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Distribution and natural regeneration of *Tilia cordata* Mill. in Ukrainian plain forests in a changing climate

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Abstract

The aim of this study was to assess the current state of small-leaved lime stands under climate change, as well as to identify optimal conditions for the occurrence and further growth of natural lime regeneration under the stand canopy to grow productive and sustainable mixed stands. The areas of small-leaved lime (*Tilia cordata* Mill.) stands in plain Ukrainian forests and mixed stands with English oak (*Quercus robur* L.) were defined according to reference materials (as of 2016). Growth and liveability peculiarities of natural regeneration of lime under the canopy of oak-lime stands in climate change were identified. The main stand characteristics contributing to maximal appearance and further development of advance growth of lime, such as composition, age and relative density of stocking, were determined. It was found that the lime stands of vegetative origin occupy the largest part of the lime forests' area, being less resilient and productive than those originated from seeds. Small-leaved lime is the best associated species in mixed oak stands. The presence of lime improves health, assortment composition, and productivity of oak stands and increases their resistance against pests and diseases. In the future, lime can play an important role in the adaptation of forests to climate change due to its biological and forest properties and adaptability to a sustainable existence in a relatively wide range of environmental conditions. A summary of the studies complements a system of knowledge about the current state of lime stands as well as peculiarities of their regeneration and growth. The data obtained can be used as a theoretical base for forest management to promote natural regeneration and maintain the sustainability of these forests.

Key words

advance growth, associated species, mixed stands, productivity, stand origin

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Introduction

Modern manifestations of climate change, such as increasing intensity and frequency of droughts and floods, are the main environmental stress, which negatively affects the growth of trees, complicates their survival, reduces resistance to pests and diseases, and generally causes forest degradation. In Ukraine, the area of forests affected by pests and diseases increased by 40–50% over a period 2000–2015, which led to their weakening and dying (Yavorovskyi 2015). Seven thousand hectares of forests were lost during 1990–2000, while 19,000 ha died during 2006–2010. The most intensive forest health deterioration and decline were manifested in 2017. In that year, the total area of dying pine, spruce and oak stands exceeded 330,000 ha. The area of dying pine stands alone exceeded 142,000 ha, with wood losses reaching about 7.2 million m^3 (Shvidenko et al. 2014, 2018).

Conservation and enrichment of biodiversity in the Ukrainian forests can be ensured by introducing resistant tree species, including species of the genus *Tilia* L., which are best adapted to climate change (Sovakova and Sydorenko 2012; Ponomaryova 2013; Hlásny et al. 2014; De Jaegere et al. 2016; Falk et al. 2016; Zaika and Karpyn 2017).

The genus *Tilia* has a total of 31 species, 5 subspecies, 25 subvarieties and 4 hybrids (Sovakova et al. 2012). In the natural forests of Europe, there are small-leaved lime (*Tilia cordata* Mill.), large-leaved lime (*Tilia platyphyllos* Scop.), common lime (*Tilia europaea* L.), Caucasian lime (*Tilia euchlora* Koch), silver lime (*Tilia tomentosa* Moench) and some others (Masalsky 2007; Pigott 2012; Oleksiychenko et al. 2013; Sovakov et al. 2017). *T. cordata* Mill. and *T. platyphyllos* Scop. occur almost over the whole European continent (Radoglou et al. 2009; Eaton et al. 2016). The range of small-leaved lime spreads from central Sweden and southern Norway in the north to northern Greece in the south and from the northern part of the Iberian Peninsula and Northern Ireland in the west to the Ural Mountains in the east (Fig. 1). *T. cordata* and *T. platyphyllos* are the closest species in biological and ecological properties; however, *T. cordata* occupies richer and moist soils (Pigott 2012; Barker et al. 2015). In the natural forests of Ukraine, the most common species is T. cordata Mill. (Hordienko and Karpenko 1996; Soshenskyi et al. 2015; Sovakov et al. 2017). The largest area of small-leaved linden stands is concentrated in the north-eastern and central parts of Ukraine (Soshenskyi et al. 2015). *T. tomentosa* Moench. grows only in the forests of the Balkan Peninsula, Bulgaria, Romania, Ukraine and Greece (Sovakov et al. 2017).

