Scientific Papers. Series B, Horticulture. Vol. LXIX, No. 2, 2025
Print ISSN 2285-5653, CD-ROM ISSN 2285-5661, Online ISSN 2286-1580, ISSN-L 2285-5653

RESULTS OF THE INTRODUCTION OF SPECIES OF THE GENUS *SALIX* L. IN UKRAINE

Liubov ISHCHUK[1], Volodymyr HRABOVYI[1], Halyna ISHCHUK[2]

[1]Sofiyivka National Dendrological Park of the National Academy of Sciences of Ukraine, 12A Kyivska Str., Uman, Ukraine
[2]Uman National University of Horticulture, 1 Instytutska Str., Uman, Ukraine

Corresponding author email: ishchuk29@gmail.com

Abstract

The aim of the study of the study was to analyze the success of the introduction of Salix species in the Right-Bank Forest-Steppe of Ukraine based on the characteristics of their growth and development, winter hardiness and drought tolerance. Ten of the autochthonous species are found in Ukraine on the southern or southeastern border of their ranges, which is explained by climate change from the northwest to the southeast of the country. Two species change their life form from a "tree" to a "bush" under conditions of introduction. Six species have not fully lignified shoots at the end of the growing season, which is an indicator of their lower winter hardiness. In Ukraine, the introduced species of the Salix genus form viable seeds, however, they do not form self-seeding and have a full (10 species) or good (6 species) degree of acclimatization. It has been established that the limiting factors for the expansion of the Salix cultural range in Ukraine are high temperature and low humidity of air and soil in summer, which leads to a decrease in their drought resistance.

Key words: *cultural area, introduction, acclimatization, life form, «tree»-«shrub», winter hardiness, drought tolerance.*

INTRODUCTION

The introduction of plants is the most important means of enriching the cultivated flora and an integral component of measures aimed at increasing plant raw material resources. In Ukraine, species of the genus *Salix* L. are widely used in landscaping, forestry, phytomelioration, phytoenergy, the chemical industry, and phytopharmacology. The natural flora of Ukraine includes 23 autochthonous willow species belonging to 15 sections (Fuchylo-Sbytna, 2009; Ishchuk, 2015b). These species differ in habitus, resistance to abiotic and biotic factors, modes of reproduction, and chorology. However, the broad range of applications of willows in various sectors of the national economy necessitates the search for ways to expand their assortment through introduction and selection. The issue of bioecological challenges in urban green construction is also relevant for various regions of Ukraine, where cultural phytocenoses of forest and park types predominate but are significantly affected by ecological and anthropogenic factors (Boiko et al., 2024). Through the reconstruction of plantations by introducing *Salix* species, it is possible to improve the ecological-cenotic and aesthetic condition of urban plantings (Rogovskyi et al., 2023).

The prediction of the successful introduction of *Salix* L. species, particularly the expansion of their cultivated range, is impossible without analyzing the current geographical distribution of species, the ecological characteristics of their habitats, and the genesis of floras (Kokhno-Kurdyuk, 1994; Yatsyk et al., 2017). Due to climate change, as well as the relatively high resistance of willows to low temperatures and diverse edaphic conditions, many *Salix* species are expanding not only their natural but also their cultivated range.

The global flora of willows comprises 300 *Salix* species (Rehder, 1949; Elias, 1980; Skvortsov, 1999). For North America, Elias (1980) reports 80 species, three of which - *S. alba* L., *S. fragilis* L., and *S. viminalis* L. - are part of Ukraine's natural flora. The *Native Trees of Canada* (1950) handbook describes 250 *Salix* species, of which only 75 have a natural distribution in North America. The American publication *Catalog of Cultivated Woody Plants* (1994) lists 30 willow species for the northeastern United States alone. In the United Kingdom and Ireland, 18 willow species are recorded (Macalpine, 2019). These figures highlight the high introduction potential of willows. Species of the genus *Salix* L. are widespread in the northern and temperate latitudes of the Northern Hemisphere. Willows are absent in the natural flora of Australia, New Zealand, Oceania, Antarctica, eastern Indonesia, and western Africa. The greatest diversity of *Salix* species is found in northern Eurasia, North America, and China (Skvortsov, 1999).

However, under the influence of new habitat conditions, introduced species may undergo certain changes in their nature, their response to factors of the new ecological environment, develop new adaptive mechanisms, and gradually acclimate to different conditions (Bulax & Shumyk, 2013; Yatsyk et al., 2017).To predict the adaptability of an introduced plant to new conditions, researchers compare the climatic and agroclimatic factors of its natural growth regions with those of potential cultivation areas. They also study the species' paleo-range and current distribution, conduct florogenetic analysis, consider past introduction experiences, and examine the plant's response to the most significant ecological factors of the region (Yatsyk et al., 2017).

Since most willows originate from northern and temperate latitudes, the primary limiting factor in expanding their cultivated range southward is drought tolerance. The issue of willow drought resistance remains a focus of many researchers and is widely discussed in the literature. A plant's ability to withstand drought is a combination of its capacity to avoid drought and endure dehydration. In an experimental study on dehydration resistance, Tipton J.L. (2024) examined desert willow, yellow bells, and mulberry, finding that desert willow and yellow bells exhibited higher relative resistance than mulberry in both humid and arid conditions. This suggests that willow leaves experiencing drought stress have adapted to minimize water loss.

In their study on the diversity of willows in Minnesota, J.A. Savage and J.M. Cavender-Bares (2011) compared the survival strategies of willow species found in wet and seasonally dry ecotopes. They determined that species occurring in dry ecotopes exhibit greater physiological divergence.

Chinese researchers investigated the sexual responses to drought and the external application of acetic acid in *S. rehderiana*, *S. babylonica*, and *S. matsudana*, finding that female specimens of these willow species demonstrated greater drought tolerance than male specimens (Xia et al., 2023). Specifically, female willows treated with acetic acid exhibited a more extensive and active root system, higher osmotic and antioxidant capacity, and increased photosynthetic rate. In contrast, male specimens showed a higher presence of reactive oxygen species and greater stomatal closure, indirectly induced by abscisic acid.

