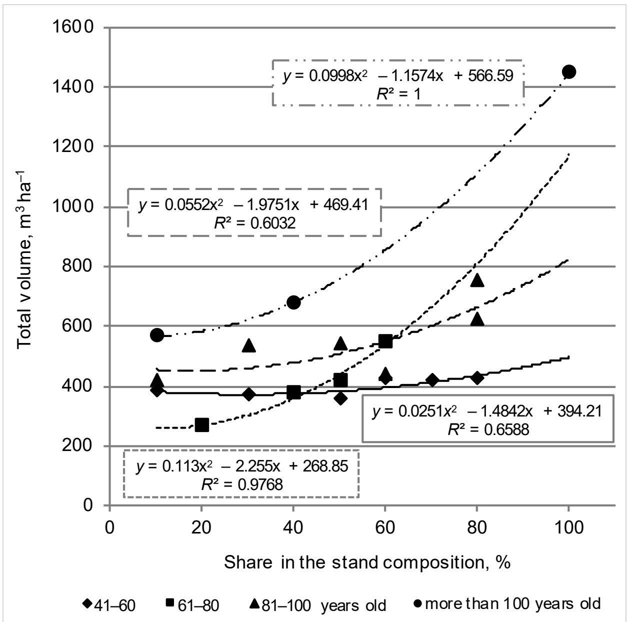

Figure 3. Relation between the total stemwood volume and the share of European larch in the plantations of different age classes under D_3 forest site conditions

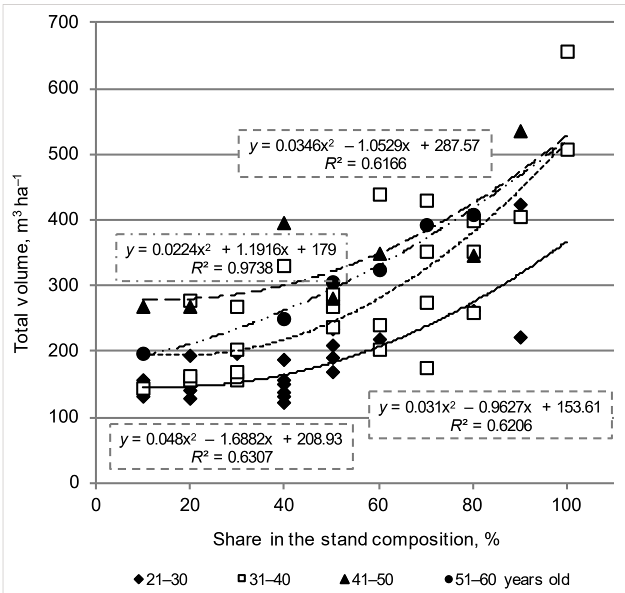

Figure 2. Relation between the total stemwood volume and the share of European larch in the plantations of different age classes under D_2 forest site conditions

tation with an increased share of larch (Figure 2). Moreover, such an increase is more noticeable in the stands aged 31–40 years, when the growth of larch is most intense. This is illustrated by the largest slope ratio of the linear function of the derivative of the corresponding regression model for this age class (0.096 vs. 0.044; 0.062; 0.070).

In the moist and fertile site types, the tendency towards increasing the stemwood volumes in the stands with increased share of European larch in their composition is mainly preserved (Figure 3). Only in the stands of the age of 41–60 with an increased share of larch, the increase in the total standing volume was insignificant, probably due to intensive intermediate felling (thinning). In general, in these forest growth conditions, the nutrient-rich conditions of the soils led to a significantly larger growing stock in larch plantations, compared with C_2 conditions.

As seen from Figures 1, 2 and 3, for C_2 type of forest growth conditions, the logarithmic regression models, which describe the change in the volume of stemwood depending on the share of European larch in the composition of plantations, turned out to be the most adequate, and for D_2 and D_3 types of polynomial regression turned out to be the most adequate. Under conditions of fairly fertile site type, the configuration of the diagrams of these regression functions shows that the increase in the growing stock in the plantation with an increased share of larch occurs at a decreasing rate, while in the conditions of fertile site type – at an increasing rate.

