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Research Article

THE INTRODUCED NORTH AMERICAN SPECIES OF THE GENUS *Juglans* L. IN THE RIGHT-BANK FOREST-STEPPE OF UKRAINE AND THEIR USE

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Abstract: The article presents generalized scientific researches and experimental data on the bioecological peculiarities of the North American species of the *Juglans* L. genus. The peculiarities of the seasonal rhythm of development are revealed. *Juglans cinerea* L., *J. rupestris* Engelm. and *J. major* (Torr.) A. Heller were the first to wake up and *J. nigra* L., *J. californica* S. Wats., and *J. hindsii* (Jeps.) Jeps. ex R.E. Sm. wake up a little later. The biorhythm of woody plants is closely related to the increase in the sum of active (+10°C) and effective (+5°C) temperatures. *Juglans cinerea* and *J. rupestris* require the smallest sum of effective temperatures for buds swelling, that is 28.9 and 34.1°C, respectively; *J. hindsii* require the largest sum of effective temperatures -57.1°C and *J. nigra* require 50.6°C. Investigation of growth dynamics shows that intensive growth of all species of the *Juglans* genus was observed in May-June. The vegetation period in all *Juglans* species lasts 183-206 days. The development cycle of North American walnuts under research conditions is shifted towards the summer-autumn period. When determining frost resistance, it was found that the species are characterized by an average degree of subfreezing. All species genus are promising for use in ornamental horticulture of the Right-Bank Forest-Steppe of Ukraine, as evidenced by the full acclimatization of *J. nigra* and *J. cinerea*, good acclimatization of *J. rupestris* and *J. major* and satisfactory acclimatization of *J. californica* and *J. hindsii*. It is established that *J. nigra* are promising for the development of highly productive forest plantations.

Özet: Bu çalışmada *Juglans* L. cinsinin Kuzey Amerika türlerinin biyolojik özellikleri ile ilgili genel bilimsel araştırmalar ile deneysel bulgular sunulmuştur. Bu türlere ilişkin mevsimsel gelişim özelliklerinin detayları ortaya konmuştur. *Juglans cinerea* L., *J. rupestris* Engelm. ve *J. major* (Torr.) A. Heller ilk uyanan türler iken *J. nigra* L., *J. californica* S. Wats. ve *J. hindsii* (Jeps.) Jeps. ex R.E. Sm. biraz daha geç uyanmışlardır. Odunsu bitkilerin biyolojik ritimleri aktif (+10°C) ve efektif (+5°C) sıcaklık değerlerinin toplamındaki artış ile yakında ilişkilidir. *Juglans cinerea* ve *J. rupestris* tomurcuklanma için en düşük toplam efektif sıcaklık değerlerine (sırasıyla 28.9 °C ve 34.1°C), *J. hindsii* ve J. nigra ise en yüksek değerlere (sırasıyla -57.1°C ve 50.6°C). Büyüme dinamiklerinin incelenmesi tüm *Juglans* türlerindeki yoğun büyümenin Mayıs-Haziranda yaşandığını göstermiştir. Tüm türlerdeki vejetasyon süresi 183-206 gün sürmektedir. Kuzey Amerika kökenli cevizlerin araştırma sahası koşullarındaki gelişim döngüsü yaz-sonbahar dönemine doğru kaymıştır. Dona dayanıklılık tespiti için yapılan çalışmalar tüm türlerin ortalama bir donma derecesi ile karakterize olduklarını göstermiştir. Tüm türler Sağ Yaka Ukrayna orman-step bölgesinde süs bitkiciliği kullanımı için gelecek vaat etmektedirler ki bu durum *J. nigra* ve *J. cinerea*'nın tam, *J. rupestris* ve *J. major*'ın iyi derecede ve *J. californica* ve *J. hindsii*'nin yeterli derecede uyum sağlamış olmalarıyla desteklenmektedir. *Juglans nigra*'nın yüksek üretkenlikte orman alanları oluşturulmasında ümit veren bir tür olduğu düşünülmektedir.

Introduction

The genus *Juglans* L. is classified in the Juglandaceae family, Juglandales order, Hamamelididae subclass, Magnoliopsida class, Magnoliophyta division according to the system of Takhtadjian (1980). De Candolle (1857), Dode (1909), Engler & Prantl (1894), Linnaei (1759), Martin, Zim & Nelson (1951), Manning (1978), APG IV

(The Angiosperm Phylogeny Group, 2016) studied the systematics of the genus, the history of its origin, the spreading pattern over the world and phylogenetic relations of the North American species of the genus. *Juglans nigra* L. was first described by Carl Linnaeus in 1737, *J. cinerea* L. in 1759, and the other North American species were described in the nineteenth century. Researchers so far identified 10 species in the genus spreading in moderately warm, subtropical and even tropical regions of Eurasia (*J. regia* L., *J. mandshurica* Maxim., *J. cordiformis* Maxim., *J. sieboldiana* Maxim.) and North America (*J. nigra*, *J. cinerea*, *J. rupestris* Engelm., *J. major* (Torr.) A. Heller, *J. californica* S. Wats., *J. hindsii* (Jeps.) Jeps. ex R.E. Sm.) (Fig. 1) (Sokolov 1957).

According to Zhukovsky (1971), *Juglans* genus has four genetic centers of origin as Central Asian, Western Asian, Chinese-Japanese and North American. *Juglans nigra*, *J. cinerea*, *J rupestris*, *J. major*, *J. californica* and *J. hindsii* are the species with North American origin center. The current occurrence areas of species of the genus are the part of one large area that existed in the past geological epochs and disintegrated because of the climate changes.

Numerous fossils indicated that the genus is known from the Upper Cretaceous, and the number of species and their distribution areas changed in past geological epochs. Representatives of the genus in terms of species diversity reached their highest peak in the Eocene, Oligocene and Miocene ages (Ishchuk 2013).

Juglans nigra and *J. cinerea* were introduced to Ukraine in the early nineteenth century. *Juglans nigra* was introduced in 1809 by the Osnoviansky Acclimatization Garden. *Juglans cinerea* has been known since 1816 and was first introduced in the Kremenets Botanical Garden in Ternopil region (Barbarich & Horhota 1952, Ishchuk 2007a). Both species underwent a long period of acclimatization and are widely represented in the dendrological collections, forest crops and street plantations of all natural-and-climatic zones of Ukraine. *Juglans rupestris*, *J. major*, *J. californica* and *J. hindsii* were introduced to Ukraine in the 1930s at Nikitsky Botanical Garden and are now rarely found in the dendrological collections of Eastern, Central and Southern Ukraine (Ishchuk 2007b). The period of acclimatization of these species continued to present day. The oldest trees of *J. nigra* are in the O.V. Fomin Botanical Garden in Kyiv (1854) and in the arboretum of Ukrainian National Forestry University in Lviv.

The North American species of the genus are rare in the Right-Bank Forest-Steppe of Ukraine because of insufficient studies on the bioecological peculiarities of their introduction. Only two species, *J. nigra* and *J. cinerea*, are found in the forest crops of this region. Other species, *J. rupestris*, *J. californica*, *J. major* and *J. hindsii*, are only present in the collections of botanical gardens and dendrological parks where they are cultivated as single trees in the territory of Ukraine.

