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Adaptation of woody and fruit berry plants in arid conditions of the Mangyshlak Experimental Botanical Garden, Aktau, Kazakhstan

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ABSTRACT

This study examines the adaptation and cultivation of woody plants in the arid conditions of the Mangyshlak Experimental Botanical Garden in Aktau, Kazakhstan. Given the increasing challenges of desertification and climate change, understanding these plants' physiological and morphological adaptations is crucial for their survival and sustainable growth. The research focuses on the transpiration rate, hydration, chlorophyll, and carotenoid content in various plant species to determine their resilience to harsh environmental conditions. Key findings highlight the importance of leaf water content and chlorophyll B in enhancing drought and salt tolerance, while carotenoids play a significant role in photoprotection. The results underscore the necessity of specific diagnostic indicators to assess plant resistance and guide the selection of species suitable for arid regions. This study contributes valuable insights for improving phytointroduction methods, thereby enhancing green construction quality in the extreme climate of Mangystau.

Keywords: Plant conservation, Physiology; Transpiration rate, Hydration, Chlorophyll, Carotenoid content.
Article type: Research Article.

INTRODUCTION

Arid zones, characterised by low precipitation and extreme temperature conditions, represent challenging conditions for plant cultivation. Woody plants' adaptation to such conditions requires a deep understanding of their physiological and morphological features, which are essential to ensure their survival and sustainable growth. In this context, the study of adaptation and cultivation of woody plants in arid conditions of the Mangystau Experimental Botanical Garden, Aktau, Kazakhstan, is of particular relevance (Imanbayeva & Belozerov 2021). The Mangystau Experimental Botanical Garden (MEBG), located in one of the driest regions of Kazakhstan, provides a unique platform for studying various tree species under extreme climatic conditions (Imanbayeva *et al.* 2024). Adaptation mechanisms and strategies for preserving plants in sterile conditions are pertinent areas of study, considering rapid and damaging climate change. The expansion of desert zones, increases in soil degradation, and rising global temperatures have inhibited the growth and development of higher vascular plant species. Despite this, most woody plants have a complex system of adaptations to unfavourable environmental factors (Christmas *et al.* 2016; Timofeeva *et al.* 2022). A good example is the well-known model plant *Arabidopsis thaliana* (L.) Heynh. It produces flavonoids and other antioxidants to mitigate the effects of ultraviolet radiation and oxidative stress (Landry *et al.* 2025). We can also take the standard tomato *Solanum lycopersicum* L. as an example. Under heat stress, tomatoes increase the production of antioxidants such as superoxide dismutase and ascorbate peroxidase, which protect cells from oxidative damage. For instance, the stomata of *Nerium oleander* L. are deeply embedded in the leaf surface and covered with trichomes (tiny hairs), which reduces water loss by minimising contact with dry air (Williams *et al.* 1989). The little-studied Mangystau desert zone of Kazakhstan is an arid territory with inhospitable conditions and virtually no sources of fresh water. It is located in the administrative region near the Caspian Sea and features brackish water up to 12.6-13.2 ppm (Zhang *et al.* 2023). This area has an experimental site called the Mangyshlak Experimental Botanical Garden (MEBG) in Aktau, which sits atop rocky (gypsum) desert soil. Its primary scientific purpose is the study of processes of adaptation and acclimatisation and introducing local and foreign cultural and natural plant species to conditions unsuitable for everyday plant life (Imanbayeva *et al.* 2024). A pronounced ultra-arid climate, waterlessness, scarcity of local flora, increased soil salinity, low fertility, and a thin profile of zonal brown soils characterise the Mangystau desert. The harsh conditions in this area have reduced the biological diversity of woody plants, negatively affecting the state of the ecosystem. One of the main reasons for this phenomenon is the insufficient resources for species diversity and the range of tree species. However, the concept of plant introduction can be executed through generally accepted methodological approaches for selecting promising plant samples. These approaches include climatic analogues (Mayr 1909), generic complexes (Rusanov 1971), ecological–historical methods (Kultiasov 1953), fluorogenic relatedness (Kormilitsyn 1977), botanical–geographical methods (Vavilov 1935), ecological–physiological methods (Petukhova 1981), and the recommended practical implementation of long-term forecasting (Lapin 1974). Most botanical gardens in the Commonwealth of Independent States (CIS) apply those above classical visual methods and approaches to selecting resistant forms that have adapted to the local environmental conditions. Other classical methods are also used to identify the optimal tool for selecting promising samples. Many existing scales have shown promise in determining potential plant forms for introduction. Most are based on ecological and biological indicators determined primarily through visual observation and measured in points. Analysis of the available methods has enabled a universal scientifically based method for plant introduction. However, the integral assessment of taxa and reliable selection for the Mangystau ecological zone needs to be improved (Meliboeva 2022). One of the optimal models for diagnosing and selecting promising plant species and woody forms is the measurement of the transpiration rate, leaf hydration, chlorophylls A and B and carotenoid contents in plant parts. The results should be gleaned by analysing signs of innovativeness within specific indicators. This form of analysis requires the creation of local databases using computer analysis and comparisons using traditional scales for rating drought resistance, phytophagy, gas tolerance (CO_2), salt tolerance, winter hardiness, and soil fertility. Various restoration methods can provide a general picture of plants' resistance to different conditions (Datt 1998). The key features of sustainability are reflected in response to the influences of internal and external factors. Drought is a principal abiotic stressor that decreases plant health. Increasing drought tolerance under drought stress is a significant goal of introductions, as it is critical for environmental safety (Salehi Lisar & Bakhshayeshan Agdam 2016). We consider drought resistance to be a leading ecological indicator of the state of tree plantations in the Mangystau desert despite the transpiration rate. The physiological restoration of water is highly relevant. Under limited soil moisture conditions, maximal plant productivity is achieved by optimising solar radiation absorption and water consumption through transpiration. The amount of water a plant evaporates is often more significant than the amount of water it contains. Additionally, economical water consumption is one of the most acute problems encountered in phytointroductions in arid regions. At normal levels, transpiration is not necessary. Thus, if plants grow in low and high soil moisture conditions, transpiration occurs with much less intensity in the former. However, plant growth within a specific humidity range should be approximately similar (within the limits of statistical error). Thus, it is necessary to identify optimal conditions by selecting a range and adjusting the watering regime. Moreover, plant organisms' transpiration and stomatal conductance indices are critical physiological processes. It is a vital defence mechanism that prevents leaves from overheating in direct sunlight. It generates a continuous flow of water and minerals from the root system to other anatomical organs (Proskuryakov & Rubanik 1986; Golovkin *et al.* 1986; Baitulin *et al.* 1992). External environmental factors activate varied physiological responses (Baccari *et al.* 2020; Myers & Bazely 2003). The leading informative physiological indicators of the plant state are vegetative green leaves, the main transpiring organ in plants. Plants' adaptation to environmental conditions can be determined based on their leaf moisture content and the percentage of their loss during transpiration. Detecting the intensity of transpiration in higher vascular plants produces positive results. Transpiration and stomatal conductance rates are strongly dependent on soil moisture, and the closely related factor of leaf water content, so that, several authors have confirmed this experimentally. (Schneider & Childers 1941). As soil moisture decreases, the rate of transpiration also declines. Reducing the water content within a plant's system directly diminishes transpiration, primarily due to regulating stomatal and extra-stomatal mechanisms. Another key physiological indicator of a plant's health is the amount of water retained in different parts of the plant. The water balance within a plant is not evenly distributed and is influenced by various factors. Of particular interest is the capacity of these different plant organs to adapt to the challenges posed by climate change. The Mangystau territory is distinguished not only by a hot and dry summer season but also by prolonged and severe winters, which require plants to be winter-hardy. Harsh climactic factors lead to soil degradation and require plants to resist low soil fertility. Additionally, plants exposed to salt stress adapt to their environments. Salt stress causes specific changes in plant metabolism, strongly affecting vegetative growth parameters: dry weight, plant height and root length, leaf area, etc. The ability of plants to detoxify radicals under salt stress is probably the essential requirement for adaptation to unfavourable conditions (Parida & Das 2005). Some plant species do not respond to increased salinity with changes in tissue water content, at least under conditions of moderate salinity, and only mild effects on plant growth have been observed (Zhang *et al.* 2022). If the water content changes under the influence of salinity, it can either increase or decrease. The combination of drought and salt stress impairs plants, reducing their ability to withstand insect attacks and urban exhaust fumes. These variable indicators can be utilised to assess plants' condition and adaptability to environmental conditions (Ievinsh 2023). For the Mangystau region, the introduction of diagnostics must account for plant drought resistance, heat resistance, salt tolerance, and requirements for soil fertility. The main limiting factors in eastern Kazakhstan are a short frost-free period, recurrent spring frosts, and low winter temperatures. Therefore, winter hardiness and frost resistance are the dominant indicators of prospective plants for introduction (Sumbembayev *et al.* 2022; Orazov *et al.* 2022; Orazov *et al.* 2024; Imanbayeva *et al.* 2024). When diagnosing adaptability, specific biophysical and other physiological properties occurring in plants, e.g., the chlorophylls A and B and carotenoid contents are necessary. There is a proven connection between plant health and chlorophyll fluorescence, chlorophyll content, calcium, and nitrogen. The leaf chlorophyll content is frequently used because it provides satisfactory results due to the high correlation between chlorophyll content and plant condition (Honda *et al.* 2005; Pérez Patricio *et al.* 2018). Plant leaves also contain a particularly informative group of substances: carotenoids. Carotenoids are natural organic pigments synthesised by higher plants that produce yellow, orange, and red colours. They play an essential role in the light-harvesting complex and photoprotection of photosystems. Several studies have shown that these compounds protect the photosynthetic apparatus from photodamage by interconverting xanthophyll molecules. Therefore, indirect, non-destructive quantitative determination of total carotenoids is essential in current studies of plants' condition under various conditions of increased high radiation (Maoka 2020). Diverse aggregated data can be analysed by creating local databases that accumulate them and provide forecasts for the near future (Perez *et al.* 2019). Various aggregated data can be analysed by creating local databases that collect information and enable step-by-step forecasting. The main objective of this study is to develop and test a universal scale based on plant forms, growth types, and sequential indicators to achieve results, acceptable species and forms of woody plants in arid conditions. For this purpose, sequential, visual, and statistical analysis methods are used. While the study focuses on the effects of indicators, it's crucial to highlight that plant form and growth type are also integral to the analysis. These factors serve as essential indicators for identifying resistance to arid conditions. The morphological indicators in this development, such as growth features and structural adaptations, play a key role in determining plant resistance, as detailed in the methods section. The results of this study demonstrate increased control over markers that can serve as indicators of woody plant resistance to conservative conditions characteristic of the Mangystau desert. These markers include the content of chlorophylls A and B, carotenoids, leaf hydration level, and significant transpiration. In addition, the data collected in local databases can be used to create predictive models that allow future possibilities for introducing and growing tree species in extreme climatic conditions to be assessed. These data are also applicable in the future with the advent of environmentally friendly phytointroduction methods in arid zones. Thus, the study's results can potentially improve phytointroduction processes, increasing biodiversity and optimising forest plantations in Kazakhstan's desert regions.