As can be seen from Model 4 (Table 2), the total growing stock of larch stands significantly correlates with the total volume of larch stemwood, which, in turn, significantly depends on its growth rate indices – the average height and the average stem diameter.

The results of regression analysis of the entire data set, which covers all year age classes and growth conditions, as well as data on forest site types, indicate a significant correlation between the main parameters of larch growth (average height, *H*, and average stem diameter at breast height, *DBH*, as a regressand and the age of larch, *A*, number of larch trees per ha, *QL*, the share of larch in the stand, *ShL*, as regressors (Table 4). Almost all obtained regression models are linear, except for Model 6. According to the set of criteria (R^2, *F*, *t*, *p*), all models are adequate, and their parameters are highly significant.

Table 4. Multiple regression models (the dependent variables are average height (*H*) and average diameter (*DBH*), independent variables are age (*A*), a number of larch trees per ha (*QL*), the share of larch trees in the stand composition (*ShL*)

No. of model	Model	R^2	F	$F_{critical}$	p
	All Site Indices				
5	$H = 12.20 + 0.20A - 0.01QL + 0.80ShL$	0.802	138.7	2.69	< 0.0001
6	$DBH = 13.78 + 0.28A - 0.06QL + 4.53ShL + 0.00005QL^2 - 0.32ShL^2$	0.697	46.4	2.30	< 0.0001
	Site Index C_2				
7	$H = 12.70 + 0.14A - 0.02QL + 1.16ShL$	0.694	12.1	3.24	0.0002
8	$DBH = 21.81 + 0.23A - 0.02QL$	0.507	8.75	3.59	0.0024
	Site Index D_2				
9	$H = 10.96 + 0.23A + 0.40ShL$	0.877	242.5	3.13	< 0.0001
10	$DBH = 17.43 + 0.23A - 0.03QL + 1.64ShL$	0.700	52.2	2.74	< 0.0001
	Site Index D_3				
11	$H = 13.59 + 0.18A + 0.87ShL$	0.724	17.1	3.81	0.0002
12	$DBH = 8.51 + 0.50A$	0.804	57.5	4.60	< 0.0001

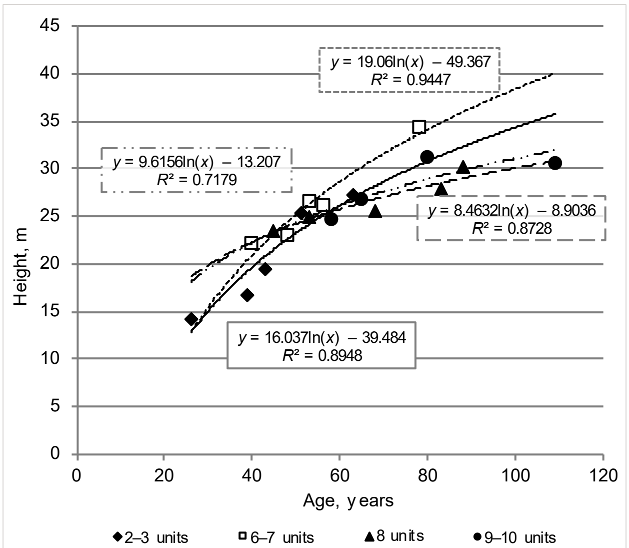

Figure 4. Dynamics of the average height of European larch in mixed plantations under C_2 forest site conditions