The drought tolerance of willows, along with their ability to withstand pollarding and topping, allows for the establishment of forage plantations near farms in New Zealand for use during dry periods (Jones & McIvor, 2013). Drought resistance is also a key criterion for selecting *Salix* species for breeding trials (Macalpine, 2019).

At the same time, the limiting factors restricting the cultivated range of North American, Euro-Siberian, and Far Eastern *Salix* species in Ukraine are high temperatures and low moisture levels – both in the soil and air - during the summer months, which reduce the drought tolerance of these species (Ishchuk, 2016; 2017c). As a result, introduced *Salix* species and their cultivars in Ukraine are primarily found in botanical garden collections, arboretums, and other scientific institutions. However, their presence in urban landscaping is significantly more limited. In the latest edition of the reference book *"Assortment of Trees, Shrubs, and Lianas for Landscaping in Ukraine"* (Kuzneczov et al., 2013), only 11 species and three cultivars are recommended for landscaping in Ukraine: *S. alba* L., *S. alba* 'Vitellina pendula', *S. babylonica* L., *S. acutifolia* Willd., *S. caprea* L., *S. matsudana* Koidz., *S. matsudana* 'Tortuosa', *S. capusii* Franch., *S. caspica* Pall., *S. myrsinifolia* Salisb., *S. cinerea* L., *S. purpurea* L., *S. purpurea* 'Gracilis', and *S. rosmarinifolia* L.

The aim of our research is to identify promising *Salix* species for implementation in landscaping, phytoremediation, and plantation forestry based on an analysis of their natural and cultivated range in Ukraine, as well as their growth, development, and ecological resilience to environmental conditions.

MATERIALS AND METHODS

The study of the cultivated range of *Salix* L. species was conducted from 2012 to 2022 in the forest, forest-steppe, and steppe natural-climatic zones of Ukraine. The analysis included *Salix* L. species in the collections of botanical gardens and arboretums in Kyiv, Bila Tserkva, Uman, Chernivtsi, Uzhhorod, Lviv, Lutsk, Vinnytsia, Ternopil, Kharkiv, Sumy, Poltava, Dnipro, Kryvyi Rih, Odesa, Kherson, and Zaporizhzhia, as well as in the landscaping of public spaces in these cities (Fig. 1). The general climatic characteristics of Ukraine's natural-climatic zones are presented in Table 1 (Climate…, 2022; Didukh, 2023).

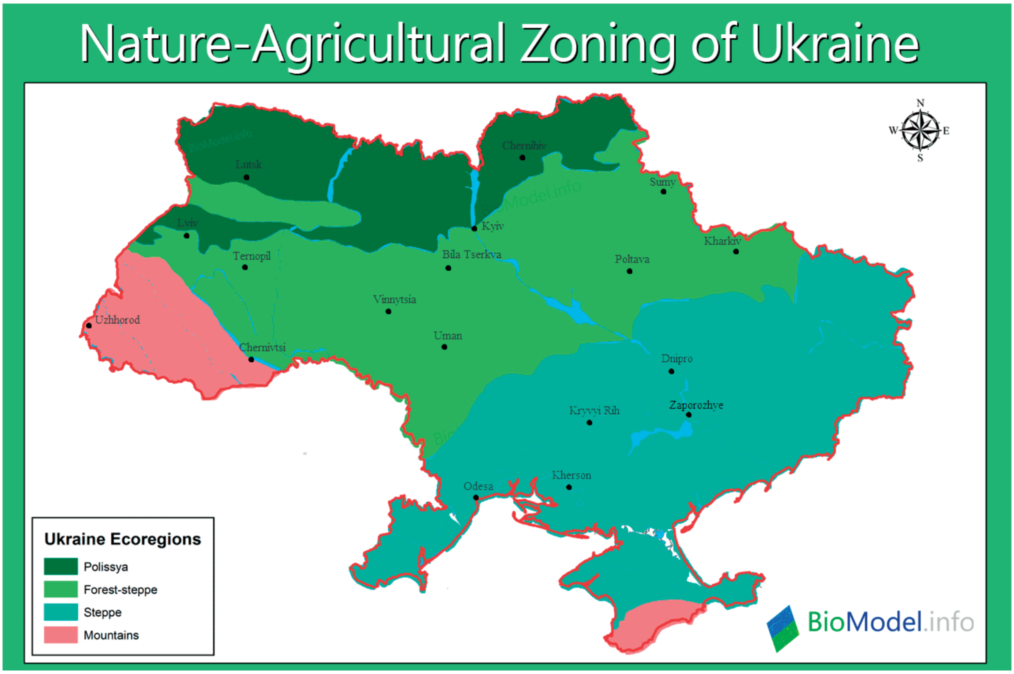

Figure 1. Distribution of introduced *Salix* L. species in Ukraine

Table 1. General Climate Indicators in the Natural-Climatic Zones of Ukraine

Indicator name	Polissya	Forest-steppe	Steppe
Average annual air temperature, ºC	+6.2…+6.6	+8.0…+8.8	+9.0…+10.9
Average January temperature, ºC	-3.0…-6.5	-4.0…-8.0	+1.5…-8.0
Average July temperature, ºC	+17.0…+19.5	+18.0…+20.0	+21.0…23.0
Absolute minimum temperature, ºC	-39.0	-36.0	-40.0
Absolute maximum temperature, ºC	+39.0	+40.0	+41.0
Frost-free period duration, days	160…210	150…190	200…230
Sum of active temperatures above +10 ºC	1940…2580	2500…3400	3450…3550
Soil freezing depth, cm	80…150	90…130	60…160
Vegetation period duration, days	160…180	180…200	200…210
Annual precipitation, mm/year	550…700	450…550	300…450

The subjects of our research were introduced species of the genus *Salix* L., including *S. adenophylla* Hook., *S. alatavica* Kar. ex Stschegl., *S. argyracea* E.L. Wolf, *S. babylonica*, *S. capusii*, *S. caspica*, *S. dasyclados* Wimm., *S. elaeagnos* Scop., *S. integra* Thunb., *S. kangensis* Nakai, *S. matsudana*, *S. miyabeana* Seemen, *S. ledebouriana* Trautv., *S. lucida* Muhl., *S. udensis* Trautv. & C.A. Mey. and *S. schwerinii* A.K. Skvortsov, which are represented in the collections of botanical gardens and dendrological parks of Ukraine. Additionally, our research included native species such as *S. fragilis* L., *S. myrtilloides* L., *S. lapponum* L., *S. caprea*, *S. aurita* L., *S. starkeana* Willd., *S. purpurea*, *S. vinogradovii* A. Skvorts., *S. viminalis* L., and *S. myrsinifolia* Salisb., which in Ukraine are located at the southern or southeastern limit of their natural range.