MATERIALS AND METHODS

Study area

The Mangyshlak Experimental Botanical Garden is located in Aktau, the centre of the Mangystau region of Kazakhstan. The study area is located on the eastern coast of the Caspian Sea at the junction of the northern and southern desert subzones, within 42 – 46° N latitude and 50 – 54° E longitude. It is administratively part of the Mangystau region. The study area is a desert vegetation zone with a sharply continental climate, short snowy winters, and long hot summers. The climate is sharply continental and extremely dry. Summer temperatures can reach from +43 to +45 °C. In winter, the average temperature in January (the coldest month) ranges from - 5 to –

8 °C in the north and from -1 to -4°C in the south of the territory. In some of the coldest winters, temperatures reach - 38°C. Frequent strong winds lead to the spread of hot winds, dust storms, and the removal (pulverisation) of salts from the Caspian Sea. The zonal brown and grey-brown soils of Mangystau are universally saline, often solonetzic, poorly saturated with organic matter and moisture, and closely underlain by dense limestone. Intrazonal soils include takyrs, solonchaks, solonetzes, sands, meadow-brown soils, and mountain outcrops. Due to unfavourable natural and climatic conditions, there are no natural tree and shrub plantations in the region that can be classified as forests (this necessitates several structural and genetic characteristics) (Imanbayeva *et al.* 2020). This region also faces a minimal deficit of atmospheric moisture (107–180 mm of precipitation per year), low soil temperatures (poor soil, thin soil profile and increased salinity), strong winds and dust storms. These harsh conditions create significant difficulties for plant introduction, gardening and phytomelioration. In the conditions of Mangystau, there are practically no natural tree and shrub plantations that could be classified as natural forests based on species composition and structural characteristics, further complicating the tasks of restoration and landscaping of the territory (Wang *et al.* 2002; Liu *et al.* 2011; Ette *et al.* 2023). The natural flora is dominated by annual (268 species, or 43.1%) and perennial (247 species, or 40%) species. Tree forms are represented by only 100 taxa or 16.2% of species. The species diversity of higher vascular plants is relatively sparse (Koshim *et al.* 2020).

Model of research process organizations

The primary process within the Mangystau desert's botanical development is the mobilisation of woody plants. The general concept of the study is a multi-stage selection of optimal samples of woody plants, which include the most resistant to the natural conditions of the Mangistau region, using physiological indicators and a score of resistance to adverse environmental factors (Nikolaevskaya & Kozlova 1999).

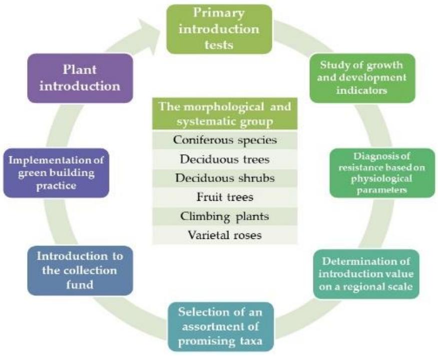


Fig. 1. The cycle of conducting research and obtaining optimal samples of woody plants for introduction.

The identification of physiological markers of biological resistance in woody plants was carried out in four stages: (i) selection of plant resistance indicators from the "DinTseR" program; (ii) compilation of summary matrices of data indicators and physiological isomers of growth and development; (iii) correlation analysis and identification of reliable relationships between selected variables; and (iv) regression analysis of research materials.

Plant material

The MEBG collection of woody plant forms was used as plant materials (Mangystau region). The study involved a core botanical assemblage of 128 specimens from various taxonomic groups and geographic origins. All plants were grown on the territory of the botanical garden. These samples represented 34 families and five subdivisions of taxa. They also represented various specialised morphological groups: 7 coniferous trees, 58 deciduous trees, 49 deciduous shrubs, four fruit-berry plants, five climbing plants (woody vines), and five varietal roses. A more detailed list of species is presented in Table 1. These plant samples were obtained as part of a bioecological study of the characteristics of various plants, including rare and endangered plants, during introduction in the conditions of the Mangyshlak Experimental Botanical Garden. This sample selection allowed us to evaluate a large group of variables and make a wide range of predictions.

Physiological study of parameters

Based on research data, phenological and electronic information aspects of introduction studies in the Mangyshlak Experimental Botanical Garden (Belozerov I, Imanbayeva A, 2020), the following leading methodological and substantiated physiological indicators of plants were selected: the content of primary pigments in the leaves (chlorophylls A and B, carotenoids), the total water content in the leaves. and transpiration rate (Ette *et al.* 2023).

Table 1. List of studied species of woody plants involved in determining physiological indicators of growth and development.