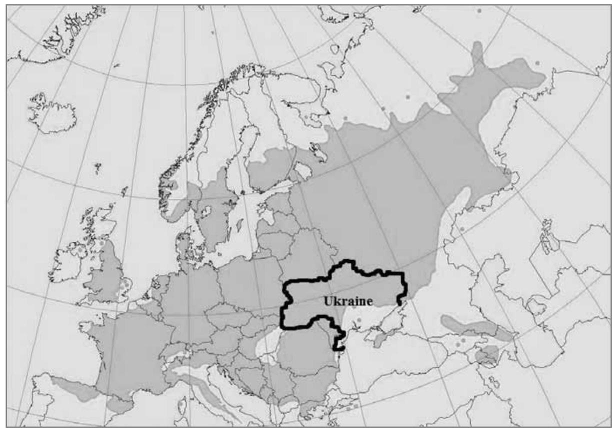

Figure 1. Distribution map of *Tilia cordata* Mill. (dark-grey) in Europe (Svejgaard 2003; Radoglou et al. 2009; De Jaegere et al. 2016)

Small-leaved lime is of considerable economic importance. It is actively used in landscaping and field shelterbelts planting as a soil-shading-associated species for ravine stands in the forest-steppe and steppe zones in Ukraine (Sovakova et al. 2012; Tsvetkova and Saranenko 2018; Sultanova et al. 2019). Lime stands are not only a source for meeting the ever-increasing demand for wood, bark and non-wood products but also an important bee forage. The melliferous capacity of lime is, according to various data, from 450 to 800 kg per 1 ha of continuous stands (Polishchuk and Bilous 1972; Vasylchenko 2010; Razanov et al. 2019). Wood is widely used in making musical instruments, household items, furniture, containers, barrels, bee houses, etc. (Praciak et al. 2013).

Due to the adaptability of *T. cordata* to sustainable existence in a relatively wide range of ecological conditions, its role in adapting forests to climate change is indisputable. Constant and comprehensive use of stands with lime in composition, as well as their management, requires in-depth knowledge of the current state of such stands, biological and ecological features, and a full range of forest values of this species.

The study of the potential possibility of small-leaved lime stands to perform ecological functions in various regions of Ukraine, as well as the ability of this species to adapt to different habitat conditions is new and practical.

The aim of this study was to assess the current state of small-leaved lime stands in the context of climate change, as well as to identify optimal conditions for the occurrence and further growth of natural lime regeneration under the stand canopy to develop effective interventions to grow productive and sustainable mixed stands.

Material and methods

The study examined stands with a predominance of small-leaved lime in the canopy layer. The stands were of different origin, age and stocking and covered the area of 13,610 ha. Also, we studied oak stands of different origin, age and relative density of stocking, which had 10–60% of small-leaved lime in the composition. The area of oak stands was 209,780 ha within six administrative regions of Ukraine, including Cherkasy Region, Chernihiv Region, Kharkiv Region, Kyiv Region, Poltava Region and Sumy Region. The study covered the forest fund of more than 60 state enterprises managed by the State Forest Resources Agency of Ukraine.

The data of the last forest survey (as of 2016) were the basis for the relevant calculations. Within the study area, 5,313 subcompartments were analysed where small-leaved lime predominated in the canopy layer and 48,062 subcompartments where it was found as a co-dominant species in oak stands.

Lime natural regeneration was studied under the canopy of oak stands of different ages and relative density of stocking within the specified administrative

Figure 2. Location of the study site (grey pattern is the distribution of oak and lime stands within Ukraine and the study area)

regions. The lime proportion in the oak stands ranged from 0% to 30% by the stock.

The natural regeneration was estimated on circular accounting sites of 10 m^2 each (R = 178 cm) according to the method developed in URIFFM (Pasternak 1990) with its classification by species, age and viability. The number of regenerated seedlings (N, trees) occurred per 1 ha was calculated by the formula (1):

$$N = \frac{n}{S} \cdot 1o^4 \quad (1)$$

where:

n – the number of individuals of the regeneration on the accounting sites,

S – an area of accounting sites, m^2.

In total, 600 accounting sites were established in six administrative regions under the canopy of 20 stands with an area of 5–18 ha, that is, 30 sites under the canopy of each of the 20 stands. For example, there were 60 sites under the canopy of two stands in the Kyiv Region (sample plots number 6 and 12 in Ivankivske Forest Enterprise), 90 sites under the canopy of three stands in the Cherkasy and Chernihiv Regions (sample plots number 2, 11 and 15 in Zolotoniske Forest Enterprise and number 1, 7 and 14 in Borznyanske Forest Enterprise) and 120 sites under the canopy of four stands in Kharkiv, Poltava and Sumy Regions (sample plots number 5, 10, 13 and 20 in Vovchanske Forest Enterprise; sample plots number 3, 9, 16 and 18 in Gadyatske Forest Enterprise; sample plots number 4, 8, 17 and 19 in Trostyanetske Forest Enterprise; Fig. 2).