The introduction process and all its key stages can generally be divided into three blocks: scientific forecasting or diagnostics, modeling or experimentation, and evaluation of results or the success of species introduction (Bulax & Shumyk, 2013). To implement the first block of the introduction process – scientific forecasting or modeling – we analyzed the geographical origin and soil-climatic conditions of Ukraine and the regions where *Salix* species were introduced. During the second stage, which involves experimental research, we assessed the introduced *Salix* species based on key life activity indicators, including growth, generative development, winter hardiness, and drought resistance. At the third stage of the introduction process, we analyzed the experimental results.

To assess the success of the introduction, we used seven key indicators: the degree of annual shoot maturation, winter hardiness, preservation of plant habitus, ability to form shoots, regularity of shoot growth, capacity for generative development, and methods of reproduction in the introduction region (Kokhno, 1983). Winter hardiness was evaluated using a 7-point scale: I – no damage (25 points); II – frost damage affects less than 50% of the length of annual shoots (20 points); III – frost damage affects 50-100% of the length of annual shoots (15 points); IV – frost damage extends to biennial and older parts of the plant (10 points); V – the crown freezes down to the snow cover level (5 points); VI – the entire above-ground part freezes (3 points); VII – the plant completely perishes (1 point).

The plant habitus was analyzed using a 3-point scale: I– plants retain their natural life form in cultivation, as observed in the wild (10 points); II – plants experience some frost damage, do not restore their above-ground parts to the previous height and volume (5 points); III – plants do not retain their characteristic growth form from nature, as they freeze annually at an early age or exhibit low growth energy (1 point).

The shoot-forming ability was assessed using a 3-point scale: I – high ability (6 or more shoots on a single two-year-old shoot) (5 points); II – moderate ability (3-5 shoots on a single two-year-old shoot) (3 points); III – low ability (2 shoots on a single two-year-old shoot) (1 point). The regularity of shoot growth was evaluated based on the presence or absence of annual increments in the main shoots or branches, considering the plant's age: Annual increment – 5 points; Non-annual increment – 2 points.

The ability of plants for generative development was analyzed using a 4-point scale: I – seeds mature (25 points); II – plants flower, but fruits do not ripen (20 points); III – plants flower, but fruits do not set (15 points); IV – do not flower (1 point). The possible modes of reproduction in the cultivated range were assessed using a 5-point scale: I – self-seeding (10 points); II – artificial sowing (7 points); III – natural vegetative propagation (5 points); IV – artificial vegetative propagation (3 points); V – plants are imported from the natural range (1 point).

In introduction practice and reference literature, the term acclimatization is widely used and interpreted as the adaptation of plants to climatic conditions that differ from those of their natural range. In reality, plants adapt not only to climate but also to soil, hydrological, and other environmental conditions (Kokhno, 1983). To ensure an objective assessment of the success of introduction and the degree of acclimatization of *Salix* species, evaluation criteria were combined and assigned numerical values in the form of a total score – the acclimatization index (Kokhno, 1983). The acclimatization index (*A*) is the sum of the scores for growth, generative development, winter hardiness, and drought resistance. The highest possible acclimatization index, 100, corresponds to the highest level of introduction success. The formula used to determine the acclimatization index is:

$$A = P \times b_4 + G_3 \times b_2 + W \times b_1 + D \times b_3, \quad (1.1)$$

where (P) is the growth indicator, (G_3) is the generative development indicator, (W) is the winter hardiness indicator, (D) is the drought

resistance indicator, and (b_1-b_4) are the weighting coefficients for each characteristic.
The indicators for growth, generative development, winter hardiness, and drought resistance were visually assessed using five-point scales. The data obtained from visual observations were compared with the weighting coefficient (b), which reflects the significance of each characteristic in the introduction process. The weighting values were determined based on their importance for successful introduction: Winter hardiness – 10, Generative development – 5, Drought resistance – 3, Growth – 2.
The degree of drought resistance in plants was determined using the following scale: good drought resistance under all conditions – 5 points; relative drought resistance (the plant partially sheds leaves during drought) – 4 points; the plant sheds all leaves during drought – 3 points; leaves lose turgor during drought but later recover – 2 points; no drought resistance (the plant dies from drought) – 1 point (Mezhens'kyj, 2007).
Based on the analysis of the viability indicators of willows, the degrees of their acclimatization were determined according to the acclimatization index value: full acclimatization (A = 100), good acclimatization (A = 80), satisfactory acclimatization (A = 60), weak acclimatization (A = 40), no acclimatization (A = 20).

RESULTS AND DISCUSSIONS

In total, the willow flora of Ukraine is represented by 43 species and 11 hybrids of the genus *Salix*, belonging to 20 sections, including 20 introduced species from Siberia, the Far East, Mongolia, China, Japan, and North America (Gorelov, 2002) (Table 2).