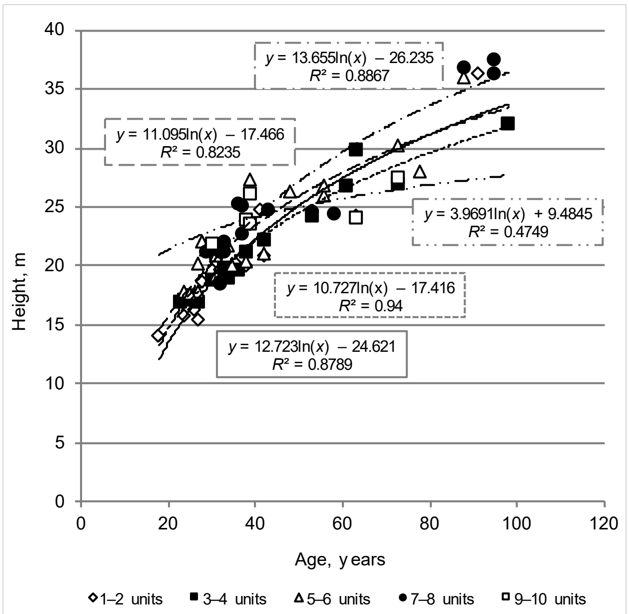

Figure 5. Dynamics of the average height of European larch in the mixed plantations under D_2 forest site conditions

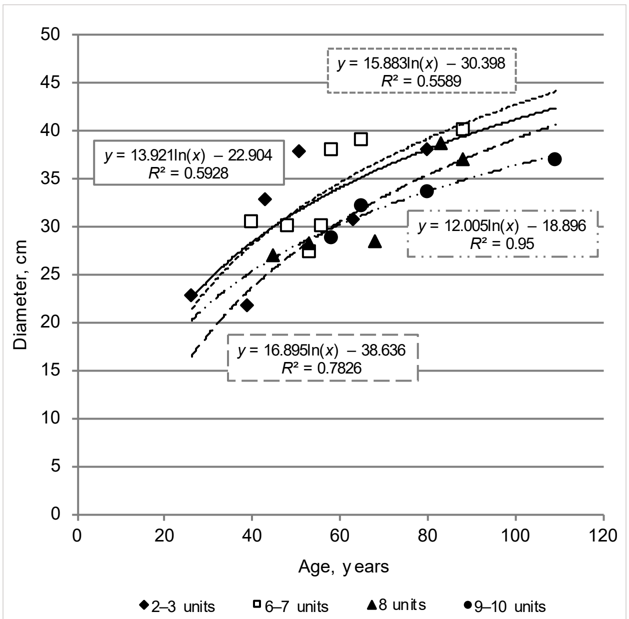

Figure 6. Dynamics of the average diameter of European larch stem in the mixed plantations under C_2 forest site conditions

Considering the obtained regression models, the next step of our study was to assess the dynamics of average growth rates of larch in the context of types of forest growth conditions, depending on larch share in the plantation composition.

Under C_2 conditions, the stand with an 80–100% share of European larch has the lowest height and the stands with a share of the species in the composition at the level of 6–7 units (Figure 4) have the highest one. In more fertile conditions of fresh oak-forest types, the highest average height is characteristic of larch plantations with a 70–80% share of larch in the composition, a slightly lower height is observed in plantations with both an insignificant share of the species (1–2 units) and moderate share (4–5 units) (Figure 5, Table 5).

The most intensive growth of the average diameter with age under C_2 conditions was observed in mixed plantations, where the share of larch is 2–3 and 6–7 units (Figure 6). With an increase in the share of larch in the composition, up to 80–100%, the *DBH* slightly decreases.