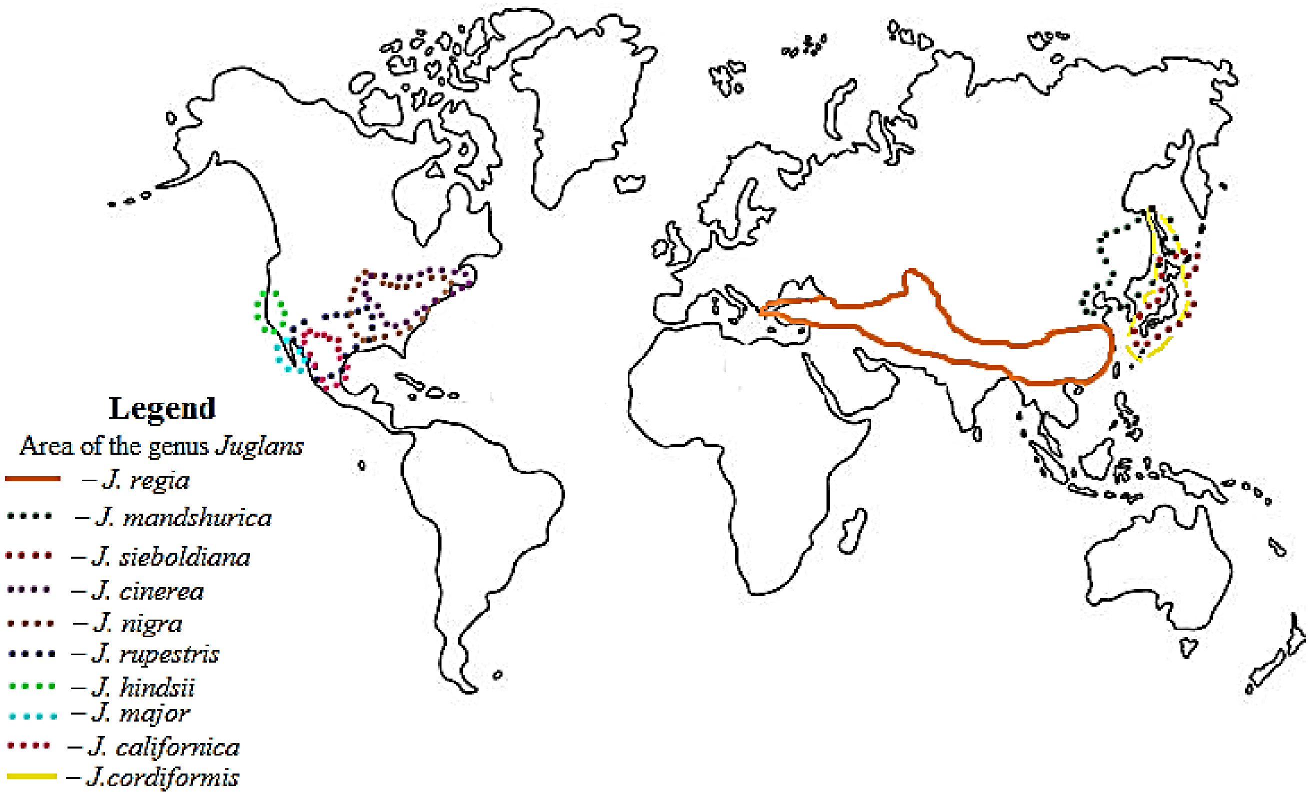

Fig. 1. The distributional area of the genus *Juglans* (according to Sokolov, 1957) 1- *J. regia*, 2- *J. mandshurica*, 3- *J. sieboldiana*, 4- *J. cinerea*, 5- *J. nigra*, 6- *J. rupestris* 7- *J. hindsii*, 8- *J. major*, 9- *J. californica*, 10- *J. cordiformis*.

During the last century, Badalov (1971) (selection of nuts and research on bioecological features of hybrids), Shchepotiev (1985) (bioecological features of *J. regia* and partly of *J. nigra* and *J. cinerea*), Bondar (1997), Shvydenko & Tsygankov (1978) (study on *J. nigra* in the forest crops), Kenig (1966), Antoniuk (1968), Hryshko-Bogmenko (1969) (studies on the introduction of some *Juglans* species in Ukraine), Zhyhalova (2007) (review of the systematic features in determining the representatives of the *Juglans* genus), Takhtadjian (1980) (systematics of the genus) were engaged in the study of the representatives of the genus. Analysis of the economic use of *J. nigra* was performed by Dubrovsky & Shved (2019).

However, most of these works were dedicated to *J. regia*, the most common in the Forest-Steppe, which originated from the Balkans, Iran and Asia Minor. In general, these sources contributed only to certain partial information about the North American species *J. nigra* and *J. cinerea* and their hybrids with *J. regia* and with themselves, which were more related to the western and northern parts of the Right-Bank Forest-Steppe and the Left-Bank Forest-Steppe of Ukraine. We found only short reports in the catalogs of botanical gardens and dendrological parks of Ukraine and in the reference books on dendrology about the rest of the North American species *J. rupestris, J. californica, J. major* and *J. hindsii* (Ishchuk 2007b).

Based on the fact that the territory of the Right-Bank Forest-Steppe of Ukraine is located at 45°-50° north latitude, that *J. nigra* and *J. cinerea* will be the most promising species among the North American species of the *Juglans* genus for green building and forest plantations. In North America, they grow at about the same latitude as our research region – the Right-Bank Forest-Steppe of Ukraine.

In this study, we aimed to choose the most promising species of the North American species of the *Juglans* genus for forest plantations and green building of the Right-Bank Forest-Steppe of Ukraine. In this regard, we analyzed the dynamics of growth and development, the degree of frost resistance, peculiarities of flowering, fruiting and seed propagation of North American *Juglans* spp.

Materials and Methods

Studies of the North American species of the genus *Juglans* were conducted during 2006-2019 at the research areas of Uman National University of Horticulture, in Moivske, Monastyryshche, Synytsia and Yurkivka forestries of the state enterprises of "Mohyliv-Podilskyi and Uman forestry" (37 sampling areas with the forest crops were laid out), in the street plantations in Uman city (Fig. 2), and by expeditions in the botanical gardens, dendrological parks, ornamental urban and rural plantations of the Forest-Steppe and Steppe of Ukraine (163 trees of the North American species of the *Juglans* genus were investigated).

In studying the species of the genus *Juglans*, we used the following research methods: bioecological, biomorphological, biometric, forest, expeditionary, visual, statistical.

The climate indicators of the region of introduction (Right-Bank Forest-Steppe of Ukraine) of the North American species of the *Juglans* genus according to Moroz & Kosenko (2006) and Buchinskij (1960) are the following: average July temperature 19.2–20.8°C, average January temperature (-5.5) - (-6.1)°C, maximum temperature +37.1°C, minimum temperature -35°C, annual precipitation 500-610 mm, snow cover height 0.3-0.5 m., the duration of the non-frosty period 159-171 days. The climate of the Right-Bank Forest-Steppe of Ukraine is continental, moderately warm with sufficient humidity.

Phenological observations of the species were conducted during 14 growing seasons of 2006-2019 on 5 sample trees of each species. The phases of swelling and budding were observed in April, the phase of flowering in late April and early May, fruit set in May, growth and woodiness of shoots in May-August, the phase of discoloration and leaf fall in September-October, and the phase of fruit ripening and falling was observed in October (Lapin 1975). The sum of effective temperatures (above +5°C) during the recording of the phases of swelling and budding, flowering, fruit set was calculated. The sum of active temperatures (above +10°C) during the recording of the phases of growth and woodiness of shoots, discoloration and leaf fall, and ripening and falling of fruits was calculated for each species.

The sum of effective temperatures is the sum of average daily temperatures deducted from the biological minimum at which plants of a given crop develop (+ 5°C). The sum of active temperatures is an indicator of supply of active plants vegetation by the warm period and consists of average daily temperatures of above +10°C. The sums of temperatures are determined by data on the average daily, average decadal and average monthly temperatures (Chirkov 1986).