Morphological and systematic group	**Species composition**
Fruit-berry plants	*Armeniaca vulgaris* Lam., *Malus niedzwetzkyana* Dieck., *Malus sieversii* (Ldb.) M.Roem., *Pyrus communis* L.
Coniferous species	*Juniperus sabina* L., *Juniperus sargentii* (Henry) Takeda et Koidz., *Juniperus virginiana* L., *Pinus eldarica* (Medw.) Silba, *Pinus pallasiana* Lamb., *Pinus silvestris* L., *Platycladus orientalis* (L.) Franco
Deciduous trees	*Acer ginnala* Maxim., *Acer henryi* Pax., *Acer laetum* C.A. Mey., *Acer negundo* L., *Acer semenovii* Rgl.et Herd., *Acer tataricum* L., *Acer truncatum* Bge., *Ailanthus altissima* (Mill.) Swingle, *Betula pendula* Ehrh., *Catalpa hybrida* L., *Catalpa ovata* G.Don, *Catalpa speciosa* Warder., *Celtis caucasica* Willd., *Cercis canadensis* L., *Cercis siliguastrum* L., *Crataegus alma-atensis* Pojark., *Crataegus ambigua* C.A.Mey, *Crataegus calycinii* Peterm f. *Curvisepala* L., *Crataegus chlorosarca* Maxim, *Crataegus collina* Chapm., *Crataegus combia* L., *Crataegus kellermanii* L., *Crataegus lavelleri* Hering., *Crataegus rivularis* Nutt., *Elaeagnus oxycarpa* Schlecht., *Fraxinus acuminata* Lam., *Fraxinus lanceolata* Borkh., *Fraxinus oxycarpa* Willd., *Fraxinus rhyncophylla* Hance., *Fraxinus sogdiana* Bge., *Fraxinus syriaca* Boiss., *Gleditsia aquatica* Marsh., *Gleditsia texana* L., *Gleditsia triacanthos* L., *Gymnocladus dioicus* (L.) C. Koch., *Juglans cinerea* L., *Juglans rupestris* L., *Koelreuteria apiculata* Rehd et Wils., *Koelreuteria paniculata* Laxm., *Maclura aurantiaca* Nutt., *Mespilus germanica* L., *Morus alba* L., *Padus grayana* Schneid., *Padus serotina* (Ehrh.) Agardh., *Platanus occidentalis* L., *Populus alba* L., *Populus bolleana* Lauche., *Populus diversifolia* Schrenk., *Quercus robur* L., *Robinia pseudoacacia* L., *Salix alba* L., *Salix dasyclados* Wimm., *Sophora japonica* L., *Sorbus aria* (L.) Crantz., *Sorbus torminalis* (L.) Crantz., *Tilia mongolica* L., *Tilia tomentosa* Moench., *Ulmus pumila* L.
Deciduous shrubs	*Ammodendron bifolium* (Pall.), *Amygdalus triloba* (Lindl.) Ricker., *Berberis iliensis* M Pop., *Berberis karkaraliensis* Korn. et Potap., *Berberis nummularia* Bge., *Berberis thibetica* Schneid., *Berberis turcomanica* Karel., *Berberis vernae* Schneid., *Berberis verruculosa* Hemsl., *Caragana aurantiaca* Koehne., *Caragana brevispina* Royle, *Colutea orientalis* Mill., *Colutea* x *media* Willd., *Cornus sanguinea* L., *Corylus avellana* L., *Cotoneaster apiculatus* Rehd.et Wils., *Cotoneaster assamensis* klotz. s Mr. Hylmo, *Cotoneaster integerrimus* Medik., *Cotoneaster multiflorus* Bunge, *Cotoneaster pekinensis* L., *Cotoneaster pseudomultiflorus* M.Popov, *Cotoneaster sternianus* (Torril.) Boom., *Cotoneaster tauricus* Pojark., *Elaeagnus angustifolia* H.B.K., *Euonymus japonica* Mig., *Fontanesia fortunei* Carr., *Forestiera neomexicana* Gray, *Halimodendron halodendron* (Pall.) Voss., *Lonicera arborea* Boiss., *Lonicera baltica* Pojark., *Lonicera lanata* Pojark., *Lonicera ruprechtiana* Regel, *Lonicera tatarica* L., *Malacocarpus crithmifolius* (Retz.) C.A. Mey, *Nitraria schoberi* L., *Paliurus spina-cristi* Mill., *Rhamnus cathartica* L., *Rhamnus dolichophylla* Gontsch., *Rosa arvensis* Hunds., *Rosa sicula* Fratt., *Sambucus canadensis* L., *Symphoricarpos microphyllus* Gray., *Syringa komarovii* (Nevski) Tzvel., *Tamarix hohenackeri* Bunge, *Tamarix laxa* Willd., *Tamarix meyeri* Boiss., *Tamarix ramosissima* Ledeb., *Viburnum opulus* L., *Zanthoxylum simulans* Hance.
Climbing plants (climbing vines)	*Campsis radicans* (L.) Seem., *Clematis mandschurica* Rupr., *Clematis orientalis* L., *Parthenocissus quinquefolia* (L.) Plansch., *Vitis amurensis* Rupr.
Varietal roses	*Rosa 'Charles De Gaulle', Rosa 'Gloria Dei', Rosa 'Medallion', Rosa 'Nicol', Rosa 'Tineke'*

Determination of the leaf water content

The gravimetric diagnostic method was used to determine the total water content in the leaves. Developed green leaves without apparent signs of damage or drying were selected from the upper and lower tiers of the tree crown; samples were collected in triplicate and stored separately; these were used as points of reference. Samples were collected at the peak of the plant's growing season. Each determination was carried out in 3 repetitions with a mass of raw leaves of at least 5 g. Each glass bottle containing plant material was weighed on an analytical balance, placed in a cabinet heated to 105 °C for 4-5 hours, cooled in a desiccator, and weighed again. However, 4–5 hours were insufficient to remove all the plant's moisture. Thus, after weighing the bottles, they were opened and placed in a drying cabinet at the same temperature. Then, the bottles were cooled in the desiccator and weighed again. This was repeated until the mass of the bottle of material was constant. The amount of water in the sample was determined by subtracting the mass of the dried material from the original plant material. The water content was calculated as a percentage of the dry and wet weight of the material, and a conclusion could then be drawn about the dependence of the water content in the leaves on their location on the plant. The gravimetric diagnostic method was used to determine the total water content in the leaves. Fully developed green leaves without visible signs of damage or drying were selected from both the upper and lower tiers of the tree crown. Samples were collected in triplicate during the peak growing season to avoid bias. The leaves were stored separately in sealed plastic bags (such as Ziploc) to prevent moisture loss and kept in refrigerated storage at 4 °C in cooling chambers (Liebherr

LKPv) until analysis. Each measurement was triplicated, using at least 5 g of fresh leaf material. The following procedure was used to determine the water content:

Initial Weighing: The leaves were placed in glass bottles (Duran Laboratory Bottles), and each bottle with plant material was weighed on an analytical balance (Mettler Toledo XS205 DualRange, with an accuracy of 0.01 mg) to record the mass of the fresh material before drying.

Drying: The bottles were placed in a drying oven (Memmert UF55 Universal Oven) heated to 105 °C. The samples were dried for 4–5 hours to remove most moisture. After drying, the bottles were cooled in a desiccator (Kartell Vacuum Desiccator) using a silica gel desiccant (Sigma-Aldrich Silica Gel) to prevent moisture absorption from the air and weighed again on the same Mettler Toledo analytical balance.

Repeated drying: Since 4–5 hours of drying was insufficient to remove all the moisture, the bottles were returned to the Memmert UF55 drying oven at the same temperature. After additional drying, the bottles were cooled in the desiccator and weighed again. This process was repeated until the mass of the bottle and its contents became constant, ensuring that all water had been removed.

Water content calculation: The total water content in the sample was determined by subtracting the mass of the dried material from the original mass of the fresh leaf material. The water content was then calculated as a percentage of the leaves' wet and dry mass.

Conclusion on water content and leaf position: The analysis results indicated that water content in leaves depends on their position in the plant. Leaves from the upper tiers of the crown, exposed to more sunlight and higher transpiration rates, typically had lower water content than leaves from the lower tiers, which were more shaded and retained more moisture. This suggests that the position of leaves on the plant has a significant impact on their water content, influenced by environmental conditions such as light exposure and temperature (Koshim *et al.* 2020).

In summary, water content in the leaves is highly dependent on their location within the plant, primarily due to differences in sunlight exposure, transpiration rates, microclimatic conditions, and access to water through the plant's hydraulic system. Upper leaves, which are more exposed to sunlight and higher temperatures, typically exhibit lower water content, while lower leaves, which are more shaded and less exposed, tend to retain higher moisture levels. This variation allows the plant to adapt to different environmental conditions across its structure.

Determination of the transpiration rate

We used a rapid weighing method to determine the transpiration rate (Nikolaevskaya & Kozlova 1999), considering changes in the mass of the transpiring organ over short periods (up to 5 minutes). This made it possible to observe transpiration in the same organ saturation state in the plant. Control leaves were cut from various parts of plants in triplicate at the peak of plant vegetative development and quickly weighed. After 5 minutes, we reweighed the control leaves and performed three replicates. The leaf mass loss between the first and second weighing showed how much water evaporated during this period. The interval between weightings did not exceed 5 min, as more prolonged exposure caused a decrease in both the leaf's water content and the transpiration rate. Subsequently, we calculated the amount of water evaporated from 1 g of raw leaves in 1 hour (Viktorov 1969).
To determine the transpiration rate, we utilised a rapid weighing method, commonly employed in plant physiology studies, to estimate water loss by measuring changes in the mass of a leaf (the transpiring organ) over short periods (usually no longer than 5 minutes) (Guzhvin *et al.* 2019). This method allows for the observation of transpiration without significantly altering the leaf's natural water saturation state (Ivanova *et al.* 2015). Control leaves were carefully excised from different parts of the plant, always in triplicate, during the peak of vegetative growth to ensure representative data. Immediately after excision, the leaves were weighed using an analytical balance (e.g., Mettler Toledo XS204), recording their initial mass. The time between cutting and weighing was minimised to prevent excess water loss through the severed xylem conduits, as water movement from the xylem to the air can artificially increase the rate of water loss. After precisely 5 minutes, the leaves were weighed again. The difference in mass between the initial and subsequent measurements represented the amount of water lost due to transpiration during that interval. This process was repeated three times for each sample to ensure the reliability of the data (Lichtenthaler & Wellburn 1983). The 5-minute interval was selected because extended exposure times lead to a significant reduction in leaf water content and transpiration intensity, affecting the accuracy of the measurements (Rohlf 1998). Longer intervals increase the risk of dehydration, which distorts natural transpiration dynamics (Orazov *et al.* 2021). Once the mass loss was recorded, we calculated the amount of water evaporated from 1

gram of fresh leaf material per hour (Anar *et al.* 2023). This allowed for a standardised measure of transpiration, facilitating comparison across different samples or experimental conditions (Sumbembayev *et al.* 2021). Although the rapid weighing method provides useful short-term transpiration estimates, it is important to acknowledge its limitations. In severed leaves, water can also be lost through the cut xylem conduits of the petiole, leading to overestimating the actual transpiration rate (Kubentayev *et al.* 2024). In addition, this method does not capture dynamic gas exchange processes (e.g., stomatal conductance, vapor pressure deficit) that occur in intact leaves under natural conditions (Kusmangazinov *et al.* 2023). More precise methods, such as leaf gas exchange measurements using devices like infrared gas analysers (IRGA) or porometers, are typically preferred for accurate transpiration rate assessments in the field or under controlled conditions (Kramer & Kozlovsky 1983). These instruments measure stomatal conductance, photosynthetic rates, and transpiration directly, providing a more comprehensive understanding of plant water relations and responses to environmental factors (Lakin 1990). While the rapid weighing method is a useful tool for estimating transpiration in controlled environments, it has notable limitations, wildly when extrapolating to whole-plant behaviour in open-field conditions (Zeinullina *et al.* 2023). The potential overestimation of water loss through severed xylem and the absence of gas exchange data should be considered, and references supporting the use of this method for estimating transpiration rates in cut leaves should be provided (Zargar *et al.* 2023). For more accurate assessments of plant transpiration under natural conditions, using leaf gas exchange systems is strongly recommended (Zhang *et al.* 2023).