Table 5. Results of ANOVA and of Tukey's HSD test for the site index D_2

Dependent variable		Results of ANOVA					Factor AGr			Factor ShGr		
		DF	*SS*	*MS*	*F*	*p <*	factors code	means	difference	factors code	means	difference
SV	AGr	7	879,539	125,648	31.4	0.0001 ***	10	595	a	10	580	a
	ShGr	10	385,350	38,535	9.6	0.0001 ***	9	546	a	9	482	ab
	AGr × ShGr	23	59,277	2,577	0.6	0.86	8	465	b	8	399	bc
	Residuals	30	120,176	4,006			7	426	b	7	368	bcd
							5	316	c	6	322	cde
							6	312	c	3	293	cde
							4	293	c	5	277	cde
							3	184	d	2	248	de
										4	242	de
										1	208	e
H	AGr	7	1,604.1	229.15	67.5	0.0001 ***	9	36.5	a	8	26.2	a
	ShGr	10	116.2	11.62	3.4	0.0043**	10	35.6	a	10	25.0	ab
	AGr × ShGr	23	75.7	3.29	1.0	0.52	8	28.2	b	7	24.9	ab
	Residuals	30	101.9	3.40			7	26.3	bc	6	24.8	abc
							6	25.1	cd	9	24.4	abc
							5	23.4	de	0.5	24.2	abcd
							4	21.в6	e	3	23.2	abcd
							3	18.4	f	5	22.8	bcde
										2	21.4	cde
										4	20.9	de
										1	19.4	e
DBH	AGr	7	2227.2	318,2	22,8	0,0001 **	10	49.3	a	3	36.4	a
	ShGr	10	436,0	43,6	3,1	0,0075**	9	40.1	b	7	33.5	ab
	AGr × ShGr	23	382,4	16.6	1.2	0.32	8	38.0	b	6	32.8	ab
	Residuals	30	417,9	13.9			6	32.4	c	5	31.8	ab
							7	30.0	cd	8	31.8	ab
							5	29.6	cd	4	29.1	bc
							4	28.6	cd	2	28.5	bc
							3	26.6	d	10	27.9	bcd
										9	27.7	bcd
										1	23.7	cd
										0.5	21.8	d

Note: * significant at 5%, ** significant at 1%, *** significant at 0.01%.

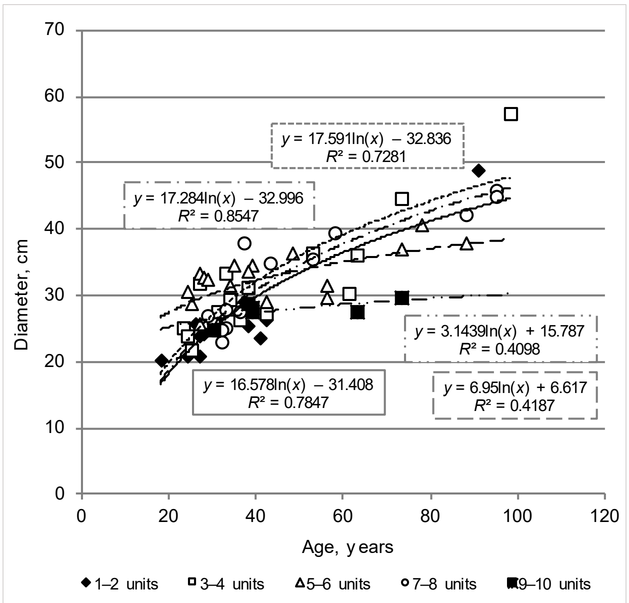

Figure 7. Dynamics of the average diameter of European larch stem in the mixed plantations under D_2 forest site conditions

In the conditions of fresh and fertile site type, the lowest average *DBH* is recorded in plantations with an insignificant (5–10%) and considerable (90–100%) share of larch in their composition (Table 5, Figure 7). The *DBH* was the highest in plantations where larch share reaches 30% and 50–70%.

Enough trial plots in larch plantations in fresh and fertile site types made it possible to conduct a multivariate analysis of variance, the results of which are presented in Table 5. As can be seen, the influence of all categorical variables (age classes and groups according to the proportion of European larch in the stand) both on the productivity of the stand (*SV*) and on the growth parameters (*H* and *DBH*) is highly significant.

Discussion

The analysis of data on the history of introduction of European larch from the 17th to the middle of the 20th century was performed by S. Jansen and T. Geburek (2016). Outside Europe, predominantly Alpine reproductive material was distributed, and genetic resources from the Sudetenland moved mainly to northeastern Germany and northwestern Poland. Genetic resources of *Larix decidua* var. *polonica* were spread mainly within Poland.