Table 2 Natural and Cultivated Range of *Salix* Species Introduced to Ukraine

Species Name	Natural Range	Cultivated Range in Ukraine
S. adenophylla	North America – from Labrador to Wisconsin, south to Pennsylvania and Illinois.	Kyiv, Bila Tserkva, Uman
S. alatavica	Southwestern Altai, Western Mongolia, Sayan Mountains, Tien Shan.	Kyiv, Bila Tserkva, Uman
S. argyracea	Southeastern regions of Kazakhstan, Kyrgyzstan, Xinjiang Uygur Autonomous Region of China.	Kyiv, Bila Tserkva, Uman
S. babylonica	China.	Kyiv, Bila Tserkva, Uman, Chernivtsi, Lviv, Vinnytsia, Ternopil, Odesa, Kharkiv, Poltava
S. capusii	Central Asia.	Kyiv, Bila Tserkva, Uman
S. caspica	Volga region, Ural, Western Siberia, Central Asia, Mongolia, Iran.	Kyiv, Bila Tserkva, Uman
S. dasyclados	Eastern Europe, western, central, and southern regions of Siberia, Far East, Mongolia, and Northern China.	Kyiv, Bila Tserkva, Uman
S. elaeagnos	Western, Southern, and Central Europe. In Ukraine, only in the highlands of the Carpathians.	Kyiv, Bila Tserkva, Uman
S. integra	Japan.	Kyiv, Lutsk, Poltava, Vinnytsia, Bila Tserkva, Uman
S. kangensis	Far East and Southeastern China.	Kyiv, Bila Tserkva, Uman
S. ledebouriana	Siberia, Kazakhstan, Mongolia.	Kyiv, Bila Tserkva, Uman
S. lucida	North America – from Newfoundland west to eastern Saskatchewan, and south to Maryland and South Dakota.	Kharkiv, Bila Tserkva
S. matsudana	China, Korea.	Kyiv, Lviv, Uzhhorod, Chernivtsi, Vinnytsia, Ternopil, Odesa, Uman, Bila Tserkva, Kharkiv, Poltava, Sumy, Dnipro
S. miyabeana	Eastern and Southern Siberia, Far East, Mongolia, and Northeastern China.	Kyiv, Bila Tserkva, Uman, Chernihiv region
S. schwerinii	Southern regions of Eastern Siberia, Far East, southern Kamchatka and Sakhalin, Mongolia and Northeastern China.	Vinnytsia, Kryvyi Rih, Uman, Bila Tserkva
S. udensis	Eastern Siberia, Far East, Southeastern China, Northern Mongolia, Korea and Japan.	Kyiv, Bila Tserkva, Uman

At the same time, it should be noted that these species are unevenly distributed across Ukraine. Ten species (*S. fragilis, S. myrtilloides, S. lapponum, S. caprea, S. aurita, S. starkeana, S. purpurea, S. vinogradovii, S. viminalis, S. myrsinifolia*) are located at the southern or southeastern limit of their range in Ukraine, which is explained by the climatic transition from the northwest to the southeast of the country (Ishchuk, 2014; 2015b; 2017c) (Figure 2).

Figure 2. The southern distribution limit of autochthonous species of the genus *Salix* L. in Ukraine:
1 - *S. lapponum*; 2 - *S. myrsinifolia*; 3 - *S. myrtilloides*; 4 - *S. aurita*; 5 - *S. rosmarinifolia*; 6 - *S. purpurea*;
7 - *S. starkeana*; 8 - *S. viminalis*; 9 - *S. caprea*; 10 - *S. fragilis*

However, isolated occurrences of these species are also found south of their continuous range. In particular, *S. starkeana* has been recorded in Poltava Oblast, 100 km south of its primary range boundary (Ishchuk & Smolyar, 2017), while *S. purpurea* is distributed in the steppe foothills of Crimea (Ishchuk & Ishchuk, 2020). Seven species (*S. herbacea, S. retusa, S. alpina, S. silesiaca, S. rhaetica, S. daphnoides,* and *S. elaeagnos*) have an insular distribution limited to the Ukrainian Carpathians and require conservation efforts (Red Book of Ukraine. Plant World, 2009; Fuchylo & Sbytna, 2009; Ishchuk, 2014; 2017a). According to V.V. Krichfalushiy (1982), *S. alpina* Scop., *S. hastata* L., *S. herbacea* L., *S. kitaibeliana* Willd., *S. lapponum* L., *S. phylicifolia* L. and *S. retusa* L. are rare arcto-alpine and alpine species – relicts of the glacial period – found exclusively in the highlands of the Carpathians. Table 3 presents the geographic distribution of *Salix* species found in Ukraine.

Table 3. Geographical groups of *Salix L.* ranges characteristic of Ukraine

Geographic Groups of Salix Ranges	Distribution in Ukraine
I. Multizonal Species (ranges covering most of the Eurasian continent):	*S. caprea, S. pentandra, S. alba, S. triandra, S. starkeana, S. cinerea*
II. European Species (ranges within Europe)	*S. fragilis, S. aurita, S. viminalis, S. purpurea, S. daphnoides, S. elaeagnos*
III. Eastern European Species (ranges within Eastern Europe)	*S. acutifolia, S. silesiaca*
VI. Eurosiberian Species (ranges covering Northern and Central Europe and Siberia)	*S. rhaetica, S. lapponum, S. myrtilloides, S. myrsinifolia, S. rosmarinifolia, S. vinogradovii*
V. Arctic-Alpine Species (ranges covering Arctic and alpine tundra)	*S. herbacea, S. retusa, S. alpina.*

In Ukraine, the cultivated range includes *S. adenophylla, S. alatavica, S. argyracea, S. babylonica, S. caspica, S. capusii, S. dasyclados, S. integra, S. kangensis, S. ledebouriana, S. lucida, S. matsudana, S. miyabeana, S. udensis* and *S. schwerinii.*

However, with the exception of the garden forms *S. integra* 'Hakuro-Nishiki', *S. integra* 'Pendula' and *S. matsudana* 'Tortuosa', most species are represented only by individual specimens in botanical garden and arboretum collections and are nearly absent from urban landscaping. The largest and oldest willow collection in Ukraine is housed at the M.M. Hryshko National Botanical Garden of the National Academy of Sciences of Ukraine in Kyiv, comprising 45 species, hybrids, and forms (Kruglyak et al., 2009). Most willow collections are concentrated in the forest-steppe zone of central Ukraine, including the Botanical Garden of Bila Tserkva National Agrarian University, the State Dendrological Park "Alexandria" of the National Academy of Sciences of Ukraine (Bila Tserkva), the Sofiyivka National Dendrological Park of the National Academy of Sciences of Ukraine (Uman), the Kryvyi Rih Botanical Garden (Kryvyi Rih), the Berezne State Dendrological Park in Rivne region and the "Ivushka" Arboretum in Poltava region (Ishchuk, 2019).Typically, in botanical gardens, *Salix* collections are planted on gentle slopes as a single generic complex, creating uniform edaphic and microclimatic conditions within the plot. This approach allows for the study of all introduced species under relatively similar environmental conditions (Kruglyak et al., 2009; Ishchuk, 2013a; 2018).