Contents of the main pigments

The primary pigments of the photosynthetic apparatus in higher plants' leaves were quantified. Each sample of plant material (100-200 mg) was crushed with scissors and placed in a small mortar. A small amount of $MgCO_3$ was added to the tip of a scalpel, and 4–5 mL of acetone was added and thoroughly ground. The resulting extract was poured onto a stick in a glass filter inserted into a Bunsen flask. Then, the liquid was pumped out. Afterward, we added more acetone to the mortar, ground it, poured it back onto the filter, and extracted it. This operation was repeated several times until the solution from the filter appeared entirely colourless. We poured the extract into a volumetric flask and rinsed the Bunsen flask several times with small amounts of acetone. Pure acetone adjusted the extract volume in the volumetric flask to the correct level. The resulting acetone extract contained a sum of green and yellow pigments. Some of the resulting extract was poured into a spectrophotometer cuvette. A second cuvette filled with pure solvent was used as a control. The chlorophylls A and B concentrations were determined using a spectrophotometer (PE-5400UF, Eco Chemistry, Russia). The cuvettes were placed in the cuvette chamber, and the optical density of the extract was determined at wavelengths corresponding to the absorption maxima of chlorophylls A and B in an 80% acetone solution at 663 and 646 nm, respectively. The optical density of the extract was determined at 470 nm to determine the carotenoid content (Guzhvin *et al.* 2019). The procedure for quantifying the primary pigments in plant leaves was adapted from a widely used method described in (Guzhvin *et al.* 2019). More recent methodologies for pigment extraction and spectrophotometric analysis are available (Ivanova *et al.* 2015). In this method, the primary pigments of the photosynthetic apparatus in higher plants' leaves were quantified. Each sample of plant material (100–200 mg) was crushed with scissors and placed in a small mortar. A small amount of $MgCO_3$ was added to the tip of a scalpel, and 4–5 mL of acetone was added and thoroughly ground. The resulting extract was poured onto a stick in a glass filter inserted into a Bunsen flask, and pumped out. Afterward, more acetone was added to the mortar, ground, and poured back onto the filter. This operation was repeated several times until the solution from the filter appeared entirely colorless. The extract was poured into a volumetric flask, and the Bunsen flask was rinsed several times with small amounts of acetone. Pure acetone adjusted the extract volume in the volumetric flask to the correct level. The resulting acetone extract contained a sum of green and yellow pigments. A portion of the extract was poured into a spectrophotometer cuvette, and a second cuvette filled with pure solvent was used as a control. The concentrations of chlorophylls A and B were determined using a spectrophotometer (PE-5400UF, Eco Chemistry, Russia). The cuvettes were placed in the cuvette chamber, and the optical density of the extract was measured at wavelengths corresponding to the absorption maxima of chlorophylls A (663 nm) and B (646 nm) in an 80% acetone solution. To determine the carotenoid content, the optical density of the extract was measured at 470 nm.

Software and statistical analysis

The obtained data were loaded into the developed "DinCeR" software. Its main principle was the formation of a database of the studied plants. This database contained the entry and storage of varied registration information on taxonomy, location in the collection, distribution areas, morphology, ecology, and herbarium specimens, illustrated with photographs of taxa. “DInCeR” is a computer program that registers and determines the introduction value of plants in arid regions of Kazakhstan. Its potential applications include the following: input and storage of various accounts and ecological–biological information about species of plants in computer memory; forecasting species’ introduction value; compilation of family lists, genera, seed selects, herbarium funds, placement in the garden, and photoprotection status; species’ degrees of sustainability, productivity, and reproductive capacity, for economic, biological, and scientific reasons; selection of plants according to given taxonomic, bio-ecological, decorative, and landscaping conditions; and printing information and exporting it to different formats for use in external graphic and text editors. The following programming languages were used: Microsoft Visual FoxPro 9 SP2, Visual Basic for Applications 7.0, HTML 4.0, and JavaScript API 2.1. Version: 3.00. The volume of information for each record and database (DB) was between 25 and 30 (with pictures and maps, up to 150–200) KB. DInCeR is registered with the Ministry of Justice of the Republic of Kazakhstan, with a state certificate of registration of rights to copyright object No. 2339 (dated December 14, 2015, IS 003261). The results were analysed using the Statistics 10 program (StatSoft STATISTICA 10.2011) and Microsoft Excel 10.1. Statistical analysis varied depending on the limits, which varied according to the standard deviation of the coefficient of variation, the mean error, the degree of confidence, and the degree of precision. A one-way analysis of variance was used to compare the results, and significant correlations were found between soil type and key plant parameters in the population. When analysing the primary data, correlation coefficients were calculated using the R Studio (IDE) statistics program for Windows (R version 3.6.0, 2019). Principal coordinate analysis (PCoA) was performed using Numerical Taxonomy and Multivariate Analysis System version 2.1. (NTSYS-pc) [44]. A principal coordinate analysis (PCoA) was applied to reveal sample groups according to morphological and systematic groups that emerged when studying the parameters of statistical coordinates. In addition, proprietary computer software was used in the research to store plant data. The copyright certificate of state registration of rights to an object of copyright was obtained (No. 2339 dated December 14, 2015) from the Minister of Justice of the Republic of Kazakhstan for registered exclusive property rights to an object of copyright under the name “DInCeR (computer program). Authors: Imanbayeva Akzhunis, and Ivan Belozerov. Patent holder: Mangyshlak Experimental Botanical Garden.”

Comprehensive rating scale

The development of the rating scale used in this study is based on fundamental research in plant physiology and methods for assessing their resilience in arid conditions. One of the key sources is the work by Levitt, J. (1980): “Responses of Plants to Environmental Stresses”, which thoroughly examines the mechanisms of plant adaptation to abiotic stresses such as drought, salinity, and extreme temperatures. Another significant contribution to the development of the methodology comes from visual scales used in the CIS countries, described by Karasev E.G. (1990) in the book “Methods for Assessing the Introductory Resilience of Plants”, which proposes methods for evaluating plant adaptability in extreme conditions. The application of regression analysis for assessing plant resilience is based on the works of Zar, J.H. (1999) “Biostatistical Analysis”, which provides detailed explanations of statistical data analysis methods. Additionally, significant contributions were made by the research of Flowers and Yeo (1995) on plant tolerance to salinity, which helped better understand the mechanisms of plant adaptation to stresses and apply this knowledge when assessing the introduction potential of plant species. The above features served as the basis for MEBG’s development of a regional comprehensive diagnostic scale of introduction suitability from 2013 to 2015. This scale includes 24 diagnostic signs, which are divided into four groups: biological stability (n = 6), decorative and household quality (n = 8), reproductive capacity (n = 3), and economic, biological, and scientific significance (n = 7). Introducing species' tolerance to living conditions consists of drought resistance, phytophagy, gas resistance, salt tolerance, winter hardiness, and demands on soil fertility. Therefore, the estimated parameters are scaled to reduce their significance in forming overall stability. Our studies utilised a developed scale to assess the complex factors influencing the introduction value of plants in the arid conditions of Mangystau. Previous research has detailed the resistance of many plants to desert habitats and external influences. We rated drought resistance on a scale from 0 (min) to 15 (max) points, salt resistance from 0 to 10, winter hardiness from 1 to 8, soil fertility requirements from 0 to 6, resistance to phytophages from 0 to 6, and gas tolerance from 1 to 5. A description of the diagnostic scale (stability conditions and assessment points) is given in Table 2. Regression analysis confirmed the validity of this scoring scale for assessing indicators of biological stability, growth, and development. On this basis, significant indicators were selected (r f > r > cr05 at a significance level of 5%). Regression equations were constructed for all meaningful relationships between the measured indicators of stability and diagnostic indicators of growth and development, and graphs for their prediction were constructed in logarithmic, power, multiplicative, and exponential forms. In the presence of curvilinear formulas, the correlation values (ηф) reflected the rigidity of the function's dependence.

Table 2. Diagnostic scales of drought resistance.