Depending on the age of natural regeneration, 1-year-old, 2-year-old, …, and 15-year-old individuals were classified. The older regeneration was not found under the stand canopy. Age was determined by cutting the trunk and counting the number of annual rings near the root collar of at least 10 individuals.

Results

In Ukraine, lime stands cover an area of 20,430 ha, which is only 0.3% of the total forest area. Their largest areas are concentrated in six administrative regions of Ukraine, which are located in the central and north-eastern parts of the country, namely Cherkasy Region – 2,660 ha, Chernihiv Region – 1,680 ha, Kharkiv Region – 1,660 ha, Kyiv Region – 1,150 ha, Poltava Region – 2,220 ha and Sumy Region – 4,240 ha. These regions were the objects of the study. Significant areas of lime stands were also registered in Ivano-Frankivsk Region – 1,830 ha and Lviv Region – 1,280 ha, which are in the western part of Ukraine. In general, 81.8% (16,720 ha) of all lime stands in the country grow in these regions (Tab. 1).

Table 1. Current state of small-leaved lime (*Tilia cordata*) stands in Ukraine (as of 2016)

Administrative regions	Total forest area (ha)	Including small-leaved lime stands	
		ha	Percent of the total area
Autonomous Republic of Crimea	227,700	150	0.1
Cherkasy Region	255,400	2,660	1.0
Chernihiv Region	355,500	1,680	0.5
Chernivtsi Region	157,300	350	0.2
Dnipropetrovsk Region	65,700	50	0.1
Donetsk Region	92,500	110	0.1
Ivano-Frankivsk Region	425,800	1,830	0.4
Kharkiv Region	282,300	1,660	0.6
Kherson Region	77,300	–	<0.1
Khmelnytskyi Region	167,400	260	0.2
Kyiv Region	355,100	1,150	0.3
Kirovohrad Region	103,500	740	0.7
Luhansk Region	228,200	150	0.1
Lviv Region	428,200	1,280	0.3
Mykolaiv Region	37,400	–	<0.1
Odesa Region	90,200	80	0.1
Poltava Region	157,300	2,220	1.4
Rivne Region	584,200	200	<0.1
Sumy Region	255,600	4,240	1.7
Ternopil Region	143,600	460	0.3
Transcarpathian Region	461,200	20	<0.1
Vinnytsia Region	199,700	580	0.3
Volyn Region	436,800	100	<0.1
Zaporizhzhia Region	34,000	10	<0.1
Zhytomyr Region	660,300	450	0.1
Total Ukraine	6,282,200	20,430	0.3

Table 2. Distribution of lime stands by origin within the study area

Administrative regions	Origin of small-leaved lime (*Tilia cordata*) stands						Total small-leaved lime (*Tilia cordata*) stands	
	vegetative		natural seed		planted seed			
	ha	%	ha	%	ha	%	ha	%
Cherkasy Region	1,129	42.4	265	10.0	1,266	47.6	2,660	100
Chernihiv Region	1,405	83.6	136	8.1	139	8.3	1,680	100
Kharkiv Region	1,305	78.6	38	2.3	317	19.1	1,660	100
Kyiv Region	574	49.9	210	18.3	366	31.8	1,150	100
Poltava Region	1,784	80.4	29	1.3	407	18.3	2,220	100
Sumy Region	2,847	67.1	609	14.4	784	18.5	4,240	100
Total	9,044	66.5	1,287	9.5	3,279	24.0	13,610	100

Within the study area (Cherkasy Region, Chernihiv Region, Kharkiv Region, Kyiv Region, Poltava Region and Sumy Region), stands of vegetative origin make up the largest part of the total area of lime stands, amounting to 66.5% (9,044 ha from 13,610 ha total). Seeded stands occupy 24.0% of the area (3,279 ha), and natural seed origin stands account for 9.5% (1,287 ha). By administrative regions, the proportion of stands of vegetative origin ranges within 42.4–83.6%, while stands of natural seed origin are 1.3–18.3%, and stands established by seeding account for 8.3–47.6% (Tab. 2).

The study showed that stands of vegetative and natural seed origin with 50–70% of lime in their composition were the most productive. For example, their stock at the age of 61–70 reached 253–266 $m^3 \cdot ha^{-1}$ for vegetative stands and 262–268 $m^3 \cdot ha^{-1}$ for the stands of natural seed origin. The stands' stock volume decreased with the increase or decrease in the lime proportion in the composition.