Measurements of shoot growth were performed every 5 days on 10 sample trees in the lower, middle and upper part of the crown using a measuring device (ruler) (Molchanov & Smirnov 1967). We measured diameter of the root collar, length of the main root, total length of the root system for every year.

Flowering and fruiting were evaluated by the following scale: 5 points – flowers and fruits are placed on the tree very abundantly and evenly covered the whole tree, 4 points – flowers and fruits are placed on the tree moderately, 3 points – flowers and fruits on the tree are twice less compared to very abundant flowering and fruiting, 2 points – flowers and fruits are widely-spaced on the tree, 1 point – only single flowers and fruits are recorded, 0 point– flowers and fruits are absent (Ivanenko 1962). The score of flowering and fruiting was determined visually on five sample trees of each species.

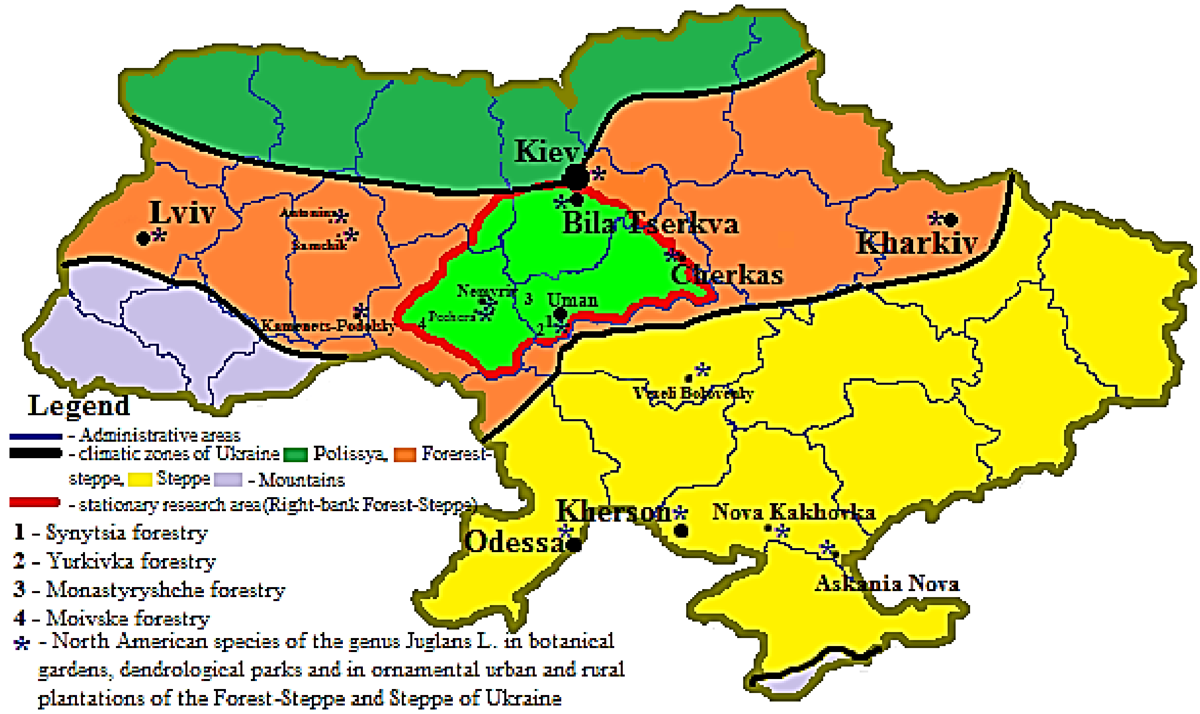

Fig. 2. The map showing the research area of the North American species of the *Juglans* genus in Ukraine.

Freezing was carried out in two stages – during the period of deep dormancy (January) at a temperature of -25ºC and -35ºC and during the period of forced dormancy (March) at a temperature of -20ºC and -25ºC (Soloviova 1982). Cuttings without freezing were taken for control. Anatomical and microscopic method to determine the nature and degree of damage of various tissues by the intensity of browning on the transversal section of shoots was used. Conditional coefficients on different physiological significance of tissues were introduced for each of them: 6 – for bark, 8 – for cambium, 4 – for wood, 2 – for core under the general estimation of frost resistance of shoots. The coefficient of 20 was introduced for a bud and the index of frost damage (IFD), i.e. sensitivity to low temperatures was determined (Potanin *et al*. 2005).

100 walnuts of each species for autumn sowing with endocarp to a depth from 2-3 cm. to 8-9 cm. were used to investigate the soil germination of North American walnuts and to determine the optimal depth of their seeds covering (Tsitsin 1980).

Sampling areas were formed in a rectangular shape, they were limited by sight lines at the sight. In each sampling area, 200 trees were selected in pure plantations, 100 trees of each species in mixed plantations, 400 trees of the investigated species in young plantations. The size of the sampling area was not less than 0.02 ha. (Hordiienko 1979). A continuous count of trees by a two-centimetre scale of the thickness degrees was performed on the sampling area. The heights of the trees were measured during the observation (Anuchin 1982). Forestry description of them was performed after limiting the sampling areas at the sight. During the description of the plantation, the type of forest vegetation conditions, soil type, method of crop production (sowing, planting), category of forest areas were determined, as well as the composition of grass vegetation and the nature of its spreading, capacity and composition of forest litter was described. Office processing of the obtained data with determining of all forestry and taxation indicators (planting composition, age of planting, type of planting habitat conditions, average diameter and height of planting, planting bonitet, planting completeness, stock of wood in the planting per 1 ha.) was carried out after the end of the field work on the sampling area.

The degree of acclimatization was determined by the acclimatization value, which is the sum of indicators of growth, generative development, winter hardiness and drought resistance of plants, expressed in points: full acclimatization 100 points, good acclimatization 80 points, satisfactory acclimatization 60 points, poor acclimatization 40 points and no acclimatization 20 points (Kokhno & Kordiuk 1994). The degree of acclimatization of the species was studied on 5 sample trees of each species.

Mathematical processing of the dynamics of shoots growth was performed by the method of descriptive statistics by determination of the arithmetic mean value (*M*), the error of the average value (*m*), the mean-square deviation (σ), the coefficient of variation (*V*), the accuracy of the study (*P*) (Moseichenko 1992). We also used the analysis of variance program (one-way ANOVA).

Results

In studies performed to determine the dormancy period of North American species of the *Juglans* genus, we found that the shortest dormancy period was observed in *J. cinerea*, i.e., it was not deep and could be disturbed by frequent winter thaws; then *J. nigra* woke up (Table 1).

However, *J. rupestris*, *J. major J. californica* and *J. hindsii* had an even longer dormancy period, which lasted until the end of January - beginning of February and only then the species entered the forced dormancy (Figs 3-4).

Under environmental conditions of Uman city, a complete small cycle of the development was observed only in *J. nigra*, *J. cinerea* and *J. rupestris* (Table 2). The small cycle was not complete in other species, because they had not yet reached reproductive age (Fig. 5).

Table 1. The sum of effective temperatures (above 5°C) at which there is a mass buds swelling and budding in species of the *Juglans* genus under environmental conditions of Uman city (average indicators for 2006-2019).

Species	Phase of development		Sum of effective temperatures (ºC) necessary for	
	date of buds swelling	date of budding	buds swelling	budding
J. nigra	7-21.04	27.04-2.05	51.7±7.6	103.0±7.2
J. cinera	3-12.04	21.04-25.04	28.9±4.8	70.9±8.0
J. rupestris	8-14.04	26.04-2.05	35.5±5.8	68.3±4.9
J. major	9-13.04	26.04-3.05	45.6±1.4	83.3±7.1
J. californica	13-17.04	28.04-2.05	49.1±4.7	86.0±9.9
J. hindsii	13-18.04	29.04-3.05	52.2±3.0	91.5±3.9

Table 2. The sum of active temperatures (°C) necessary for flowering, fruit setting and ripening of the species of the *Juglans* genus under environmental conditions of Uman city (average indicators for 2006-2019).