Adaptability conditions	Evaluation points
Drought resistance	0–15
Salt tolerance	0–10
Winter hardiness	0–8
Requirements for soil fertility	0–6
Phytophage resistance	0–6
Gas resistance	0–5
Total amount	0–50

RESULTS

The results were analysed using the described methods and presented in tabular form. The physiological parameters are defined using primary statistical parameters. The basic statistics of the physiological parameters are given in Table 3. The average age of plants was 14.1 years, with a variation coefficient of 78.5%. The average transpiration rate during the growing season was 226.8 mg g^{-1} with a variation of 51.7%; the minimum and maximum rates were 104.1 (61.8%) and 388.2 mg g^{-1} (67.0%) respectively. The average water content in leaves during the growing season is 58.9% with a variation of 12.1%; the minimum and maximum were 52.9% (16.1%) and 65.9% (13.4%) respectively. The average chlorophyll A content during the growing season was 3.21% with a variation of 37.1%; the minimum and maximum were 1.98% (63.4%) and 4.39% (28.5%) respectively. The average chlorophyll B content during the growing season was 1.31% with a variation of 52.2%; the minimum and maximum were 0.58% (95.3%) and 2.24% (53.2%) respectively. The average carotenoid content during the growing season was 1.10% with a variation of 27.3%; the minimum and maximum were 0.69% (53.6%) and 1.53% (24.8%) respectively. An evaluation was also carried out using the introduction diagnostic scale. The results are summarised in Table 4. Table 4 contains the scores on the complex regional introduction and diagnostic scale of plants in arid conditions of the Mangistau region. The average score of drought resistance was 8.60 points with a variation coefficient of 42.4%, the minimum and maximum scores were 0 and 15 points respectively. The average score of salt tolerance was 5.57 points (Cv = 40.0%), with a minimum and maximum values of 0 and 10 points respectively. The average score of winter hardiness was 6.27 points (Cv = 27.0%), with a minimum and maximum of 1 and 8 points respectively. Soil fertility requirements were estimated at an average of 4.04 points (Cv = 39.0%), with a minimum and maximum of 0 and 6 points respectively. The average score of phytophages was 4.53 points (Cv = 39.9%), with a minimum of 0 and a maximum of 6 points. Gas resistance was estimated at 3.38 points on average (Cv = 29.4%), the minimum and the maximum were 1 and 5 points respectively. The total assessment points for biological resistance were 32.37 on average (Cv = 24.6%), the minimum and the maximum were 14 and 48 points respectively. Decorativeness were estimated at 11.04 points on average (Cv = 25.3%), the minimum and maximum were 2 and 17 points respectively. The average reproduction score was 6.14 points (Cv = 34.3%), with the minimum of 1, and the maximum of 10 points. Economic, biological and scientific significance was estimated at 11.55 points on average (Cv = 45.8%), with the minimum of 3, and the maximum of 20 points. The input value of plants was estimated at an average of 61.11 points (Cv = 21.7%), the minimum and maximum were 33 and 86 points respectively. The value class has an average value of 6.61 points (Cv = 21.5%), with the minimum value of 4, and the maximum of 9 points. The materials were analysed to determine the correlation of the calculated indicators: drought resistance, phytophage resistance, gas resistance, salt resistance, soil fertility, winter hardiness, plant requirements, and their dependent indicators. Our statistical analysis of the physiological indicators of growth and development produced results that correlated with the calculated scores of biological resistances. The obtained correlation results are presented in Table 5. Table 5 presents the correlation between the calculated biological resistance scores and the physiological indices of the growth and development of woody plants. Plant age has a low correlation with various aspects of resistance, such as drought resistance (0.034) and salt resistance (0.000). The transpiration rate showed a negative correlation with drought resistance for the mean (-0.118) and maximum (-0.116) values and a positive correlation between phytophagy (0.117) and gas resistance (0.109). Leaf water content, mainly the minimum (0.236) and mean (0.172) values, correlated positively with drought resistance and salt resistance (0.253), however exhibited a low or negative correlation with winter hardiness. The chlorophyll A content in leaves displayed a weak positive correlation with drought resistance (0.086) and salt tolerance (0.103), however a negative correlation with winter hardiness. The chlorophyll B content in leaves demonstrated a significant positive correlation with drought resistance (0.200) and salt tolerance (0.229).

Table 3. Basic statistics of physiological indicators.

Indicator	**X**	**S**	**C_v (%)**	**S_x**	**p (%)**	**X_{min}**	**X_{max}**	**R_v**
Age, years	14.1	11.0	78.5	1.0	6.9	4	42	38
Transpiration rate, mg g^{-1} wet leaf weight per hour:								
- average for the growing season	226.8	117.3	51.7	10.4	4.6	56	720	664
- minimal	104.1	64.3	61.8	5.7	5.5	14	302	288
- maximum	388.2	260.2	67.0	23.0	5.9	108	1519	1411
- variation rank (medium)	284.0	268.1	94.4	23.7	8.3	6	1387	1381
Leaf water content as a percentage of crude weight:								
- average for the growing season	58.9	7.1	12.1	0.6	1.1	40.7	85.1	44.4
- minimal	52.9	8.5	16.1	0.8	1.4	26.3	79.9	53.6
- maximum	65.9	8.8	13.4	0.8	1.2	46.8	96.4	49.6
- variation rank (medium)	13.0	9.1	70.2	0.8	6.2	0.6	50.5	49.9
Chlorophyll A content in leaves as a percentage of raw weight:								
- average for the growing season	3.21	1.19	37.1	0.11	3.3	1.12	5.47	4.35
- minimal	1.98	1.26	63.4	0.11	5.6	0.06	5.33	5.27
- maximum	4.39	1.25	28.5	0.11	2.5	1.67	5.76	4.09
- variation rank (medium)	2.41	1.20	49.9	0.11	4.4	0.23	5.00	4.77
Contents of chlorophyll B in leaves as a percentage of crude weight:								
- average for the growing season	1.31	0.68	52.2	0.06	4.6	0.35	3.24	2.89
- minimal	0.58	0.55	95.3	0.05	8.4	0.00	2.34	2.34
- maximum	2.24	1.19	53.2	0.11	4.7	0.57	5.68	5.11
- variation rank (medium)	1.66	1.13	68.1	0.10	6.0	0.30	5.48	5.18
Carotenoid content of leaves as a percentage of crude weight:								
- average for the growing season	1.10	0.30	27.3	0.03	2.4	0.35	1.76	1.41
- minimal	0.69	0.37	53.6	0.03	4.7	0.01	1.56	1.55
- maximum	1.53	0.38	24.8	0.03	2.2	0.62	2.44	1.82
- variation rank (medium)	0.84	0.42	50.2	0.04	4.4	0.14	2.40	2.26

Note: X is the average value of the variable; S is the standard (RMS) deviation; Cv is the coefficient of variation (%); Sx is the standard error of the mean; p is the average accuracy (%); Xmin and Xmax are the minimal and maximal values of the variable, respectively; Rv is rank variation.

Table 4. Evaluation points are based on the complex regional introduction and diagnostic scale of plants in the arid conditions of the Mangystau region.

Indicator	**X**	**S**	**C_v (%)**	**S_x**	**p (%)**	**X_{min}**	**X_{max}**	**R_v**
Scores								
- drought resistance	8.60	3.65	42.4	0.35	4.0	0	15	15
- salt tolerance	5.57	2.23	40.0	0.21	3.8	0	10	10
- winter hardiness	6.27	1.69	27.0	0.16	2.6	1	8	7
- soil fertility requirements	4.04	1.57	39.0	0.15	3.7	0	6	6
- phytophagic	4.53	1.81	39.9	0.17	3.8	0	6	6
- gas resistance	3.38	1.00	29.4	0.09	2.8	1	5	4
Evaluation points:								
- biological resistance	32.37	7.95	24.6	0.76	2.3	14	48	34
- decorativeness	11.04	2.79	25.3	0.27	2.4	2	17	15
- reproduction	6.14	2.10	34.3	0.20	3.3	1	10	9
- economic, biological, and scientific significance	11.55	5.29	45.8	0.50	4.4	3	20	17
- introductory value	61.11	13.27	21.7	1.27	2.1	33	86	53
Value class	6.61	1.42	21.5	0.14	2.1	4	9	5

Note: n is the number of observations (measurements) – 128; X is the average value of the variable; S is the standard (RMS) deviation; Cv is the coefficient of variation (%); Sx is the standard error of the mean; p is the average accuracy (%); Xmin and Xmax are the minimal and the maximal values of the variable, respectively; Rv refers to rank variation.

The carotenoid content in leaves showed a negative correlation with drought resistance and salt tolerance, however a positive correlation with phytophagy. The critical value of the correlation coefficient at a significance level of 5% was 0.176, which allowed us to estimate the significance of the obtained correlations. Additionally, the levelling results were interpreted as a graph predicting the degree of studied physiological stability via drought resistance indicators according to physiological indicators of the growth and development of woody plants ($\eta cr05 = 0.176$). The data analysis from the table shows that the following trends and features are essential for assessing plant resistance in arid conditions.