Among stands grown from seeds, the highest productivity (190 $m^3 \cdot ha^{-1}$) was recorded for those with 60–70% of lime in their composition. The significantly smaller growing stock volume of planted stands is associated with their younger age (51–60 years), as well as slower growth compared to stands of vegetative origin. Another reason is the reduced resistance to adverse environmental factors compared to stands of natural seed origin, particularly at a young age, when planted stands have not yet formed a fully functional forest environment. If the lime proportion in the planted stands decreased or increased, their stock also decreased (Fig. 3).

Small-leaved lime, as already mentioned, serves as an associated species in oak stands in the Ukrainian forests; it has quite high growth rates in rich forest site conditions (fresh and moist fertile sites).

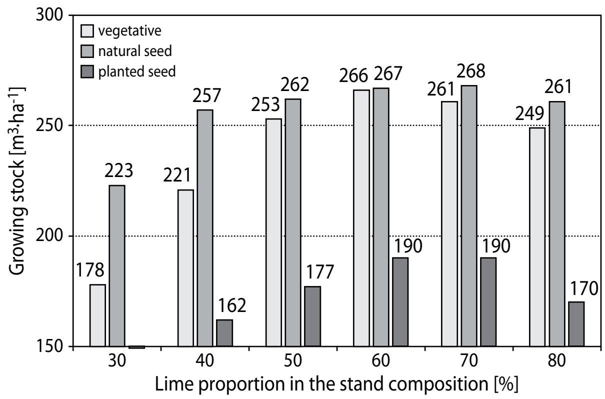

Figure 3. Productivity of stands with different lime proportion in their composition

Our results show that small-leaved lime grows as part of oak stands of various origins on an area of 209,780 ha. By regions, the area of oak-lime stands varied from 11,740 ha in Chernihiv Region to 59,860 ha in Cherkasy Region (Tab. 3). The part of the area of oak-lime stands in the total area of oak forests in these regions ranges within 22–51% (38.9% on average).

In these regions, mixed oak stands with 10–60% of lime in their composition are formed. The largest part of the area is occupied by stands, in which lime is 10–20%. For example, the areas of such stands were 82.8% in Cherkasy Region, 75.0% in Chernihiv Region, 85.6% in Kharkiv Region, 86.2% in Kyiv Region, 78.7% in Poltava Region and 76.7% in Sumy Region (Tab. 4).

Table 3. Percentage of oak-lime stands in the total area of oak forests

Administrative regions	Area of oak stands [ha]	Area of oak-lime stands [ha]	Percentage of oak-lime stands
Cherkasy Region	117,690	59,860	50.9
Chernihiv Region	54,560	11,740	21.5
Kharkiv Region	150,800	52,310	34.7
Kyiv Region	64,380	14,440	22.4
Poltava Region	55,780	24,910	44.7
Sumy Region	95,500	46,520	48.7
Total	538,710	209,780	38.9

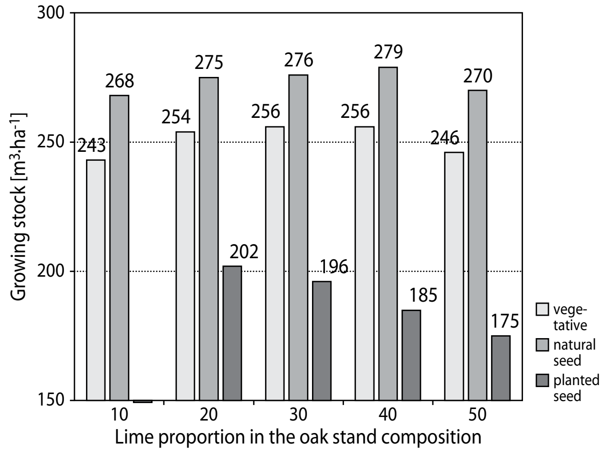

Figure 4. Productivity of oak stands with different lime proportion in their composition

The highest productivity was recorded for mixed oak-lime stands with 20–40% of lime in their composition. For example, the stock volume of the mixed stands of vegetative origin was 254–256 $m^3 \cdot ha^{-1}$ at the age of 71–75, while that of the stands of natural seed origin amounted to 275–279 $m^3 \cdot ha^{-1}$ at the age of 75–80. At that, the stock volume of the stands grown from seeds

Table 4. Distribution of the area of oak stands with different proportions of lime in their composition (numerator – ha, denominator – % of the area)