The introduction trials in the Forest-Steppe zone of Ukraine also included *S. aurita, S. elaeagnos, S. lapponum, S. myrsinifolia,* and *S. myrtilloides*, whose natural range is limited to the northern and western parts of Ukraine, primarily within the Polissya zone (Ishchuk, 2015a; 2017b).

To assess the success of introductions in the cultivated range, evaluations were conducted on the willow species' life form, annual shoot growth, and degree of lignification by the end of the growing season, as well as their winter hardiness, drought resistance, and methods of propagation in cultivation.

When transferred to the cultivated range, *S. argyracea, S. schwerinii, S. udensis* and *S. kangensis* exhibited a change in life form from "tree" to "shrub." Meanwhile, *S. capusii* and *S. caspica*, which naturally grow as small trees or shrubs in their native habitat, formed only the "shrub" life form in Ukraine (Table 4). The remaining introduced species did not undergo changes in life form.

Table 4. Results of the evaluation of the introduction success of *Salix* species using an integrated scale in Ukraine

Species	Life form:		Age of Plants (Years)	Winter Hardiness Score	Viability Indicators (Points):							Overall Assessment:	
	in the wild	in cultivation			Shoot Lignification	Winter Hardiness	Shape Retention	Shoot Formation	Height Growth	Possible Methods of Preservation in Cultivation	Possible Methods of Propagation in Cultivation	Total Viability Indicators Score	Prospect Group
S. aurita	shrub	shrub	1–10	1	20	20	10	3	5	25	3	87	I
S. adenophylla	shrub	shrub	1–10	1	20	20	10	3	5	25	3	87	I
S. alatavica	shrub	shrub	10	1	20	25	10	3	5	25	3	97	I
S. argyracea	tree	shrub	1–10	1	20	25	10	3	5	25	3	89	I
S. babylonica	tree	tree	1-60	2	15	20	10	3	5	25	3	80	I
S. capusii	small tree-shrub	shrub	1–10	1	20	25	10	3	5	25	3	89	I
S. caspica	small tree-shrub	shrub	1–10	1	20	25	10	3	5	25	3	89	I
S. dasyclados	shrub	shrub	1–10	1	20	25	10	3	5	25	3	91	I
S. elaeagnos	tree	tree	1–10	2	15	20	10	3	5	25	3	83	I
S. integra	tree	tree	10	2	15	20	10	3	5	20	3	78	I
S. kangensis	tree	shrub	10	1	20	25	10	3	5	20	3	87	I
S. lapponum	shrub	shrub	1–10	1	20	20	10	3	5	25	3	87	I

S. matsudana	tree	tree	1-10	2	15	20	10	3	5	20	3	75	I
S. miyabeana	shrub	shrub	1-20	2	15	20	5	3	5	25	3	78	II
S. myrsinifolia	shrub	shrub	1–10	1	20	20	10	3	5	25	3	87	I
S. myrtilloides	shrub	shrub	1–10	1	20	20	10	3	5	25	3	87	I
S. ledebouriana	shrub	shrub	1–10	1	20	25	10	3	5	25	3	91	I
S. lucida	tree	tree	1–8	1	20	20	10	3	5	25	3	87	I
S. schwerinii	tree	shrub	1–10	1	20	25	8	3	5	25	3	90	I
S. udensis	tree	shrub	10	1	15	15	8	3	5	25	3	75	II

The frost resistance score was evaluated based on the degree of lignification of the shoots. Incompletely lignified shoots by the end of the growing season were recorded in *S. integra*, *S. elaeagnos*, *S. babylonica*, *S. matsudana* and *S. miyabeana*, which indicates a lower frost resistance of these species. In their natural habitat, they have a longer growing period (Ishchuk, 2018). The low degree of frost resistance of *S. matsudana* in the conditions of Western Ukraine was also confirmed by the researchers of the Botanical Garden of the National Forestry University of Ukraine in Lviv (Melnyk et al., 2010).

The process of shoot formation and growth in all the studied species within their natural and cultivated ranges remained unchanged. All the studied *Salix* species in the cultivated range in Ukraine propagate through lignified cuttings. At the same time, while studying the energy properties of willows, scientists established that the annual growth of willows and the number of shoots per shrub, including *S. dasyclados*, depend on planting density and the amount of nitrogen fertilizer applied in the plantation (Sinchenko et al., 2022). Our studies of *S. dasyclados*, *S. caspica*, *S. capusii*, *S. adenophylla*, *S. argyracea*, *S. ledebouriana*, *S. schwerinii* and *S. udensis*, which are also promising species for energy plantations, fully confirm these findings.

Based on the sum of viability indicators, all the studied species in the cultivated range in Ukraine, with the exception of *S. miyabeana* and *S. udensis*, belonged to the highest first group of introduction prospects.

When determining the acclimatization level for each introduced willow species in Ukraine, growth, generative development, frost resistance, and drought tolerance indicators were analyzed. By analyzing the average annual growth, we recorded a wide range of values, from 15 cm (*S. alatavica*, *S. lapponum*) to 103 cm (*S. dasyclados*) (Figure 3). This can be explained by the fact that the studied willow species in their natural habitats also exhibit different growth energies, especially in small shrub forms with a compact crown structure, such as *S. lapponum*, *S. miyabeana*, *S. myrsinifolia* and *S. myrtilloides*. However, the annual growth range for most species fluctuates between 50 and 100 cm, ensuring the preservation of a similar plant habitus in both natural and cultivated ranges.

The expansion of the cultivated range of *Salix* species in Ukraine, particularly under global climate change, is most influenced by the drought tolerance of willows. This trait is a limiting factor for increasing the diversity of willows in the southern and eastern regions of Ukraine (Gorelov, 2016; Ishchuk, 2016; 2017c). However, most researchers agree that *Salix* species have a certain potential for drought tolerance. Under artificial drought stress conditions, *S. myrsinifolia* seedlings were more susceptible to drought stress than hybrids of *Salix myrsinites L.* × *Salix myrsinifolia* (Turtola et al., 2006). According to Polish researchers, *S. viminalis* is characterized by high drought tolerance (Drzewiecka, 2023), and in Ukraine, it also has insular habitats outside its continuous range in the Odesa region. At the same time, in studies by Chinese scientists, *S. babylonica* was found to be less drought-tolerant than the desert willow *Salix gordejevii* (Yang et al., 2004).