Table 5. Correlation between the calculated scores of biological resistance and physiological indicators of growth and development of woody plants.

	Assessment scores					
Indicator	**Drought resistance**	**Salt tolerance**	**Winter hardiness**	**Soil fertility requirements**	**Phytophagic**	**Gas resistance**
Age	0.034	0.000	0.068	−0.081	−0.052	0.000
Transpiration rate:						
- average	−0.118	−0.032	−0.035	−0.094	0.117	0.109
- minimal	0.025	0.015	−0.213	−0.027	−0.017	0.083
- maximum	−0.116	−0.031	0.077	−0.010	0.124	0.114
- variation rank	−0.119	−0.034	0.126	−0.004	0.124	0.091
The water content of leaves:						
- average	0.172	0.253	−0.055	0.130	−0.004	0.024
- minimal	0.236	0.181	−0.045	0.171	−0.046	−0.029
- maximum	0.039	0.196	−0.051	0.053	0.041	0.047
- variation rank	−0.181	0.020	−0.009	−0.108	0.081	0.072
Chlorophyll A content of leaves:						
- average	0.086	0.103	−0.128	0.113	0.020	0.096
- minimal	0.055	0.060	−0.164	0.170	0.005	0.009
- maximum	0.074	0.075	−0.137	0.041	−0.014	0.073
- variation rank	0.020	0.016	0.029	−0.135	−0.020	0.066
Chlorophyll B content of leaves:						
- average	0.200	0.229	−0.149	0.208	−0.032	0.150
- minimal	0.117	0.111	−0.299	0.118	−0.044	0.052
- maximum	0.258	0.296	−0.011	0.244	−0.017	0.178
- variation rank	0.215	0.258	0.134	0.199	0.003	0.163
Carotenoid content of the leaves:						
- average	−0.102	−0.093	−0.081	−0.017	0.054	−0.119
- minimal	−0.193	−0.234	−0.205	−0.102	0.030	−0.085
- maximum	−0.020	0.029	−0.009	0.049	0.024	−0.122
- variation rank	0.152	0.232	0.173	0.133	−0.005	−0.037

Note: The critical value of the 5% significance level correlation coefficient is 0.176.

Drought resistance was positively correlated with leaf water content (incredibly minimum and average values) and chlorophyll B content (average and maximum values), however negatively correlated with transpiration rate. Salt tolerance was also positively correlated with leaf water and chlorophyll B content. Winter hardiness was negatively correlated with minimum transpiration rate and chlorophyll A content. Soil fertility requirements were positively correlated with leaf water and chlorophyll B content. Phytophagy was positively correlated with average transpiration rate and leaf water content. Gas resistance was positively correlated with chlorophyll B content and negatively with carotenoid content. Essential features for assessing plant resistance were leaf water content, chlorophyll B content, transpiration rate, chlorophyll A content and carotenoid content. These parameters can be critical indicators for assessing and improving plant resistance in arid conditions. In evaluating drought resistance, we considered the minimum and degree of change in leaf hydration, the average, maximum, and degree of change in chlorophyll B content, and the minimum content of carotenoids (Fig. 2).

Leaf water content: The minimum leaf water content (WCLmin) positively affected drought tolerance, while a high variation rank of water content (WCLRrv) had a negative effect.

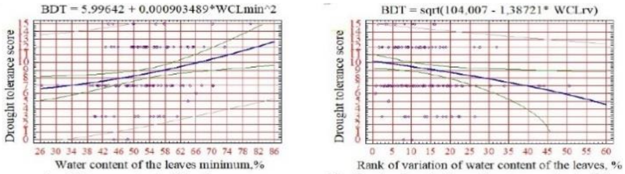
Chlorophyll B content: Both the mean and maximum chlorophyll B content (ChlBav and ChlBmax) positively impacted drought tolerance. The variation rank of chlorophyll B content (ChlBrv) also correlated positively with drought tolerance.

Carotenoid content: The minimum carotenoid content (CRTNmin) significantly negatively affected drought tolerance. These graphs show which physiological parameters are crucial to improving drought tolerance in woody plants under arid conditions. In assessing salt tolerance, we analysed maximum and average leaf moisture, maximum and average chlorophyll B content, rank variations in its content, and minimum carotenoid levels (Fig. 3). It is important to note that chlorophyll B content is not an unambiguous indicator of salt tolerance, but changes in its concentration may indicate the degree of damage to the photosynthetic apparatus of plants.

Leaf water content: Maximum and average leaf water content positively influenced salt tolerance.

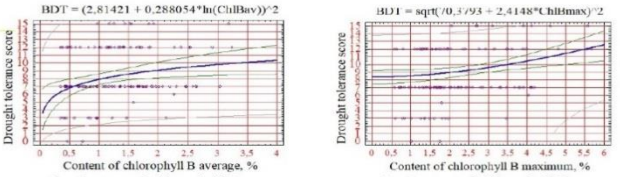
Chlorophyll B content: Both average and maximum chlorophyll B content and the variation rank of chlorophyll B content positively correlated with salt tolerance.

Carotenoid content: Minimum carotenoid content negatively influenced salt tolerance. These graphs show vital physiological parameters that affect the salt tolerance of woody plants and can serve as indicators for assessing and improving salt tolerance in arid conditions. For winter hardiness, we considered the minimum content of chlorophyll B and carotenoids in the plants (Fig. 4).



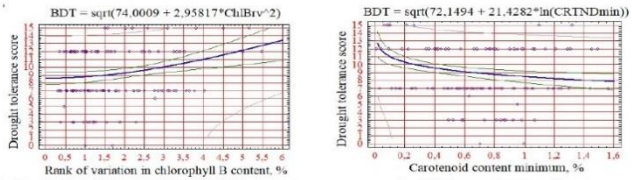
A - Water content of the leaves minimum -WCLmin ($\eta_{\varepsilon} = 0.235$)

B - Rank of variation of water content of the leaves - WCLrv (η_{ε} = -0,204)



C – Content of chlorophyll B average - ChlBav ($\eta_{\varepsilon} = 0.241$)

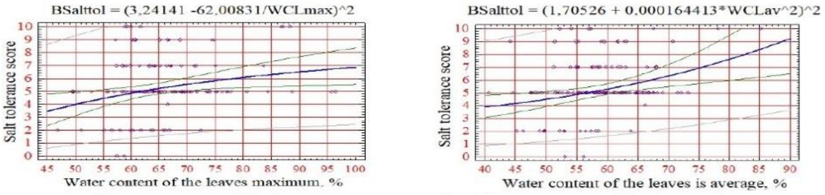
D - Content of chlorophyll B maximum - ChlBmax ($\eta_{\varepsilon} = 0.260$)



E - Rank of variation in chlorophyll B content - ChlBrv ($\eta_{\varepsilon} = 0.259$)

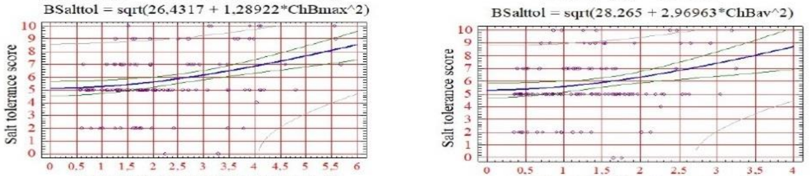
F - Minimum Carotenoid Content - CRTNDmin (η_{ε} = -0.326)

Fig. 2. Equations and graphs predict the degree of drought tolerance (BDT) via physiological indicators of the growth and development of woody plants (ηcr05 = 0.176): A – The water content of the leaves, B – Rank of variation of the water content of the leaves, C – Content of chlorophyll B average, D – Content of chlorophyll B average maximum, E – Rank of variation in chlorophyll B content, F – Minimum Carotenoid content.



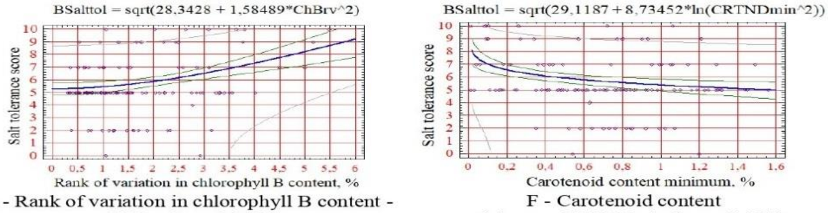
A - Water content of the leaves maximum - WCLmax ($\eta_{\varepsilon} = 0.229$)

B - Water content of the leaves is average – WCLav ($\eta_{\varepsilon} = 0.264$)



C – Content of chlorophyll B maximum - ChBmax ($\eta_{\varepsilon} = 0.341$)

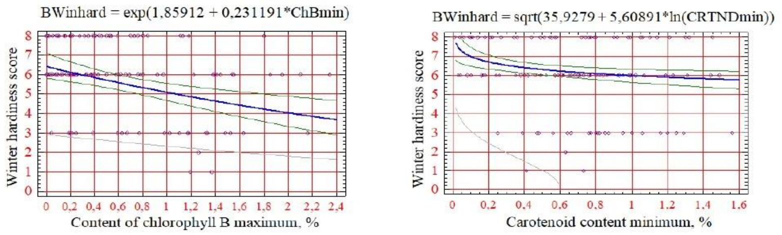
D - Chlorophyll B content average – ChBav (η_{ε} = 0,255)



E - Rank of variation in chlorophyll B content - ChBrv ($\eta_{\varepsilon} = 0.342$)

F - Carotenoid content minimum -CRTNDmin (η_{ε} = -0.327)

Fig. 3. Equations and graphs for predicting the degree of salt tolerance (BSalttol) according to physiological indicators of the growth and development of woody plants (ηcr05 = 0.176); A: The water content of the leaf's maximum; B: The water content of the leaves is average; C: Content of chlorophyll B maximum; D: Chlorophyll B content average; E: Rank of variation in chlorophyll B content; F: Carotenoid content minimum.