Origin of small-leafed lime (*Tilia cordata*) stands	Unit	Lime proportion in oak stands						
		10%	20%	30%	40%	50%	60%	total
1	2	3	4	5	6	7	8	9
Cherkasy Region								
Vegetative	ha	14,894	11,734	3,285	731	155	60	30,860
	%	48.3	38.0	10.6	2.4	0.5	0.2	100
Natural seed	ha	8,503	6,205	1,848	506	101	10	17,172
	%	49.5	36.1	10.8	2.9	0.6	0.1	100
Planted seed	ha	4,078	4,126	1,959	963	488	214	11,828
	%	34.5	34.9	16.6	8.1	4.1	1.8	100
Total	ha	27,474	22,065	7,092	2,201	744	284	59,860
	%	45.9	36.9	11.8	3.7	1.2	0.5	100
Chernihiv Region								
Vegetative	ha	3,330	2,177	922	337	174	28	6,969
	%	47.8	31.2	13.2	4.8	2.5	0.4	100
Natural seed	ha	1,208	1,018	661	380	48	8	3,324
	%	36.3	30.6	19.9	11.4	1.5	0.2	100
Planted seed	ha	589	484	232	91	33	24	1,452
	%	40.5	33.3	16.0	6.2	2.3	1.7	100
Total	ha	5,126	3,679	1,813	808	254	60	11,740
	%	43.7	31.3	15.4	6.9	2.2	0.5	100

1	2	3	4	5	6	7	8	9
Kharkiv Region								
Vegetative	ha	22,774	11,231	3,730	1,053	196	42	39,025
	%	58.4	28.8	9.6	2.7	0.5	0.1	100
Natural seed	ha	4,541	2,823	723	276	155	26	8,543
	%	53.2	33.0	8.5	3.2	1.8	0.3	100
Planted seed	ha	1,917	1,467	872	222	166	99	4,742
	%	40.4	30.9	18.4	4.7	3.5	2.1	100
Total	ha	29,232	15,521	5,324	1,551	517	167	52,310
	%	55.9	29.7	10.2	3.0	1.0	0.3	100
Kyiv Region								
Vegetative	ha	4,481	1,173	422	187	11	29	6,303
	%	71.1	18.6	6.7	3.0	0.2	0.5	100
Natural seed	ha	2,850	1,116	489	185	83	18	4,741
	%	60.1	23.5	10.3	3.9	1.8	0.4	100
Planted seed	ha	2,020	802	329	131	82	31	3,396
	%	59.5	23.6	9.7	3.9	2.4	0.9	100
Total	ha	9,351	3,091	1,240	503	177	78	14,440
	%	64.8	21.4	8.6	3.5	1.2	0.5	100
Poltava Region								
Vegetative	ha	8,823	6,398	2,772	760	208	28	18,988
	%	46.5	33.7	14.6	4.0	1.1	0.1	100
Natural seed	ha	1,333	971	423	165	35	13	2,940
	%	45.3	33.0	14.4	5.6	1.2	0.5	100
Planted seed	ha	1,191	890	479	254	106	61	2,982
	%	39.9	29.9	16.1	8.5	3.6	2.1	100
Total	ha	11,346	8,259	3,674	1,179	349	103	24,910
	%	45.5	33.2	14.7	4.7	1.4	0.4	100
Sumy Region								
Vegetative	ha	12,140	9,267	4,309	1,593	462	155	27,925
	%	43.5	33.2	15.4	5.7	1.7	0.6	100
Natural seed	ha	5,884	4,893	2,137	572	151	38	13,674
	%	43.0	35.8	15.6	4.2	1.1	0.3	100
Planted seed	ha	1,890	1,595	811	418	168	41	4,921
	%	38.4	32.4	16.5	8.5	3.4	0.8	100
Total	ha	19,913	15,754	7,256	2,582	781	233	46,520
	%	42.8	33.9	15.6	5.6	1.7	0.5	100

was 185–202 $m^3 \cdot ha^{-1}$ at the age of 50–55. With a decrease or increase in the lime proportion in oak stands, their stock gradually decreases (Fig. 4).

The number of lime natural regeneration aged under 15 was insignificant under the canopy of oak stands and ranged within 100–2,100 trees per ha. Its proportion in the total natural regeneration was 0.8–25.6%. It should be noted that the largest number of naturally regenerated lime seedlings, from 1,000 to 2,100 trees per ha (1,100 ± 210 on average), was recorded under the canopy of oak stands with 10–30% of lime in their composition. These stands were 101–130 years old and had relative density of stocking of 0.65–0.80. In older stands (131–200 years old), the number of lime seedlings was much smaller (100–600 trees per ha, 310 ± 73 on average). In stands aged from 50 to 100, the lime regeneration varied within 200–500 trees per ha (340±53 on average; Tab. 5). Mann–Whitney *U* test showed that the number of lime seedlings was significantly higher only for 101- to 130-year-old oak stands ($U = 3.254$, $p \leq 0.05$).