Due to its rapid growth, high adaptability, high-quality and durable wood, European larch is an important forest cultivation species outside its natural range. In northwestern Europe (Great Britain, Scandinavia) *Larix decidua* has been widely cultivated since the 16th century, and in some cases, it is a naturalized species. Since the mid-20th century, European larch has also been introduced to plantations in southern Canada and the northeastern United States. In New Zealand, European larch is classified as a naturalized and invasive species (Da Ronch et al. 2016).

European larch has been successfully cultivated in the western, central and northern parts of Ukraine for more than 200 years outside its natural range. By the mid-1980s, more than 3,000 stands with the inclusion of larch had been counted in Ukraine, the total area of which was 14,000 ha (Logginov 1988). As of January 1, 2006, the area of stands with both the dominance of larch in their composition and with an insignificant share of the species, amounted to 27,513 ha in Ukraine (Goroshko et al. 2011).

Based on the study of morphological features of European larch in the western region of Ukraine, V.S. Peshko (1965) supposed it to be of Tyrolean origin. According to Z.N. Zhivitskiy (1968), the largest area among the larch forests of the Ukrainian Carpathians is occupied by stands of larch of the Sudeten, Alpine and Tatra origin. More recent studies of natural and artificial populations of European larch, carried out by genetic methods, indicate a possible mixing over the past centuries of its genetic resources stored in separate refugia (Wagner et al. 2015). It is clear that this could most likely occur during the artificial recolonization of the species. Therefore, this factor cannot be excluded in the comparative analysis of growth and productivity of larch plantations.

The results of our studies have shown that most of the artificial plantations of *Larix decidua* are concentrated in the West of the country. In the Western Forest-Steppe, as of the beginning of 2000s, plantations with a predominance of larch in their composition covered 5,579 ha (Debryniuk 2003). It should be noted here that the whole Forest-Steppe of Ukraine should be a promising area for plantation cultivation of European larch.

This is evidenced by the optimistic results of studies of provenance trial plantations of larch species in the Sumy region (Hryhorieva et al. 2016) and an artificial population of European larch in the Kharkiv region (Los et al. 2018).

As it is shown in Table 5, larch plantations within the conditions of D_2 are characterized by high growth rate and productivity: the growing stock of the stands of age class 10 (91–100 years) is on average 595 m^3 ha^{-1}, the average height is at the average of 35.6 m, the average stem diameter is 49.3 cm. According to a retrospective analysis of materials on the growth and productivity of European larch, the potential for increasing its mensuration indices with age is significant. Thus, in the fund of the Horodnytsia forest district, Zhytomyr region, the multi-storeyed uneven-aged *Larix decidua* var. *polonica* stand, planted in 1805, according to the forest inventory of 1945, had a growing stock of 1,155 m^3 ha^{-1}, the average height of the upper storey was 45 m, with a maximum height of larch trees being 49–50 m, and an average diameter of 88.3 cm. The diameter of the thickest larch tree was 117 cm, and the volume of its stem was 22.3 m^3 (Stakheiko 1962).

Larix decidua plantations in the Western Forest-Steppe at the age of 150 years had an average growing stock change in the range of 7.7–8.7 m^3 ha^{-1} per year, i.e., they belonged to the category of fast-growing stands. The study of a 200-year-old plantation of European larch showed that it grew with site class 1^c, had a growing stock of 1,200 m^3 ha^{-1} and an average change rate in the growing stock of 6.0 m^3 ha^{-1} per year (Fuchylo et al. 2016).

In the Western Forest-steppe and the Carpathians, the growing stock of larch stands at the age of 60 years amounts to 720–880 m^3 ha^{-1}, and at the age of 100 years, the volume of stemwood is 920–1,100 m^3 ha^{-1} (Nikitin 1966). In the Volyn Forest-Steppe on humus-rich, sandy-loam soil, European larch at the age of 90, for a density of 1.0, had the average height, diameter and stemwood volume of 50.8 m, 43.2 cm, and 979 m^3 ha^{-1}, respectively (Sobinov 1947). In the Starokostiantyniv forest district, Khmelnytskyi region, within the conditions of C_3, a 60-year-old larch plantation accumulated a growing stock of 647 m^3 ha^{-1}, and in the Horodnytsia forest district, under the same conditions, a 120-year-old larch plantation had the growing stock of 830 m^3 ha^{-1} at the average height and diameter of 39 m and 52 cm, respectively (Lavrinenko 1965).