Species	Duration of flowering (days)	Sum of active temperatures (above +10°C) necessary for			
		beginning of flowering	ending of flowering	fruit setting	fruit ripening
J. nigra	13-17	135.2±8.7	192.8±3.2	720.7±19.1	2555.7±15.4
J. cenerea	15-17	141.4±12.3	199.8±7.9	855.4±14.9	2367.8±12.1
J. rupestris	9-16	113.0±9.2	148.5±10.8	810.5±12.8	3045.0±14.0

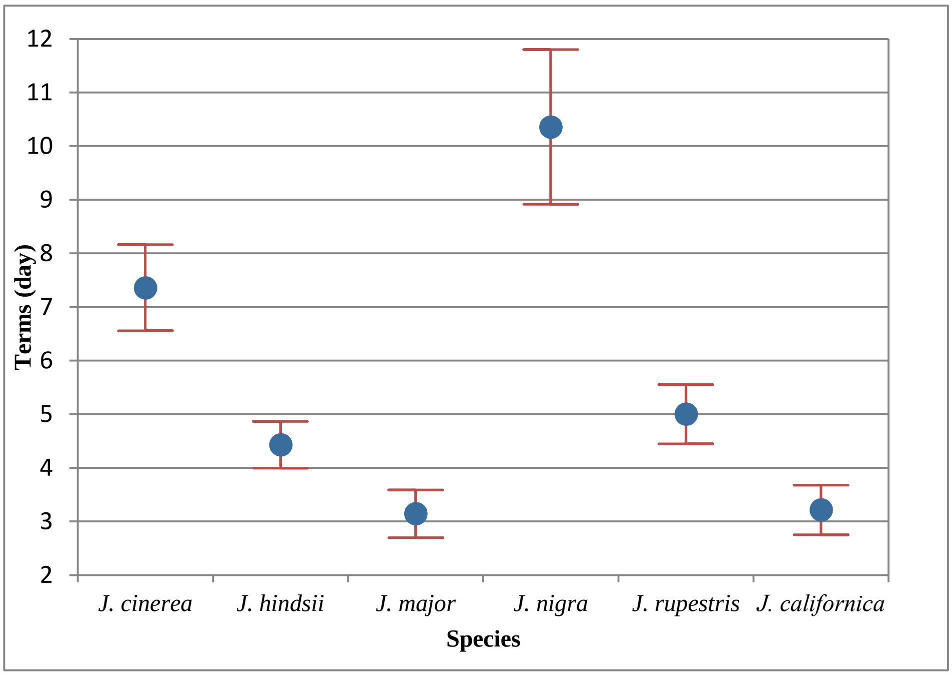

Fig. 3. Means plot (95% CI) of the swelling phase of tree buds.

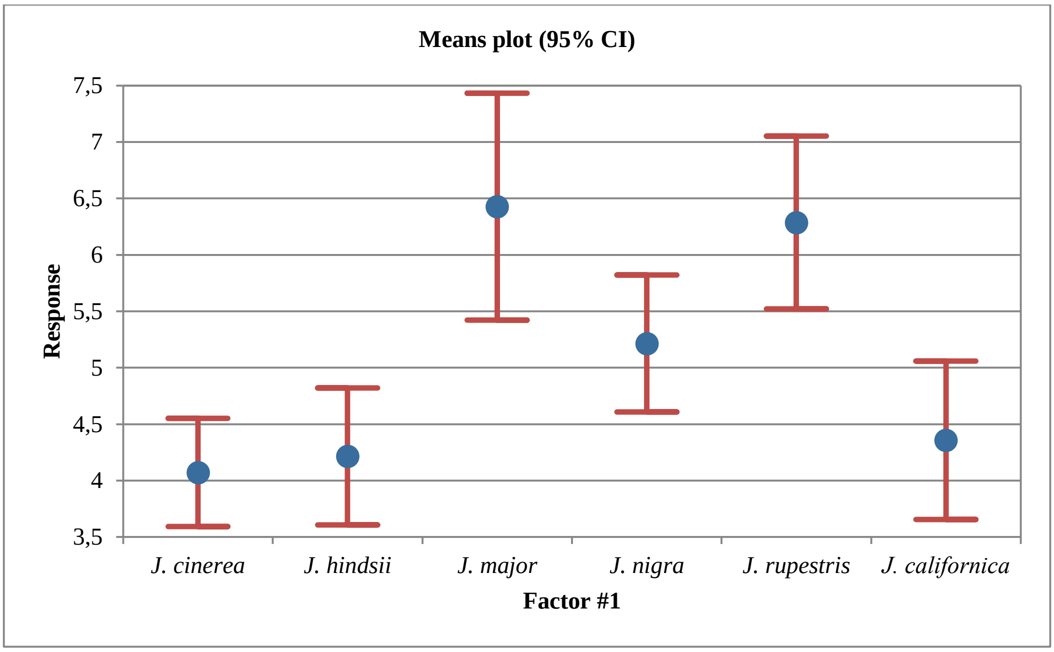

Fig. 4. Means plot (95% CI) of duration of bud burst.

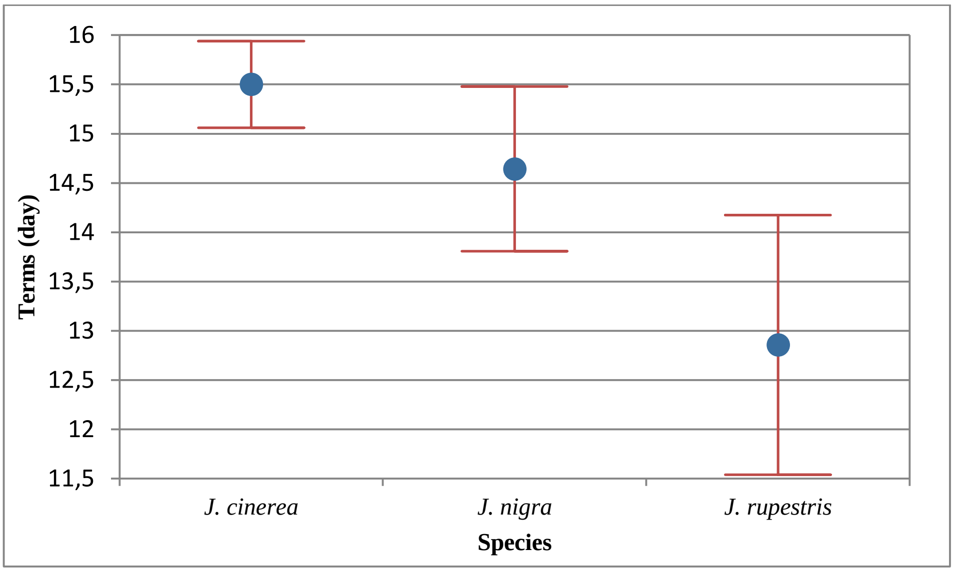

Fig. 5. Means plot (95% CI) of flowering duration.

Juglans cinerea, *J. rupestris*, and *J. major* were the first to wake up in the conditions of Uman city and *J. nigra*, *J. californica*, *J. hindsii* woke up later. The shoots became completely woody much later in *J. nigra*, *J. rupestris*, *J. major*, *J. californica*, *J. hindsii*, so they freeze more often.