Under the canopy of the investigated stands, the natural regeneration of other tree species such as Eng-

Table 5. Natural regeneration aged below 15 years under the canopy of oak stands of different ages, compositions and relative densities of stocking

Sample plot number	Characteristics of oak stands			The number of naturally regenerated seedlings		
	stand composition	age [years]	relative density of stocking	total [trees ha^{-1}]	including small-leaved lime: trees [ha^{-1}]	including small-leaved lime: %
Oak stands aged 50–100 years						
1	Oak 50%, ash 30%, N-maple 10%, lime 10%	50	0.85	4,300	200	4.7
2	Oak 40%, ash 30%, N-maple 20%, lime 10%	60	0.65	8,300	200	2.4
3	Oak 50%, ash 30%, lime 10%, N-maple 10%	70	0.60	14,600	400	2.7
4	Oak 80%, ash 10%, lime 10%	70	0.60	14,800	400	2.7
5	Oak 70%, lime 30%	79	0.80	6,500	500	7.7
6	Oak 90%, lime 10%	92	0.62	12,900	200	1.6
7	Oak 60%, lime 20%, ash 10%, N-maple 10%	99	0.83	11,600	500	4.3
	Mean	74	0.71	10,400	300	3.7
Oak stands aged 101–130 years						
8	Oak 60%, lime 30%, N-maple 10%	104	0.76	5,900	1,200	20.3
9	Oak 70%, lime 20%, N-maple 10%	104	0.75	22,100	1,100	5.0
10	Oak 70%, lime 20%, N-maple 10%	105	0.75	3,900	1,000	25.6
11	Oak 70%, ash 10%, lime 10%, N-maple 10%	108	0.70	16,700	300	1.8
12	Oak 70%, lime 20%, ash 10%	110	0.65	12,200	800	6.6
13	Oak 60%, ash 20%, lime 20%	115	0.66	8,600	2,100	24.4
14	Oak 80%, lime 10%, N-maple 10%	124	0.80	9,400	1,400	14.9
	Mean	110	0.70	11,300	1,100	14.1
Oak stands aged 131–200 years						
15	Oak 50%, ash 20%, lime 20%, N-maple 10%	144	0.80	8,100	400	4.9
16	Oak 50%, ash 20%, N-maple 20%, lime 10%	157	0.74	10,200	200	2.0
17	Oak 100%	183	0.61	12,900	100	0.8
18	Oak 90%, lime 10%	188	0.66	25,000	600	2.4
19	Oak 100%	193	0.69	26,800	300	1.1
20	Oak 50%, lime 30%, ash 10%, N-maple 10%	198	0.59	13,000	200	1.5
	Mean	177	0.70	16,000	300	2.1

Note: Oak – English oak (*Quercus robur* L.), ash – common ash (*Fraxinus excelsior* L.), N-maple – Norway maple (*Acer platanoides* L.), lime – small-leaved lime (*Tilia cordata* Mill.).

lish oak, common ash, Norway maple (*Acer platanoides* L.), field maple (*Acer campestre* L.), wych elm (*Ulmus glabra* Huds.) and aspen (*Populus tremula* L.) was also recorded. In some sites, the proportion of the regenerated seedlings of these species was 75–99% of their total number.

Discussion

The data of some studies (Soshenskyi et al. 2015) indicate a decrease in the area of small-leaved lime stands in Ukraine. For example, as of 2014, the area of stands with small-leaved lime predominance was 22,213 ha, with a total stock volume of about 5 million m^3. Among them, 77% of the area was occupied by lime stands of natural origin, in particular, 58% vegetative and 19% seed. Planted lime stands occupied 23% of the area. Middle-aged (45%) and mature (27%) stands dominated in the age structure. Approaching maturity and overmature stands occupied an area of 14% and 12%, respectively, while young stands covered less than 2%.

In the forest-steppe zone of Ukraine, small-leaved lime stands occupy 1.1% of the total area of forests. The distribution of their area by origin is as follows: vegetative origin – 66%, natural seed origin – 12%, and stands established by seeding – 22% (Soshenskyi et al. 2018). Our study also revealed a significant predominance of stands of vegetative origin (66.5% of the total area of lime stands) and a small proportion of the most valuable and productive stands of natural seed origin (9.5%). The remaining area (24%) is occupied by artificially seeded stands.