The drought tolerance of willows is also significantly influenced by the origin of the species. According to our observations in the cultivated range, the most drought-tolerant species are those of southern origin from the Volga region, southern Siberia, Central Asia, Iran, Mongolia, and China, including *S. capusii*, *S. caspica*, *S. babylonica*, *S. miyabeana*, *S. ledebouriana* and *S. schwerinii*,

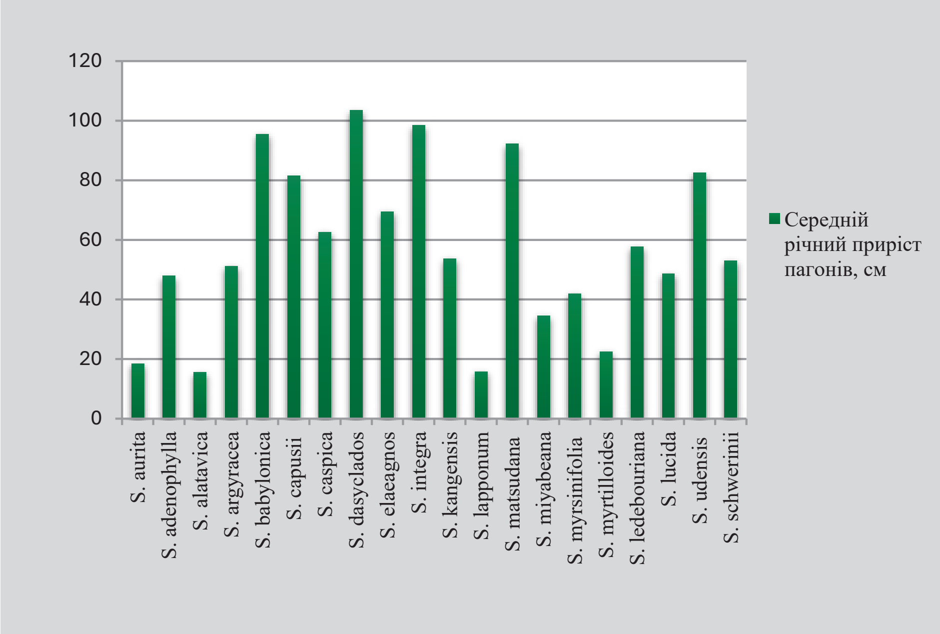

Figure 3. Average annual shoot growth of *Salix* species introduced to Ukraine

as confirmed by studies conducted in Kyiv by O. Gorelov (2016). At the same time, despite its origin from Korea and China, *S. matsudana* was found to be less drought-tolerant in our studies. Our findings on the drought tolerance of *S. matsudana* align with experimental research conducted in Canada (Doffo et al., 2016).

Salix species are dioecious plants with unisexual flowers arranged in catkins. They bloom depending on the species – before leaf bud break, simultaneously with it, or after the leaves have fully unfolded. In the cultivated range in Ukraine, only three willow species (*S. argyracea*, *S. miyabeana*, *S. udensis*) bloomed but did not produce fruits or seeds (Table 5). The other species regularly bloomed in Ukraine, and we recorded the first flowering of trees and shrubs propagated vegetatively at the age of 4-6 years.

Table 5. Degree of acclimatization of introduced *Salix* species in Ukraine

Species	Indicators				Acclimatization Index	Degree of Acclimatization
	growth	generative development	frost resistance	drought resistance		
S. aurita						
S. adenophylla	10	25	50	10	95	full
S. alatavica	10	25	50	10	95	full
S. argyracea	10	15	50	10	85	good
S. babylonica	10	25	40	15	90	full
S. capusii	10	25	50	15	100	full
S. caspica	10	25	50	15	100	full
S. dasyclados	10	25	50	10	95	full
S. elaeagnos	10	25	40	10	85	good
S. integra	10	25	40	10	85	good
S. kangensis	10	25	50	10	95	full
S. lapponum	10	25	50	10	85	good
S. ledebouriana	10	25	50	15	100	full
S. lucida	10	25	50	10	95	full

S. matsudana	10	25	30	10	75	good
S. myrsinifolia	10	25	50	10	75	good
S. myrtilloides	10	15	50	10	85	good
S. miyabeana	10	15	40	15	80	good
S. schwerinii	10	20	50	15	95	full
S. udensis	10	15	50	10	85	good

According to the acclimatization index, which includes the sum of integral indicators for growth, generative development, frost resistance, and drought tolerance, nine species (*S. argyracea*, *S. elaeagnos*, *S. integra*, *S. matsudana*, *S. myrsinifolia*, *S. myrtilloides*, *S. miyabeana*, *S. lapponum*, *S. udensis*) have demonstrated good acclimatization in the forest-steppe zone of Ukraine, while the remaining species have fully acclimatized to the new soil and climate conditions. A decade of experience with the cultivation of introduced willows in Ukraine has shown that species from the eastern and northern regions of North America, Siberia, Mongolia, the Far East, Japan, and northern China are most effectively optimized for introduction (Ishchuk, 2013b; 2015a).

CONCLUSIONS

As long-term experience with *Salix* cultivation in Ukraine shows, introduced species of the *Salix* genus differ in their geographic origin and exhibit varying degrees of introduction success. Ukraine cultivates twenty introduced willow species, with the greatest diversity represented in scientific collections in cities of the forest-steppe zone – Kyiv, Bila Tserkva and Uman. Most of these species have fully acclimatized to the new conditions, except for *S. argyracea*, *S. elaeagnos*, *S. integra*, *S. lapponum*, *S. matsudana*, *S. myrtilloides*, *S. miyabeana* and *S. udensis*, which are characterized by a good degree of acclimatization.

For southern-origin species such as *S. integra*, *S. elaeagnos*, *S. babylonica*, *S. matsudana* and *S. miyabeana*, delayed shoot maturation is characteristic, which leads to reduced frost resistance. However, these species exhibit a high ability to form shoots, which aids in the rapid restoration of their habitus. Six species – *S. argyracea*, *S. capusii*, *S. caspica*, *S. kangensis*, *S. schwerinii* and *S. udensis* – under cultivated conditions change their life form from “tree” or “small tree” to “shrub”.