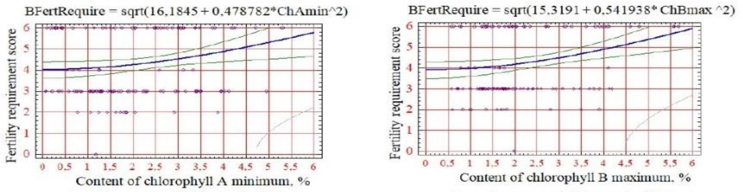


A – Chlorophyll B content is minimal - ChBmin (η_f = -0,310)

B - Carotenoid content minimum - CRTNDmin (η_f = -0.264)

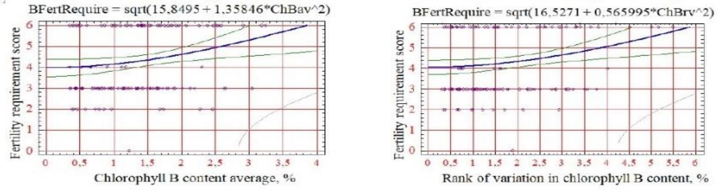
Fig. 4. Equations and graphs predicting the degree of winter hardiness (BWinhard) via physiological indicators of the growth and development of woody plants (ηcr05 = 0.176); A: Chlorophyll B content is minimal; B: Carotenoid content minimum.

Minimum chlorophyll B content: negatively affected winter hardiness of woody plants. The higher the minimum chlorophyll B content, the lower the winter hardiness. Minimum carotenoid content also negatively affected winter hardiness. The lower the minimum carotenoid content, the lower the winter hardiness. These graphs demonstrate vital physiological parameters that affect the winter hardiness of woody plants and can serve as indicators for assessing and improving winter hardiness in arid conditions. In evaluating soil fertility requirements, we considered the minimum content of chlorophyll A and the maximum, average, and degree of change in chlorophyll B (Fig. 5).



A – Content of chlorophyll A minimum - ChAmin (η_f = 0,217)

B – Content of chlorophyll B maximum - ChBmax (η_f = 0.272)



C – Chlorophyll B content average - ChBav (η_f = 0.220)

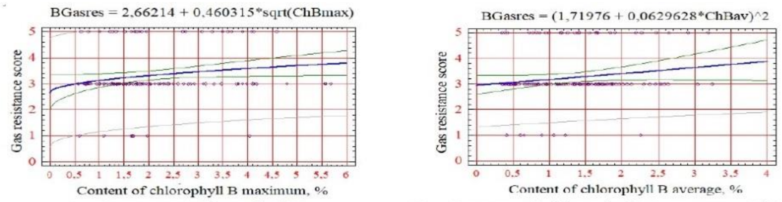
D – Rank of variation in chlorophyll B content - ChBrv (η_f = 0.220)

Fig. 5. Equations and graphs predicting soil fertility requirements (BFertRequire) using physiological indicators of the growth and development of woody plants (ηcr05 = 0.176); A: Content of chlorophyll A minimum; B: Content of chlorophyll B maximum; C: Chlorophyll B content average; D: Rank of variation in chlorophyll B content.

Minimum chlorophyll A content: positively influenced soil fertility requirements. The higher the minimum Chlorophyll A content, the higher the soil fertility requirements.

Maximum and average chlorophyll B content: Both values positively influenced soil fertility requirements. The higher these values, the higher the requirements.

Variation rank of chlorophyll B content: positively correlated with soil fertility requirements. The higher the variation rank, the higher the requirements. These graphs demonstrate key physiological indices that influence soil fertility requirements for woody plants and can serve as indicators for assessing and improving soil fertility in arid conditions. In evaluating gas resistance, we considered the maximum and average chlorophyll content (Fig. 6).



A – Content of chlorophyll B maximum - ChBmax (η_f = 0.180)

B – Content of chlorophyll B average - ChBav (η_f = 0.182)

Fig. 6. Equations and graphs for predicting the degree of gas resistance (BGasres) via physiological indicators of the growth and development of woody plants (ηcr05 = 0.176); A: Content of chlorophyll B maximum; B: Content of chlorophyll B average.

Maximum chlorophyll B content: positively influenced gas resistance of woody plants. The higher the maximum chlorophyll B content, the higher the gas resistance. Average chlorophyll B content also positively influenced gas resistance. The higher the average chlorophyll B content, the higher the gas resistance. These graphs demonstrate that chlorophyll B content (both maximum and average) was an essential physiological indicator that positively influenced the gas resistance of woody plants in arid conditions. We correlated the data on the physiological state of the woody plant samples with the scaled data on physiological resistance. The results are presented as a correlation matrix in Fig. 7. The correlation matrix in Fig. 7 shows the relationships between various physiological indices and indices of plant physiological resistance. The magnitude and direction of the correlation are shown by the colour and size of the dots: blue and large dots indicate a positive correlation, and red and large dots indicate a negative correlation.

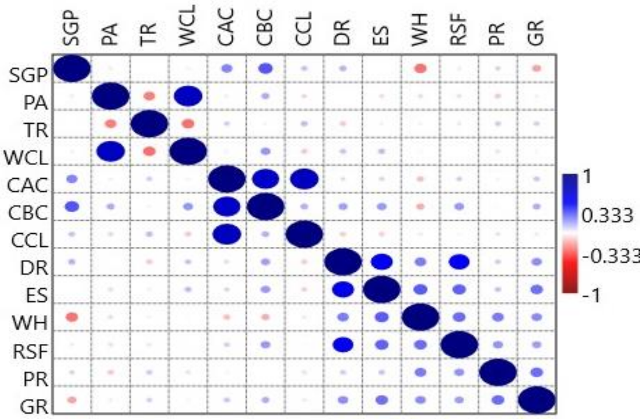


Fig. 7. Correlation matrix of physiological indicators and results of the physiological stability scale: specialised group of plants (SGP); plant age (PA); transpiration rate (TR); water content of leaves (WCL); chlorophyll A content (CAC); chlorophyll B content (CBC); carotenoid content in leaves (CCL); drought resistance (DR); endurance of salt (ES); winter hardiness (WH); requirements for soil fertility (RSF); resistance to phytophages (PR); and gas resistance (GR). The size of the dot indicates the magnitude of the value.

The correlation matrix shows that chlorophylls A and B contents and carotenoids in leaves are vital indicators that positively correlate with various aspects of plant physiological resistance, such as drought, salt, winter hardiness, and gas resistance. On the contrary, plant age and transpiration rate most often negatively correlate with resistance indicators. The results of PCoA are presented in Fig. 8.

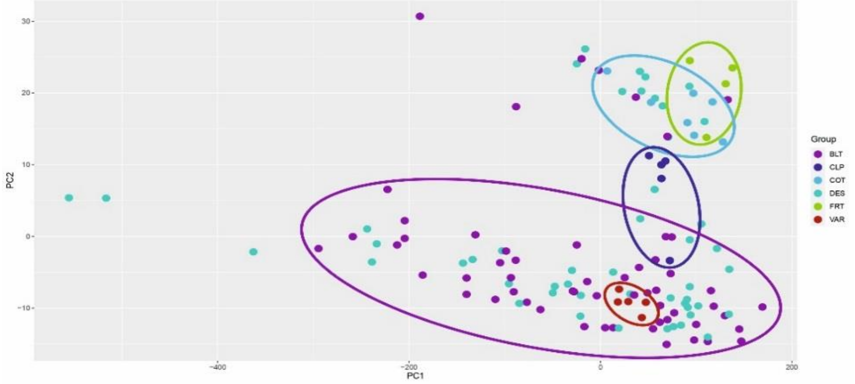


Fig. 8. Principal coordinate analysis (PCoA) based on the main results of the parameters of morphological and systematic groups: coniferous trees (COT), broad-leaved trees (BLT), fruit-berry plants (FRT), deciduous shrubs (DES), climbing plants (CLP), and varieties of roses (VAR).

Clustering of groups: The groups of conifers (COT), fruit-berry plants (FRT) and deciduous shrubs (DES) tend to cluster together in the upper right part of the graph, indicating the similarity of their morphological and systematic parameters. Climbers (CLP) form a separate cluster, close to, but still distinct from, the group of broadleaf trees (BLT). Broadleaf trees (BLT) show a wide distribution across the graph, indicating high variability within this group. Rose cultivars (VAR) are separated from the other groups and form a compact cluster in the lower right part of the graph.