In the forests of Lithuania, only *T. cordata* occurs, the pure stands of which cover an area of 4,600 ha comprising 0.24% of the total forest area. It also grows as individual trees in mixed forests with English oak (*Quercus robur* L.) and common ash (*Fraxinus excelsior* L.) (Semaškiene 2006). Stands of *T. cordata* and *T. platyphyllos* make up 1.1% of the total forest area in the forests of the Czech Republic and 0.4% in the forests of Slovakia. In recent decades, the proportion of lime stands in the Czech Republic has decreased from 6.5% in 1970–1990 to 1.1% in 2012 (Čihák et al. 2014).

In the past, in European forests and, in particular, in Ukraine, small-leaved lime occupied much larger areas as the main species or as an admixture in other deciduous stands. However, due to the much lower economic value of its wood at the present-day market, it gave way to more valuable tree species, including English oak and common ash in fertile forest site conditions, as well as Scots pine (*Pinus sylvestris* L.) in infertile sites (Hordienko and Karpenko 1996; Pigott 2012). In recent decades, mostly pure oak stands are established on felled areas in fertile forest types, where 76% of small-leaved lime stands are concentrated. When establishing oak stands in fresh fertile oak forest sites, the proportion of small-leaved lime in their composition should be up to 30% (Hordienko and Karpenko 1996; Karpenko 1999). Zaika and Kalenyuk (2018, 2019) proposed to add up to 40% of lime in the composition of oak stands in hornbeam-oak forests in Western Podillya (Vinnytsya, Ternopil and Khmelnytskyi Regions, Ukraine) to grow resilient and productive mixed stands. According to their data, the timber volume for such a proportion of lime in the mature stands is 409–487 m^3 ha^{-1}. Lime increases the stand resistance to pests and diseases, as well as to the negative impact of climate change; it also improves soil fertility and enriches the biological diversity of the stands. Our results confirm the conclusions of Zaika and Kalenyuk (2018, 2019) that productivity is the highest in mixed oak and lime stands with 20–40% of lime in their composition. The stock volume gradually decreases with a decrease or increase of lime proportion in oak stands.

Also, small-leaved lime, black alder (*Alnus glutinosa* L.) and silver birch (*Betula pendula* Roth.) have the highest carbon-absorbing capacity, which is 60–100 tonnes per ha (Moroz et al. 2017).

Small-leaved lime along with Norway maple and European hornbeam (*Carpinus betulus* L.) is the most common nursing tree species for English oak and common ash in the fertile oak forest sites within Ukrainian forest-steppe (Hordienko and Karpenko 1996; Karpenko 2013). This species shows intensive growth in natural mixed stands in fresh fertile forest type (Karpenko 2013). For example, at the age of 91–107, lime trees reach an average height of 22.1–27.2 m and an average diameter of 24.9–40.1 cm. According to Murakhtanov (1981), in the Volga River basin (Russian Federation), lime stands aged 110 had an average height of 25.6 m and an average diameter of 34.2 cm.

In 66-year-old mixed oak and lime stands with 60% of English oak and 40% of small-leaved lime in the composition, planted within Kirovohrad Region in central part of Ukraine, the average height of oak was 21.2 m, and the average diameter was 24.5 cm. In 66-year-old planted mixed oak and maple stands with 70% of English oak and 30% of Norway maple, the average height of oak was found to be 20.9 m, and average diameter was 23.0 cm. In 66-year-old planted mixed oak and hornbeam stands with 80% of English oak and 20% of European hornbeam, the average height of oak was 18.1 m and average diameter was 20.8 cm. In 68-year-old planted pure oak stands (100% of English oak), the average height of oak was 19.4 m while the average diameter was 19.2 cm. Thus, the best values of average height and diameter were recorded in oak-lime stands. They exceeded pure oak stands by 8% in average height and by 22% in average diameter (Hordienko and Karpenko 1996).

In oak-lime stands, the crown closure in a row occurs at the age of 5 years while in pure oak stands at the age of 6–7 years, due to the annual decomposition of organic litter by 70% in the mixed stands, while in pure oak stands this value is only 14% (Karpenko 2013; Shpak et al. 2017). Lime leaf litter reduces soil acidity during decomposition and enriches the soil with humus, thus improving the fertility of acidic soils more actively than English oak, European larch (*Larix decidua* Mill.) and others do because lime leaves contain calcium. Therefore, lime trees are effectively used for ecosystem restoring in places with heavy anthropogenic impact (Alekseev and Vinnichenko 2012; Tsvetkova and Saranenko 2018).