We found that the intensive growth of shoots of all species was observed in May-June; the energy of shoot growth decreased in July and stopped in August. One-year seedlings of *J. nigra* and *J. cinerea* grew to 31.5 cm, *J. rupestris* and *J. major* to 16.2-16.7 cm, and *J. californica* and *J. hindsii* to 14.1-14.3 cm in height. The study was performed on 30 one-year seedlings of each species (Table 3). The growth of annual seedlings was determined on 30 samples of each species. Statistical data processing of the dynamics of growth is presented in Table 4.

The vegetation period in *J. nigra* began on April 8-20 and ended on October 7-12 and lasted for 183 days on average. It began on April 1-11, ended on October 1-5 in *J. cinerea*, and lasted for 184 days on average. The vegetation period in *J. major* and *J. rupestris* began on April 8-10 and ended on November 1-3, lasting for 206-208 days on average. It began on April 12-18 in *J. californica* and *J. hindsii*, and ended the latest on November 2-5, lasting for 201-203 days. The vegetation period in all North American species of the *Juglans* genus was shifted towards the summer-autumn season (Table 5, Fig. 6).

Table 3. Characteristics of one-year seedlings of species of the *Juglans* genus under environmental conditions of Uman city.

Species	Height (cm)	Diameter of the root collar (cm)	Length of the main root (cm)	Total length of the root system (cm)	First branching from the root collar (cm)
J. nigra	31.5±2.3	1.0±0.5	125.7±2.85	453.5±3.9	25.1±0.5
J. cinerea	31.2±2.6	1.0±0.5	118.4±3.2	420.7±3.7	10.3±0.5
J. rupestris	16.7±1.7	0.8±0.3	100.8±1.9	285.2±3.2	8.8±0.3
J. major	16.2±1.4	0.5±0.2	80.1±1.6	215.0±2.9	5.2±0.3
J. californica	14.3±1.2	0.5±0.1	74.3±1.5	198.6±3.0	6.9±0.2
J. hindsii	14.1±1.3	0.5±0.1	92.5±1.1	255.9±3.1	7.0±0.2

Table 4. Statistical *data* processing of the dynamics of growth of the North American species of the *Juglans* genus.

Name of the species	Year of observation														Height* (cm)				
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	*M*	*m*	*σ*	*V*	*P*
J. nigra	30.5	35.2	30.5	26.9	32.5	30.4	33.5	37.5	26	36.4	29.1	35	27	31.1	31.54	2.33	3.50	0.11	66.49
J. cinerea	36.8	30	36.7	30.6	36.5	25	30.1	30.2	26.6	28	30.8	30.4	30.2	35.1	31.21	2.63	3.59	0.12	73.25
J. rupestris	17.7	16.9	13.3	16.8	16.1	15.9	14.5	17.2	16	18.3	12.5	21.2	15.5	21.9	16.70	1.70	2.51	0.15	67.76
J. major	16	14.3	16.5	16.6	21	13.7	16.9	16.8	15	15.9	12.6	15.9	19.7	16.1	16.21	1.41	2.09	0.13	67.82
J. californica	10.2	14.9	13	15.9	14	15.2	16	13.5	14.8	13.6	13	15.3	14.2	16.8	14.31	1.23	1.59	0.11	76.98
J. hindsii	15	14.4	18	15	12.9	11.9	14.9	14.2	8.9	14.2	13.6	15	14.8	15	14.13	1.32	1.95	0.14	67.50

* *M* is the arithmetic mean value, *m* is the error of the average value, *σ* is the mean-square deviation, *V* is the coefficient of variation, *P* is the accuracy of the study.

Table 5. The vegetation period of species of the *Juglans* genus under environmental conditions of Uman city (average indicators for 2006-2019).

Species	Beginning of the vegetation	Autumn coloring of leaves	Leaf fall	Duration of the vegetation period (days)
J. nigra	8.04-20.04	25.09 -10.10	7-12.10	183±7
J. cinerea	1.04-11.04	20.09-1.10	1-5.10	184±5
J. rupestris	8.04-12.04	15.10-1.11	1.11-3.11	208±2
J. major	10.04-14.04	15.10-23.10	1.11-3.11	206±2
J. californica	12.04-14.04	15.10-20.10	29.10-2.11	201±2
J. hindsii	12.04-18.04	28.10-4.11	2.11-5.11	203±1

Abundant harvests of nuts were observed in 2007, 2011 and 2018 in the conditions of the Right-Bank Forest-Steppe of Ukraine during 2006-2019. The average score of flowering and fruit bearing of the species in the plantations of Uman city and Synytsia arboretum was 3.5 points for *J. nigra,* 3 points for *J. cinerea* and 1.5 points for *J. rupestris* (Fig. 7).

In our studies on the freezing of shoots, we found that the highest rate of frost damage (from 33.1 in *J. cinerea* to 52.4 in *J. rupestris*) was obtained in the experimental variant for cambium and bark of all species in sections through the apex shoots at t = -35°C during the period of deep dormancy (Table 6). The wood and core of shoots in all species when cutting through the node of the shoot middle was the least damaged. The highest index of frost damage was recorded in *J. rupestris* (57.5) for the bark and cambium of the upper part of the shoots when freezing at t = -25°C during the period of forced dormancy (Table 6). This indicator was much lower (from 30.0 to 48.5) in all species in all tissues of the middle of the shoot at t = -25°C. Determined the degree of frost resistance of 5 shoots of each species in 3 repetitions. Bud had a very high level of damage in all cases of freezing. A medium degree of freezing was characterized for the species.

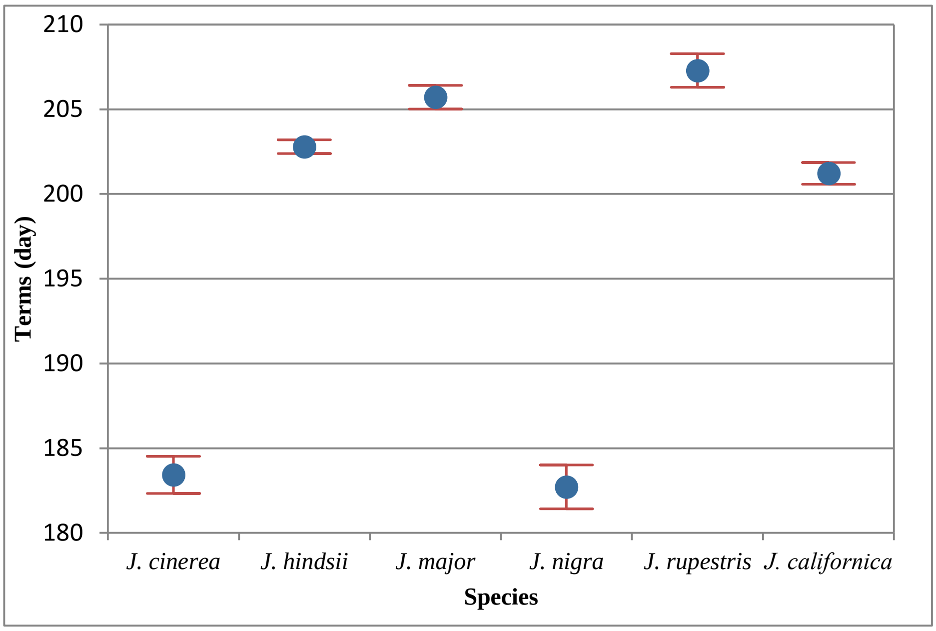

Fig.6. Means plot (95% CI) during the growing season.

Table 6. Situational and potential frost resistance of *Juglans* species under artificial freezing during deep and forced dormancy.