Variability within groups: The broadleaf trees (BLT) have the highest variability, as their points are scattered throughout the graph. The rose cultivars (VAR) have the lowest variability, as their points are concentrated in a small area.

Similarities between groups: The close arrangement of coniferous tree (COT), fruit tree (FRT) and deciduous shrub (DES) groups indicated possible morphological and systematic similarities between them. Rose cultivars (VAR) differed significantly from other groups, which may be due to the unique morphological characteristics of this group. The Principal Coordinates (PCoA) plot effectively demonstrated the differences and similarities between different morphological and systematic groups of plants. The analysis allowed for identifying key groups and assessing their internal variability, which may be helpful for further research and classification. The groups formed correspond to morphological and systematic groups of plants. Such diverse results can be interpreted to identify and predict resistant forms of woody plants that are optimal for the region under study.

DISCUSSION

In many botanical centres in Kazakhstan, plant prospects are forecasted based on visual (mainly phenological) observations. This approach gives good results but does not reveal the mechanisms of plant adaptation to unfavourable and stressful environmental conditions (Lichtenthaler & Wellburn 1983; Rohlf 1998; Orazov *et al.* 2021; Anar *et al.* 2023). Previous studies of introduced plants' winter hardiness, water regime, and heat resistance have revealed some features of their adaptive response. Carotenoids, a large group of plant pigments, give different colours to plants' vegetative and generative organs. This predetermines their seasonal variability, and at the same time, they are necessary for the plant to absorb solar energy [50]. One phenological feature of the seasonal rhythms of introduced plants developing in the Mangystau region is their late colouring and leaf fall, a peculiar reaction to the weather in the desert zone. Related diverse results are backed by generally accepted concepts published in various scientific works (Munns 2002, Parida & Das 2005, Munns & Tester 2008, Munns 2011, Shelden & Roessner 2013, Munns & Gilliham 2015, Negrão *et al.* 2017, Perri *et al.* 2019, Perri *et al*. 2020, Shan *et al.* 2022). The calculated correlation coefficients showed a meagre value for all diagnostic signs of stability (0.009–0.299) in absolute numerical terms, which shows the significance of these results. Therefore, the significant proximity of the relationship was identified by comparing the actual (r f) and critical (r cr05) values of the correlation coefficients, and r f should be greater than r cr05 (Kusmangazinov *et al.* 2023; Kubentayev *et al.* 2024). As can be seen from the obtained dependencies (Figs. 2–6), none of the diagnostic features of biological resistance can be directly attributed to the criterion of resistance of woody plants. This is due to the significant variability of the transpiration process and its multifactorial intensity. However, a reasonably close dependence on the water content in the leaves was revealed (Figs. 2A, B and 3A, B). By an elevation in the variability of this indicator, the resistance of plants to arid conditions, as a rule, increases due to an improvement in their ability to self-regulate water exchange and, as a consequence, the salt regime of the leaf apparatus (Kramer, & Kozlovsky 1983). Noteworthy, the transpiration rate, water use efficiency, and salt tolerance can be closely related to the internal features of the leaf, which were not discussed in detail in this work. In particular, such characteristics as the length of the roots and their architecture can also play an essential role in the resistance of trees and shrubs to drought and salt. Still, these parameters were not considered in the analysis. In addition, to more accurately understand the impact of transpiration on plant resistance, it is necessary to consider not only the intensity of transpiration, but also the conductivity of stomata since they regulate the process of water evaporation. Including such indicators in the analysis would provide a more complete picture of the adaptation mechanisms of woody plants in dry conditions. A decrease occurred in the indicators of drought resistance, salt resistance, and winter hardiness of introduced species by an elevation in the minimum threshold of carotenoid content (Figs. 2E, 3E, and 4B). This confirms their significant role in the adaptation of plants to the arid conditions of the research region (Lakin 1990). Significant focus is placed on studying the adaptive abilities of introduced species in the introduction zone. Important indicators of adaptive response in the Mangystau desert are the transpiration rate, leaf hydration, and chlorophyll and carotenoid concentrations. Therefore, in our studies, these physiological indicators were the main factors used to determine the biological stability of woody and ornamental introduced plants. At the same time, this fact indirectly confirms a close connection between the selected isomers and the indicators of plant resistance and their adaptive capabilities in the arid conditions of Mangystau. Significant variability did not hinder the accuracy of the average values of the physiological isomers, as these values were within the permissible value of 5% in most cases. Similarly, the leaf chlorophyll content was studied as a physiological indicator. It not only characterises the ontogenetic, age, and genetic characteristics of plants, but also reflects the reaction of plant organisms to growing conditions. Additionally, funds for a specific natural and climatic zone may be granted after observing and determining optimal plant growth technologies (Zeinullina *et al.* 2023; Zargar *et al.* 2023). Our complex regional scale shows a significant spread of assessment scores, even for domestic and foreign plants with high biological resistance. This critical conclusion proves the scale's high reliability and compliance with the preliminary opinion of introducers on the value of specific taxa. The distribution of taxa across classes appears nearly symmetrical compared to previously tested scales (Zhang *et al.* 2023), relative to the "average" that accounts for 23.9% of the plants tested. In summary, the MEBG bio-ecological approach used for assessing plants' introduction at a comprehensive regional scale has produced positive results. The next stage of its improvement was the 2015 translation in a unique piece of software called "DinTseR", which uses an electronic language. At the same time, during the tests, problems were encountered in ranking the resistance indicators of exotic species into groups and classes. Such issues were due to the lack of literature data and the extreme complexity of comparative experimental determination of many taxa of the collection's gene pool. Thus, the primary goals and objectives were achieved. Therefore, one of the objectives of this study was to identify the most easily diagnosed and reliable physiological indicators of winter hardiness, drought resistance, heat resistance, salt tolerance, and the demands of introducers on soil fertility.

CONCLUSION

Thus, as a result of the study, indicators of the physiological resistance of woody plants to the arid conditions of the Mangystau region were established. The study was carried out in four stages: (i) development of a computer program, DInCeR, including scoring diagnostic signs of biological resistance; (ii) creation of data matrices for data processing; (iii) correlation analysis of the research material; and (iv) regression analysis. The research involved 128 coniferous trees, deciduous fruits, and creeping woody plants from 34 botanical families evaluated for growth and resistance to desert habitats. The introduction value of the experimental taxa ranged from 33 to 86 points, and the value class ranged from 4 (low) to 9 (very high). Significant variation (up to 51.7–52.2%) was found in all studied physiological parameters due to taxa of different geographical origins with other ecological and biological properties in one sample. The accuracy of their determination was within the permissible range (5%). Deciduous trees, shrubs, and rose varieties had the highest transpiration rates (205–243 mg g^{-1} fresh leaf mass per hour). Climbing plants had the highest leaf water content (68.9%). The highest contents of chlorophylls A and B (3.46–3.93 and 1.34–1.84%) were found in deciduous trees, fruit-berry plants, and varietal roses. There was practically no difference between groups of deciduous plants in the saturation of leaves with carotenoids (1.12–1.17%). In coniferous species, the content of carotenoids was almost two times less (0.63%). Correlation analysis of physiological indicators and calculated indicators of woody plant resistance revealed shallow correlation coefficient values (0.009–0.299). In this case, statistically reliable relationships were established by comparing the correlation coefficients' actual and critical values. As a result, the following statistically reliable physiological indicators were identified: (i) in the case of drought resistance, the minimum and rank of variation in the water content in leaves, the average, maximum, and rank of variation in chlorophyll B content, and the minimum of carotenoid content; (ii) To assess the tolerance to maximum and average leaf water content, maximum, average and rank variations in chlorophyll B content, minimum carotenoid content, in this species, resistant to high radiation, accumulates more carotenoid pigments, which may be associated with oxidative stress; (iii) in the case of winter hardiness, the minimum content of chlorophyll B and carotenoids; (iv) for soil fertility, the minimum content of chlorophyll A, the maximum, average, and rank of variation in the content of chlorophyll B; and (v) in the case of gas resistance, the maximum and average content of chlorophyll B. No reliable correlations were found for indicators of resistance to phytophages. As a result of regression analysis, 20 forecast graphs of stability indicators and the derived dependence formula had logarithmic, power, multiplicative, and exponential forms. The research results contribute to improving and implementing the ecological method of phytointroduction. This will significantly reduce the time and financial resources required to conduct introductory research and select appropriate plants. As a result, in the extremely harsh climatic conditions of the Mangystau region, the quality of green construction will significantly improve.

Patents

The copyright certificate of state registration of rights to an object of copyright was obtained (No. 2339 dated December 14, 2015) from the Minister of Justice of the Republic of Kazakhstan for registered exclusive property rights to an object of copyright under the name "DInCeR (computer program). Authors: Imanbayeva Akzhunis, Belozerov Ivan. Patent holder: Mangyshlak Experimental Botanical Garden."

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

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