The limiting factors that restrict the cultivated range of Euro-Siberian and Far Eastern *Salix* species in Ukraine are high air temperatures and low soil moisture in summer. These conditions lead to growth suppression, reduced leaf blade size, temporary loss of leaf turgor, and overall decreased ornamental value.

Promising regions for expanding the biodiversity of willows in Ukraine are areas with a temperate climate, such as North America, as well as Siberia, the Far East, Mongolia, Japan, and northern China.

ACKNOWLEDGEMENTS

The research was conducted from 2012 to 2022 in the Department of Dendrology and Park Construction of the Sofiyivka National Dendrological Park of the National Academy of Sciences of Ukraine within the framework of the following scientific projects: “Theoretical Foundations of Monitoring, Assessment, and Inventory of Perennial Plantations in Historical Parks of Ukraine” (State Registration No. 0112U002030), “Theoretical and Practical Principles of Formation and Maintenance of Monocultural and Thematic Gardens” (State Registration No. 0114U000064) and “Biological and Technological Features of Growing Planting Material of Woody Plants Suitable for Distribution in the Right-Bank Forest-Steppe of Ukraine” (State Registration No. 0115U002090).

REFERENCES

Boiko, L. I., Yukhymenko, Yu. S. & Danylchuk, O. V. (2024). *Introduction of tree plants in the industrial region of the Steppe zone of Ukraine and their use in urban gardening*. Monograph. Kryvyi Rih: Talkom. 268 p.

Bulax, P. Ye. & Shumyk, M. I. (2013). *Theoretical foundations and experience of introduction of woody plants in Ukraine*. Kyiv: Naukova Dumka. 151 p.

Catalog of cultivated woody plants of the Southeastern United States. (1994). Agricultural research Servis. P. 187-188.

Climate change and adaptation of soybean producers in Ukraine. Handbook (2022). Kyiv. 40 p. URL.: https://surl.li/cacyjd

Didukh, Ya. P. (2023). *World of plants of Ukraine in aspect of the climate change.* "Scientific book" project. Monograph Kyiv: Naukova dumka. 202 p.

Doffo, G. N., Monteoliva, S. E., Rodríguez, M. E. & Luquez, V. M. C. (2016). Physiological responses to alternative flooding and drought stress episodes in two willow (*Salix* spp.) clones. *Canadian Journal of Forest Research* 3 October 2016 https://doi.org/10.1139/cjfr-2016-0202

Drzewiecka, K., Gawrysiak, P., Wozniak, M. & Rybak, M. (2023). Metal Accumulation and Tolerance of Energy Willow to Copper and Nickel under Simulated Drought Conditions. *Sustainability* 15, 13084. https://doi.org/10.3390/su151713084

Elias, T. S. (1980). *Trees of North America*. New York, Van Nostrand, Reinhold company, New York, 948 p.

Fuchylo, Ya. D. & Sbytna, M. V. (2009). *Willows of Ukraine (biology, ecology, use)*: monograph. Kyiv: Logos.

Gorelov, O. M. (2016). Comparative assessment of drought resistance of willows from the collection of the National Botanical Garden named after M.M. Grishko of the NAS of Ukraine. *Introduction of Plants*. No. 2. P. 25-33. 97.

Ishchuk, L. P (2017a). Analysis of willow (Salix L.) *Flora in Ukrainian Carpathians. Journal of botany*. Vol. IX, Nr. 1 (14). P. 50-55.

Ishchuk, L. P. (2014). Assortment, peculiarities of growing and perspectives of using of the arctic mountain species of the genus *Salix* L. *Scientific bulletin of Ukrainian National Forestry University*. Issue 24.4. P. 28-35.

Ishchuk, L. P. (2013a). Collection of representatives of the *Salicaceae* family Mirbel at the biostationary of the Bila Tserkva National Agricultural University. *The role of botanical gardens and arboretums in the preservation and enrichment of biological diversity of urbanized territories:* Proceedings of the International Scientific Conference (Kyiv, May 28-31, 2013). Editor-in-chief V.G. Radchenko. Kyiv: NCEBM NAS of Ukraine, PJSC "Vipol". P. 217-218.

Ishchuk, L. P. (2019). Family *Salicaceae* Mirbel.: biology, adaptive potential, protection and use in Ukraine: abstract of the dissertation for the degree of Doctor of Biological Sciences: specialty: 03.00.05 Botany. Kyiv. 47 p.

Ishchuk, L. P. (2016). Influence of drought resistance on species chorology of the genus *Salix* L. in Ukraine. *Native and Alien Plant Sciences*. Issue 12. P. 81-85.

Ishchuk, L. P. (2015a). Introduced species of the genus *Salix* L. in plantations of the Right-Bank Forest-Steppe of Ukraine. *Current problems of botany and ecology:* Materials of the International Conference of Young Scientists dedicated to the 120th anniversary of the birth of D.K. Zerov (Poltava, September 15-20, 2015). Poltava. P. 132-133.

Ishchuk, L. P. (2013b). Peculiarities of the introduction optimization of willows of Siberia, the Far East, Mongolia and northern China in Ukraine. *Preservation and reconstruction of botanical gardens and arboretums in conditions of sustainable development:* Materials of the IV International Scientific Conference dedicated to the 225th anniversary of the dendrological park "Olexandria", (September 23-26, 2013). Part I. Bila Tserkva. P. 98-101.

Ishchuk, L. P. (2017b). Taxonomic composition and peculiarities of propagation of species of genus *Salix* L. in the Ukrainian Polissya. *Nature of Western Polissya and adjacent territories Collection of scientific papers.* Edited by F.V. Zuzuk. Lutsk: Lesya Ukrainka East European National University. Vol. II. P. 33-37.

Ishchuk, L. P. (2015b). The genus *Salix* L. in Ukraine. Biosphere Reserve "Askania Nova" Reports. Issue 17. P. 97-100.

Ishchuk, L. P. (2018). Winter hardiness of species and cultivars of the *Salicaceae* family Mirbel in the conditions of the Right-Bank Forest-Steppe of Ukraine. *Preservation of plant diversity in botanical gardens and arboretums: traditions, modern prospects*: Proceedings of the International Scientific Conference on the 230th anniversary of the Oleksandria Arboretum of the NAS of Ukraine. (September 19-20). Bila Tserkva: Publishing house "Bilotserkivdruk". P. 175-182.