Species	Freezing temperature (°C)	Index of frozen damage of different shoot parts			
		bud	upper internode	middle internode	middle node
I decade of January (period of deep dormancy)					
J. nigra	Control	20.0	37.2	30.4	17.4
	-25	32.0	39.6	27.4	37.4
	-35	90.0	36.2	32.5	28.4
J. cinerea	Control	10.0	25.0	21.5	12.5
	-25	28.3	37.3	34.4	26.5
	-35	75.0	33.1	30.2	26.5
J. rupestris	Control	30.0	40.2	35.0	24.6
	-25	41.5	52.0	46.5	38.2
	-35	100.0	52.4	48.6	45.5
I decade of March (period of forced dormancy)					
J. nigra	Control	10.8	40.0	23.7	15.3
	-20	28.2	20.0	14.6	10.3
	-25	78.5	30.9	30.0	24.0
J. cinerea	Control	8.5	35.6	20.6	12.5
	-20	25.6	20.3	12.8	10.0
	-25	65.8	30.0	28.5	22.4
J. rupestris	Control	15.6	52.0	28.4	22.5
	-20	38.2	30.5	22.4	18.5
	-25	90.0	57.5	48.5	36.4

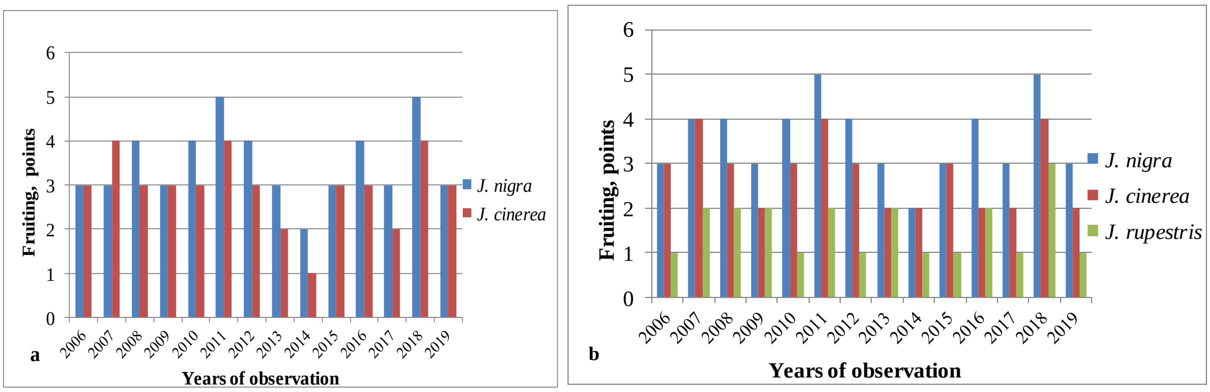

Fig. 7. Estimation of fruit bearing of the species of in Uman city (a) and Synytsia arboretum (b).

Table 7. Influence of the depth of the seed sowing of the species on their field germination and gum of planting materia (initial number of walnuts was 100 pcs.).

Species	Depth of seed covering Shved cm)	Field germination (%)	Date of mass nut field germination	Gum of planting materia (%)
J. nigra	2-3	25	10.05	25.5
	3-4	28	12.05	28.5
	4-5	54	15.05	54.5
	5-6	62	15.05	62.5
	6-7	68	20.05	70.0
	7-8	70	22.05	49.5
	8-9	50	26.05	38.7
J. cinerea	2-3	20	10.05	19.5
	3-4	32	14.05	31.5
	4-5	55	17.05	54.5
	5-6	62	18.05	52.5
	6-7	67	20.05	60.0
	7-8	53	23.05	66.5
	8-9	20	27.05	31.5
J. rupestris	2-3	10	18.05	9.5
	3-4	15	23.05	14.5
	4-5	25	27.05	24.5
	5-6	45	28.05	44.5
	6-7	41	28.05	39.5
	7-8	38	30.05	37.5
	8-9	30	3.06	29.5

Seeds were best sown with endocarp in autumn to a permanent place, or in spring under the condition of the nut's stratification of *J. rupestris*, *J. major* for 160 days, *J. nigra*, *J. cinerea* for 120 days and *J. californica*, *J. hindsii* for 100 days in the wet sand at t = 1-3°C. Seed hardness of fruits could be broken by scarification, hydrothermal and chemical methods. The action of sulfuric acid was the most effective way to break the hardness. The optimal depth of seed covering during spring and autumn sowing was 5-6 cm for *J. rupestris*, 7-8 cm for *J. nigra* and *J. cinerea* and was determined experimentally which allowed to increase germination by 25-30% (Table 7).

Juglans nigra and *J. cinerea* under favourable soil and climatic conditions were restored by self-seeding. Self-seeding of *J. cinerea* and *J. nigra* were observed mainly in the botanical gardens and dendrological parks but they were not found in the forest plantations. The best self-seeding of *J. cinerea* was observed in the botanical garden of N.V. Karazin Kharkiv National University, and *J. nigra* – in the Synytsia arboretum of the "Uman Forestry" state enterprise.

Our research established the optimal timing and methods of sowing nuts in forest nurseries. In autumn, in October, nuts together with the endocarp were sown in the seed-plots by band sowing with a width between the rows in the bands of 10-12 cm, and between the bands – 50-55 cm. The distance between the nuts in a row was 3-5 cm. The depth of seed covering was 6-7 cm (Fig. 8).

Pure and mixed forest crops of *J. nigra* in Moivske forestry in Vinnytsia region, Yurkivka, Synytsia and Monastyryshche forestries in Cherkasy region were studied (Table 8).

It is found that forest crops had a good growth and were characterized by high wood and seed productivity. The oldest 87-year-old cultures of *J. nigra* (Fig. 9) in Moivske forestry were presented in the "Filitsianivskyi forest" natural landmark.

Fig. 8. *Juglans nigra* in the seed-plot of Moivske forestry of Vinnytsia region.

Fig. 9. Forest crops of *J. nigra* in Moivske forestry.

Table 8. Characteristics of mixed *J. nigra* plantations of different ages in the forestries of the state enterprises "Mohyliv-Podilskyi forestry" and "Uman forestry".

Forest planning quarter	Plantation composition (by rows)	Age of planning (year)	Average height (m)	Average diameter (cm)	Forest appraisal index	Forest site type	Stand density	Stand volume (m^3/ha^{-1})
Yurkivka forestry								
107	8 *J. regia*, 2 *J. nigra*	63	17.4±0.6	21.0±1.6	II	new hornbeam-oak wood	0.6	123.6
108	6 *J. regia*, 3 *J. mandschurica* Maxim., 1 *J. nigra*	65	15.2±0.4	19.5±1.7	III	new hornbeam-oak wood	0.6	113.4
124	8 *J. nigra*, 2 *Fraxinus excelsior* L.	30	10.6±0.2	17.4±1.0	Ia	new hornbeam-oak wood	0.6	57.8
Synytsia forestry								
106	8 *J. nigra*, 2 *J. regia*	65	21.5±0.7	28.3±1.8	I	new hornbeam-oak wood	0.7	2448
106	6 *J. nigra*, 3 *F. excelsior*, 1 *J. regia*	59	23.1±0.8	26.7±1.2	Ib	new hornbeam-oak wood	0.8	318.2
108	4 *J. nigra*, 4 *J. mandschurica*, 1 *J. regia*, 1 *Betula pendula* Roth.	34	11.6±0.3	18.6±1.4	III	new hornbeam-oak wood	0.7	96.8
Potash forestry								
135	5 *Quercus robur* L., 1 *Carpinus betulus* L., 1 *J. nigra*, 1 *Robinia pseudoacacia* L., 2 *Tilia cordata* Mill.	62	22.7±0.7	24.2±1.3	Ia	new hornbeam-oak wood	0.7	220.7
Moivske forestry								
75	5 *Q. robur* 2 *F. excelsior*, 1 *T. cordata*, 1 *J. nigra*, 1 *Acer campestre* L. + *C. betulus* + *F. excelsior*	87	22.5±0.5	48.5±0.6	I	new hornbeam-oak wood	0.7	324.5

Table 9. The degree of acclimatization of *Juglans* species under environmental conditions of the Right-Bank Forest-Steppe of Ukraine (by Kokhno & Kurdiuk 1994).