Natural seed regeneration of small-leaved lime under the stand canopy and on cut-over sites is generally poor (Pigott 1975; Murakhtanov 1981; Hordienko and Karpenko 1996; Radoglou et al. 2009; Shayakhmetov and Sejdafarov 2016; Zaika and Kalenyuk 2018, 2019; Kalenyuk and Zaika 2019, Sultanova et al. 2019, 2020). This is due to unfavourable conditions for the germination of lime seeds and further development of advance growth such as high air temperature, overgrowth of grass vegetation and lack of moisture in the soil.

Small-leaved lime is one of the most shade-tolerant tree species (Murakhtanov 1981). The shade tolerance of *T. cordata* is exceeded only by silver fir (*Abies alba* Mill.), European beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* (L.) Karsten) and hornbeam. The small-leaved lime trees are propagated successfully by seeds and shoots from stumps (Iurkevich et al. 1998; Sovakova et al. 2012; Sultanova et al. 2019, 2020). Small-leaved lime seedlings appear and develop if the light is 2.0–2.5% of full sunlight (Shayakhmetov and Sejdafarov 2016). In addition to insufficient light and humidity, other reasons for the death of lime seedlings are considered to be their severe damage by fungal diseases, freezing in the autumn–winter period and periodic drying of litter and root layer of soil. Lime bears seeds annually, but high crop occurs in 2–5 years, and medium one in a year (Murakhtanov 1981). Thus, in Polissya and forest-steppe zones in Ukraine, lime trees produce an abundant crop of seeds every 2–3 years (Hordienko and Karpenko 1996). The seeds tend to germinate only in the second year after ripening (Aas 2016).

Zaika and Kalenyuk (2019) showed that in hornbeam-oak forests of the Western Podillya in Ukraine, the viability of lime seeds remains high (55–94%) in different years. However, the natural seed regeneration of lime is mostly poor. This is due to unfavourable conditions for the seed germination under the stand canopy and on felling sites (Hordienko and Karpenko 1996; Bondar 2004). Examining the natural regeneration of small-leaved lime in Podillya in Ukraine, Bondar (2004) found the advance regeneration of this species in 44% of felling sites of different ages, where its number ranged from 4 to 1,320 trees per ha. The results of our research also indicate the poor natural regeneration of lime under the canopy of oak and oak-lime stands.

Lime is adapted to different soil types; however, it grows best on chernozems. Fresh and moderately moist, enriched with forest humus, loose and well-drained sandy-loam and light loamy soils are optimal (Murakhtanov 1981; Matusyak 2017; Tsvetkova and Saranenko 2018; Kalenyuk and Zaika 2019). It is intolerant to bogging (De Jaegere 2016) but can tolerate high soil acidity and grow in the pH range from 4 to 8. However, neutral soils are optimal, where pH does not exceed 5–6 (Radoglou et al. 2009).

Conclusions

In Ukrainian forests, the total area of stands with a predominance of small-leaved lime in the canopy layer is almost 20.5 thousand hectares (only 0.3% of the total forest area). More than 80% – about 16.7 thousand hectares – of their total area is concentrated in eight administrative regions of the country, which are territorially assigned to the central, north-eastern and western parts of Ukraine: Cherkasy Region, Chernihiv Region, Kharkiv Region, Kyiv Region, Poltava Region, Sumy Region, Ivano-Frankivsk Region and Lviv Region.

On a large area, almost 210,000 ha, or 38.9% of the total area of oak forests in the above regions, small-leaved lime occurs as part of oak stands of various origins and quite intensively grows in fertile forest conditions (fresh and moist fertile oak sites). The oak-lime stands with 20–40% of lime in the composition have the highest productivity.

Lime natural regeneration is mostly poor under climate change. The largest number of lime natural regeneration, from 1,000 to 2,100 trees per ha, was recorded under the canopy of 101- to 130-year-old oak stands with 10–30% of lime in their composition and relative density of stocking of 0.65–0.80. In older (131–200 years) and younger (50–100 years) stands, the number of lime regeneration was much smaller (up to 600 trees per ha).

The development of highly productive mixed oak-lime forests should be ensured by carrying out appropriate forestry practices in oak forests with a focus on their natural regeneration, in particular, partial main-use felling and further forest tending in young stands on clear-cuts. At the same time, it is necessary to preserve lime advance growth as much as possible. Tending felling should ensure 20–40% of lime in the composition of mixed stands. When focusing on the artificial regeneration of oak stands, it is necessary to introduce 20–30% of lime in the forest crop composition.

The generalization of the research results complements the knowledge system on the current state of lime forests, as well as small-leaved lime regeneration and development specificities. Also, it can be used as a theoretical basis for developing a system of forestry practices to promote natural regeneration.

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