The possibility of a more intensive introduction of European larch eastward is also evidenced by the results of long-term testing of the species in the provenance trial plantations of the Serebryanoborsk experimental forest district near Moscow, Russia (Merzlenko et al. 2018). The studies of 66-year-old coniferous species introduced in the plantations of the western part of Moscow region, included seven species of the genus *Larix,* five species of the genus *Pinus*, one species of the genus *Picea* and one species of the genus *Pseudotsuga* showed that the highest silvicultural effect (site class 1^a) was observed in artificial plantations represented by the introduced coniferous species viz. *Larix decidua* var. *polonica*, *Larix kaempferi*, *Larix sukaczewii*, and *Pinus densiflora* (Merzlenko et al. 2017). The results of the study of introducing six species of larch in the north-eastern part of Moscow region showed that at a maturity age the European larch reaches the highest productivity; this species, having a high biotic resistance, forms stands with the stemwood volumes of 550–1,300 m^3 ha^{-1} (Melnik et al. 2005).

According to the study results, forest growth conditions is one of the determinants of the growth and productivity of larch plantations. And this is typical not only for European larch. Thus, the productivity of stands of other larch species (*Larix olgensis* A. Henry) varies from 5.4 to 11.7 m^3 ha^{-1}, depending on the site quality (Peng et al. 2018). Plantations involving European larch are highly productive and are of high decorative value even not under very favourable conditions of urbanized ecosystems (Dubenok et al. 2020), as well as under mountain conditions (Yatsyk et al. 2017).

The tendency towards increasing the total growing stock in the plantation with an increased share of European larch, revealed by us, is manifested not only within the conditions of the Western Forest-Steppe of Ukraine. As a result of studying *Larix decidua* Mill. plantations in the Tver region, Russia, it has been found that with a square planting of trees with a density of 550 trees per ha, larch up to the age of 120 years forms stands with its dominance in the composition and with the growing stock of up to 1,000 m^3 ha^{-1} (Merzlenko et al. 2016).

Conclusion

In Ukraine, most artificial plantations of *Larix decidua* have been established in the Western part of the country, in particular in the Lviv and Ternopil regions. However, the potential zone for effective cultivation of the species is not only the Western but also the Right-Bank and Left-Bank Forest-Steppe.

European larch plantations, with the appropriate technology of establishment and cultivation, are marked by intensive growth, high resistance, accumulates significant volumes of wood in a relatively short time. Under conditions of C_2, D_2, and D_3, there is a tendency towards increasing the volumes of stemwood in the plantations following an increased share of larch in them. The most noticeable influence of larch on the stand volume is observed at the age of 20–40 years when coniferous species have the highest growth rate.

The studies have shown different productivity and the character of growth of larch plantations in different types of forest growth conditions. European larch can form steady-state and highly productive plantations not only in fresh but also in moist types of forest growth conditions of the Western Forest-Steppe, the highest growth rate is observed on well-aerated soils of moist and fertile site types, and the smallest growth rates are observed in fresh and fairly fertile site types.

Under conditions of fresh and fairly fertile site type of the Western Forest-Steppe, larch is characterized by high values of mensuration indices throughout almost the entire period of forest growth, with its share in the composition being in the range of 20–30 to 60–70%. Within the conditions of fresh and fertile site type, high indices of average height are inherent in larch with a high share in the composition of plantations (6–10 units), and the average stem diameter with an average share of the species (3, 5–8 units).

The technology for the establishment of artificial larch plantations should be differentiated depending on the type of forest growth conditions by applying optimal mixing and spacing schemes and appropriate silviculture regimes that regulate the share of larch in these stands.

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