Species	Indicators of				Acclimatization value (point)	Acclimatization degree
	growth	generative development	frost-resistance	drought-resistance		
J. nigra	10	25	50	15	100	complete
J. cinerea	10	25	50	15	100	complete
J. rupestris	8	25	40	15	88	good
J. major	8	25	40	15	88	good
J. californica	8	25	30	15	78	satisfactory
J. hindsii	8	25	30	15	78	satisfactory

In the forests of the "Uman Forestry" state enterprise forest crops of *J. nigra* were presented in the new oak-hornbeam forests on grey and dark-grey forest soils and loamy chernozem. The oldest plantations of *J. nigra* were investigated in Yurkivka forestry. The age of these plantations was 65 years. The height of *J. nigra* varied from 10.6 to 17.4 m, the diameter of the trunk was in the range of 17.4 to 21.0 cm. The closure of the planting crowns was in the range of 0.6-0.8.

The oldest forest crops in Synytsia forestry in the Pankivske natural landmark were of 59-65 years of age (Fig. 10). These plantations belonged to the forests of I group performing protective functions. Usually, *J. nigra* was planted in a mixture with *J. regia*. The height of *J. nigra* here varied from 21.5 to 23.1 m, and the diameter from 26.7 to 28.3 cm. From the point of view of the recreational evaluation, they were forest crops. The age of the oldest crops in Potash forestry was 62 years. The height of *J. nigra* was 22.7 m and its diameter was 24.2 cm. *Juglans nigra* regularly bore fruit in these plantations, although freezing of branches was observed in some frosty years. In the last 5-8 years, a number of new mixed forest crops were created with the participation of *J. nigra* in Monastyryshche and Mankivka forestries. These plantations appeared to be open forest crops of 1-8 years ages (Fig. 11).

Studies on the complete acclimatization of North American *Juglans* species in the the Right-Bank Forest-Steppe of Ukraine are shown in Table 9.

In view of this, the degree of acclimatization of the North American *Juglans* species confirmed our hypothesis on the prospect of *J. nigra* and *J. cinerea* in green building and forest plantations. The remaining North American species *J. rupestris*, *J. major*, *J. californica* and *J. hindsii* require further experimental research in Ukraine.

Fig. 10. Forest crops of *J. nigra* in Synytsia forestry.

Fig. 11. Forest crops of *J. nigra* in Monastyryshche and Mankivka forestries.

Discussion

Juglans nigra and *J. cinerea* were introduced to Ukraine in the early 19th century, underwent a long period of acclimatization and were widely presented in the dendrological collections, forest crops and street plantations of all natural-and-climatic zones of the country. *Juglans rupestris, J. major, J. californica,* and *J. hindsii* were introduced to Ukraine in the 1930s of the previous century, but they were rarely found in the dendrological collections in Eastern, Central and Southern Ukraine. Due to their low distribution and spatial isolation, these species do not interbreed and do not need protection, as *J. hindsii* in natural habitats in North America (Potter *et al.* 2018).

The introduction area (Right-Bank Forest-Steppe of Ukraine) has a certain similarity to the climate of the eastern regions of North America in terms of precipitation (Ishchuk 2009, Buzovkyn 1960, Vitvicki 1953), although there is a significant difference in absolute values. In these areas, most of the precipitation falls during the warm season. Temperatures also have some similarities, although they differ significantly by the indicator of average annual temperature, average minimum and maximum temperatures of the introduction area. All areas are characterized by the presence of some period with an average daily minimum of temperatures below 0°C.

The climatic conditions of the introduction area were favorable for the introduction of all North American species of the *Juglans* genus, although the Right-Bank Forest-Steppe differed from the natural conditions of North America in terms of temperature, light and moisture. The conditions of heat and moisture supply, which affected plants not only directly but also by physical and chemical and microbiological processes occurring in the soil were the most important among the set of climatic factors that determined the success of plant introduction (Ishchuk & Ishchuk 2019).

The small development cycle of *Juglans* species was directly dependent on the sum of active and effective temperatures. The cycle of development of North

American species is shifted towards the summer-autumn period under environmental conditions of the Right-Bank Forest-Steppe of Ukraine. Vegetation of the species began in the period from April 1–20 with swelling of the generative buds. They were characterized by annual, abundant flowering, which began in the I-II decades of May for *J. cinerea*, and in the II–III decades of May for *J. nigra, J. rupestris, J. californica, J. major*, and *J. hindsii* and lasted for 9-17 days depending on the amount of active temperatures. Based on a meta-analysis by Gill *et al.* (2015), we concluded that the phase of autumn leaf coloration was significantly stayed at 25-49° of north latitude. Moreover, Uman city, where we conducted stationary research, is located at 48°45′44″ of north latitude where plants are more sensitive to temperature. In more northern latitudes, the photoperiod affects leaf senescence. The lack of constant connections between air temperature and time of leaf senescence suggests that various factors may influence autumn leaf senescence. The date of the first autumn frosts is variable in temperate and boreal ecosystems and does not always correspond to the linear cooling tendency. Our observations also confirm this fact.

Shoot growth began after buds breaking in late April-early May, and ended in July–August and trees were characterized by good growth of 0.5-0.6 m per year under sufficient moisture. The maximum increase was observed in May-June. The increase in one-year-old plants in height and diameter of the root collar under autumn sowing is twice as large as under spring sowing, which is also proved by experimental data obtained by Zaharova (2016) under environmental conditions of Nizhny Novgorod region of Russia. Growth increased almost twice in two-year seedlings. However, growth in all types of seedlings decreased when the roots were pruned. Our results showed that two-year seedlings of *J. nigra* and *J. cinerea* had the most powerful root system. *Juglans rupestris*, *J. californica* and *J. hindsii* had a much shorter length of the root system; these species were characterized by weaker growth, the root system was less branched and located in the surface layers of the soil. The biological needs of *J. nigra, J. cinerea, J. rupestris, J. major, J. californica, J. hindsii* were fully met by the natural conditions of the Right-Bank Forest-Steppe of Ukraine during the vegetation period and thermal regime.

Enduring by the North American walnut species, especially *J. rupestris, J. californica, J. major* and *J. hindsii* of some period with an average daily minimum of temperatures below zero without damage under environmental conditions indicates their rather wide biological potential for frost resistance, which was formed during the evolution of species, and the possibility of successful introduction in the context of climate change in Ukraine. A decrease in frost-resistance of tissues in a row: bark–cambium–wood–core in the model experiments with artificial freezing of shoots at temperatures of -25, -30 and -35°C (Ishchuk 2010) and the quantitative microscopic analysis of the level of low-temperature damages was found. This meant that the survival of shoots after overwintering would depend on the ability of cells of the bark and cambium parenchyma to restore physiological processes and form new tissues with the beginning of the favorable temperature conditions of the vegetation period. According to Moroz & Kosenko (2006) and Uman Meteorological Station (https://meteopost.com/weather/climate/), the maximum negative air temperature for the last 50 years in Uman city in January was -32.2°C. Therefore, the North American species of the *Juglans* genus are characterized by a medium degree of freezing.

Studied species needed special care, which should include measures for pruning, enhanced nutrition and watering. They also needed light fertile chernozem or gray forest soils, but they grew satisfactorily on other soil differences under conditions of watering and fertilizing. All the species are light demanding, but they could withstand shading at a young age. In addition, they were resistant to air pollution by carbon, nitrogen, lead compounds, had phytoncidal and antimicrobial properties and deserved widespread introduction into recreational plantations (Ishchuk 2015).