Ishchuk, L. P. (2017c). Water-holding capacity leaves species of *Salix* L. *Formation of urban geen areas.* No 1 (14). P. 93-98.

Ishchuk, L. P. & Ishchuk, H. P. (2020). Family *Salicaceae* Mirb. in the natural flora of Ukraine: taxonomy, chorology, protection. *Scientific developments of Ukraine and EU in the area of natural science:* Collective monograph. Riga: Izdevnieciba «Baltija Publishing». P 1. P. 307-327. DOI https://doi.org/10.30525/978-9934-588-73-0/1.16

Ishchuk, L. P., Maslovata, S. A. & Ishchuk, H. P. (2018). Salicarij as a modern form of monogarden Willow (*Salix* L.). *Formation of urban green areas*. No1 (15). P. 53-60.

Ishchuk, L. P. & Smolyar, N. O. (2017) Current status, productivity and sociological value of indigenous willow-poplar communities in the lower reaches of the Vorskla River. *Scientific notes of the Ternopil Pedagogica l University. Biology series*. No. 1 (68). P. 52-58.

Jones, T. & McIvor, I. (2013) Willows and poplars for drought mitigation. *Plant & Food.* November URL: https://surl.li/mhlvzo

Kokhno, M. A. (1983). *On the success of woody plant introduction. Introduction of woody plants and greening of Ukrainian cities*. Kyiv: Naukova. dumka, 1983. P. 2–8.

Kokhno, M. A. ℬ Kurdyuk, A. M. (1994). *Theoretical foundations and experience of introduction of woody plants in Ukraine*. Kyiv: Naukova. dumka, 1994. 184 p.

Krichfalushij, V. V. (1982). Species of the genus *Salix* L. in the Ukrainian Carpathians. *Ukrainian Botanical Journal*. Vol. 39, No. 2. pp. 52-56.

Kruglyak, Yu. M., Minchenko, N. F. & Gorelov, O. M. (2009). The collection of willows (*Salix* L.) of M.M. Gryshko national botanical gardens of the NAS of Ukraine. *Plant introduction*. No 3. P. 8-11.

Kuzneczov, S. I., Levon, F. M. & Pushkar, V. V. (2013). *Assortment of trees, bushes and vines for landscaping in Ukraine* / edited by F.M. Levon. Kyiv. 256 p.

Macalpine, W. J. (2019). *Identifying drought tolerant short rotation coppice willows.* Dissertation for the degree of Master of Philosophy. Newport: Harper Adams University. 125 p.

Melnyk, Yu. A., Melnyk, A. S., Yefremova, O. O., Meleshko, I. G. & Chujko, T. M. (2010). Introduction plants of the East-Asiatic flora vascular plants in the conditions of the west of Ukraine. *Scientific Bulletin of the National Forestry University of Ukraine*. Vol. 20.3. P. 8-13.

Mezhens'kyj, V. M. (2007). Unification of assessment scales used in the introduction of woody plants. *Plant Introduction*. No. 4. P. 26-37.

Native trees of Canada. Canada. (1950). Ottawa. 291 p.

Red Book of Ukraine. Plant World. (2009). Edited by Ya. P. Didukh. Kyiv: Globalconsulting. 900 p.

Rehder, A. (1949). *Manual of cultivated trees and shrubs*. New York, the Macmillan company, 996 p.

Rogovskyi, S. V., Ishchuk L. P. & Ishchuk H. P. (2023). Chornobyl’s current dendroflora: analysis of natural successions in the abandoned urban phytocoenoses. *Trakya University Journal of Natural Sciences*. 24(2). P. 5-21 DOI: 10.23902/trkjnat.1246847

Savage, J. A. & Cavender-Bares, J. M. (2011). Contrasting drought survival strategies of sympatric willows (genus: *Salix*): consequences for coexistence and habitat specialization. *Tree Physiology* 31, 604–614 doi:10.1093/treephys/tpr056

Sinchenko, V. M., Fuchy`lo, Ya. D., Ganzhenko, O. M., Gumenty`k, M. Ya., Gnap, I. V. & Ivanyuk, I. D. (2022). *Introduction of high-yielding varieties of energy willow and technological aspects of its cultivation.* Monograph. Kyiv: Komprint. 206 p.

Skvortsov, A. K. (1999). *Willows of Russia and Adjacent Countries. Taxonomical and Geographical Revision.* Joensuu: University of Joensuu. 307 p.

Tipton, J. L. (2024). Relative Drought Resistance of Desert Willow, Fruitless Mulberry, and Yellow Bells. Turfgrass and Ornamentals Research Summary URL.: https://surl.li/ivfetw

Turtola, S., Rousi, M., Pusenius, J., Yamaji, K., Heiska, S., Tirkkonen, V., Meier, B. & Julkunen-Tiitto R. (2006). Genotypic variation in drought response of willows grown under ambient and enhanced UV-B radiation. *Environmental and Experimental Botany.* Volume 56, Issue 1, May 2006, Pages 80-86. https://doi.org/10.1016/j.envexpbot.2005.01.007. URL: https://www.sciencedirect.com/science/article/abs/pii/S0098847205000092?via%3Dihub

Xia, L., Yao, Yu, Zeng, Yi, Guo, Z. & Zhang, S. (2023). Acetic acid enhances drought tolerance more in female than in male willows. *Physiologia plantarum*. Vol. 175, Issue 2. e13890. https://doi.org/10.1111/ppl.13890 URL.: https://surl.li/zxwibl

Yatsyk, R. M., Gajda, Yu. I. & Hudyma, V. M. (2017). *Fundamentals of introduction and adaptation of tree and shrub species of plants*. Ivano-Frankivsk: NAIR. 175 p.

Yang, J., Zhao, H. & Zhang, T. H. (2004). Heat and drought tolerance of two willow species, Salix gordejevii and *Salix babylonica*: A comparative study. *Israel Journal of Plant Sciences* - ISRAEL J PLANT SCI. 52. 301-306. 10.1560/H66B-FM80-K7PJ-J992. URL: https://surl.li/dlwiov