All North American *Juglans* species of the in the crop under environmental conditions of the region included in our study are well propagated by seed. Seed is best sown with endocarp in autumn or spring providing stratification. The optimal stratification time for *J. rupestris, J. major* is 160 days, *J. nigra, J. cinerea* – 120 days and J *californica, J. hindsii* – 100 days in moist sand at a temperature of 1-3°C. In contrast, researchers in the USA consider vermiculite to be better substrate for stratification of *J. nigra* and *J. cinerea* (Cobb *et al.* 2020). The optimal depth of seeding-down of *J. rupestris* seeds is 5-6 cm., and *J. nigra* and *J. cinerea* – 7-8 cm, which allows to increase germination by 25-30%. Our multi-year researches coincide with the data of American researchers (Brauer *et al.* 2010), who consider the best practice of growing high-quality planting material of the North American walnuts by sowing seeds in containers. Our studies showed that the highest germination of seedlings under autumn sowing at a depth of seeding-down was 6-8 cm in *J. nigra* and 6-7 cm in *J. cinerea* which almost coincides with similar investigations made by Zaharova (2016) under environmental conditions of Nizhny Novgorod region of Russia. At the same time, the germination of stratified seed under environmental conditions of dry oak-forest in the south-east of Ukraine was 61-64% (Aboimova & Polyakov 2012), which can be explained by drier soil-and-climatic conditions compared to the Right-Bank Forest-Steppe of Ukraine. In our opinion, the low abundance of seedlings and poor growth of *J. nigra* and *J. cinerea* on site condition of Uman city could be explained by the lack of moisture in the recent drought years in the surface layers of very dense soil and litter for young nut roots, which led to their massive fall from planting. Only a few seedlings survived until the following year.

In recent decades, *J. nigra* was increasingly introduced into both pure and mixed forest crops in the conditions of the Right-Bank Forest-Steppe of Ukraine, in particular, in Vinnytsia and Cherkasy regions. This, in turn, required the expansion of the seed base and the creation of its nurseries in the seed-plots. However, the technology of growing of *J. nigra* planting material in various forestries had its differences. Their sowing in Monastyryshche forestry in Cherkasy region was practiced immediately to a permanent place in the forest due to the fact that walnuts had a tap-root system and bore replanting badly under environmental conditions of the Right-Bank Forest-Steppe. Therefore, nut seedlings were not grown in the seed-plots. There was somewhat different technology of material growing planting in Moivske forestry in Vinnytsia region.

Introduced *J. nigra* in pure and mixed forest crops of Vinnytsia (Ishchuk & Shlapak 2007) and Cherkasy regions grows in different age plantations. Pure *J. nigra* plantations of 159.4 ha (21%) are dominated by the share in the plantation composition on the territory of the Right-Bank Forest-Steppe of Ukraine. Among *J. nigra* plantations, the largest area is occupied by young plants (536.2 ha, 70.7%) and middle-age plantations (196.1 ha, 25.9%). The largest total stock of wood in forest stands of this species (21 thousand m^3) is concentrated in middle-age plantations. *Juglans nigra* plantations grown by the first and highest classes of bonitet cover the area of 433.1 ha which is more than half of the area (57%) of their distribution. The division by the type of forest vegetation conditions and by area showed that 72% of black walnut plantations grow under environment conditions of young oak-forest by the I class of bonitet (Filonenko 2017).

Our investigations showed that *J. nigra* is highly competitive with aboriginal forest species (*Quercus robur*, *Fraxinus excelsior*, *Acer campestre*, *Tilia cordata*, *Carpinus betulus*) in terms of forestry-and-taxonomic indicators and has good growth, high quality wood and high seed productivity. The growth of *J. nigra* under conditions of plantation cultivation at the age of 10 in mixed forest crops is higher than in pure single-breed plantations of this species under environmental conditions of the south-east of Ukraine (Aboimova & Polyakov 2012).

We also recommend using *J. nigra* and *J. cinerea* for planting tree belt areas on agricultural lands in the Right-Bank Forest-Steppe of Ukraine. This view is also supported by Gauthier & Jacobs (2010), who studied the effects of lighting and thinning of plantations, and American researchers and Wolz & DeLucia (2019), who propose to plant alley cropping of *J. nigra* on soybean and corn plantations in Midwest of the USA in order to increase productivity of the farm lands.

Complete (A = 100) acclimatization of *J. nigra* and *J. cinerea* was confirmed, good (A = 80) acclimatization of *J. rupestris* and *J. major* and satisfactory (A = 60) acclimatization of *J. californica* and *J. hindsii* in the conditions of the Right-Bank Forest-Steppe of Ukraine was defined by the studies. *Juglans nigra* and *J. cinerea* successfully adapted to the natural conditions of the Right-Bank Forest-Steppe of Ukraine and reached the highest degree of acclimatization – naturalization. Evidence of this fact was their ability to successfully regenerate by natural seed way. The natural regeneration of *J. nigra* and *J. cinerea* was confined to well-lit and moist areas with the presence of the scalping of the upper mineral horizon of the soil.

Obtained results of the success of the introduction concerning *J. nigra* completely coincide with the results of the research of Nicolescu *et al.* (2020), who studied the process of introduction and adaptation of this species into forest plantations in Europe.

Conclusion

Biological needs of *J. nigra, J. cinerea*, *J. rupestris*, *J. major, J. californica,* and *J. hindsii* were completely satisfied with the natural conditions of the Right-Bank Forest-Steppe of Ukraine during the vegetation period and thermal regime.

Bioecological evaluation of the species of the *Juglans* genus suggested that the studied species, except *J. cinerea*, had a shift of vegetation towards the summer-autumn period. *Juglans cinerea* needed the smallest sum of effective temperatures for growth and development – 28.9 and 72.3°C, respectively, and *J. rupestris* – 34.1 and 66.8°C, the largest sum was required by *J. hindsii* – 51.7 and 90.5 and by *J. nigra* – 50.6 and 105.0°C. Vegetation duration was 183–208 days under the sum of active temperatures of above + 10°C of 2367.8–3050.0°C.

North American nuts in the region of introduction are able to withstand temperatures down to -25°C. Thus, the highest index of frost damage was recorded in *J. rupestris* (57.5) for the bark and cambium of the upper part of the shoots when freezing at t = -25°C during the period of forced dormancy. This indicator was much lower (from 30.0 to 48.5) in all species of *Juglans* in all tissues of the shoot middle at t = -25°C. Buds had a very high level of damage in all cases of freezing.

Forest crops of *J. nigra* could be established both by pure plantings, and in combination with deciduous local forest species. Higher growth rate than the main forest-forming species in terms of the main taxonomic indicators in the young growth phase, and much lower – in the following age groups was characteristics for the introducer.

All North American species of the *Juglans* genus are promising for use in the plantations of the Right Bank Forest-Steppe of Ukraine, as evidenced by the complete acclimatization of *J. nigra* and *J. cinerea*, good acclimatization of *J. rupestris* and *J. major* and satisfactory acclimatization of *J. californica* and *J. hindsii*. These species were suitable for introduction not only into forest plantations, but also into phytomelioration, garden and park construction of the Right-Bank Forest-Steppe of Ukraine due to high ecological resistance to unfavorable climatic conditions and high decorativeness of both plantations and individual trees.

Ethics Committee Approval: Since the article does not contain any studies with human or animal subject, its approval to the ethics committee was not required.

Author Contributions: Concept: H.I., Desing: O.B., Execution: H.I., Material Supplying: L.I., Data acquisition: H.I., L.I., O.B. S.K., Data analysis/interpretation: H.I., L.I., Writing: H.I., L.I., Critical Review: V.S.

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