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Fraxinus sogdiana Bunge forests in Charyn Canyon, Kazakhstan

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ABSTRACT
This research investigates the biodiversity and ecological status of the *Fraxinus sogdiana* Bunge forests within Charyn Canyon, Kazakhstan, a unique ecosystem known for its high biodiversity and geological significance. Charyn Canyon, stretching for 154 km, contains over 1,500 plant species, 17 of which are listed in the Red Book of Kazakhstan. The relict grove of *F. sogdiana* occupies over 800 hectares of the 5,000-hectare floodplain area. The study assessed the photosynthetic parameters of *Fraxinus* L. and *Populus* L., measuring key indicators such as minimum fluorescence (Fo), variable fluorescence (Fv), maximum fluorescence (Fm), and chlorophyll content (mg m^{-2}). Results show that *F. sogdiana* exhibited an Fv/Fm ratio of 0.735–0.828, indicating that some individuals are under stress. In contrast, *Populus* species showed higher photosynthetic efficiency with a maximum Fv/Fm value of 0.834. Floristic analysis revealed a complex plant community with significant species diversity, including xerophytes, mesophytes, and halophytes, indicative of the region's varied ecological zones. Vegetation indices derived from UAV mapping, including NDVI, GNDVI, and OSAVI, further supported these findings, showing higher photosynthetic activity and chlorophyll content in *Populus* than in *Fraxinus*. Correlation analysis between physiological parameters and vegetation indices highlighted significant relationships, particularly between NDVI and photosynthetic efficiency, providing insights into the health of the forest canopy. The study underscores the significant anthropogenic threats to the region, such as deforestation and uncontrolled grazing, accelerating habitat degradation, and reducing genetic diversity. The critical findings of this research underscore the urgent need for conservation efforts and provide a wealth of information that can guide these efforts, enlightening us about the state of these unique ecosystems and the measures needed to preserve them.

Keywords: Biodiversity, Charyn, conservation, *Fraxinus* L., NDVI.
Article type: Research Article.

INTRODUCTION
The biological diversity of Kazakhstan's forests is one of the main factors that form a unique habitat for most plant and animal species (Zhang *et al.* 2020), with some endemic and rare species restricted to a specific mountain or isolated canyon terrain (Kubentayev *et al.* 2024). Moreover, Kazakhstan's forest resources provide many ecosystems, such as mountain, steppe, desert, and unique canyon forests, that regulate complex ecological and hydrological cycles and link them with various processes. However, many forest ecosystems in Kazakhstan face several threats, including deforestation, environmental degradation, and uncontrolled grazing, which threaten species diversity (Orazov *et al.* 2021). These threats have significant implications for the existence of plant species

diversity, which are integral and vital components of the complex ecosystems of Kazakhstan and Central Asia. Due to ongoing habitat loss and high anthropogenic pressure, the genetic diversity of most forest plant species in Kazakhstan and Central Asia is declining, making them increasingly vulnerable. This could threaten their availability for the conservation of plant species for commercial and pharmaceutical research, which includes the development of new medicines, agricultural products, and other valuable resources (Imanbayeva *et al.* 2024). Worldwide, forest plant biodiversity is a critical source of genetic resources for assessing the state of biodiversity in affluent areas of our planet (Orazov *et al.* 2024; Myrzagaliyeva *et al.* 2024). The growing demand for increased pastureland and cultivation of various crops highlights the importance of identifying and conserving forest plant biodiversity (Belgica *et al.* 2024). The current study on the biodiversity status of different forest and forest-steppe areas of Kazakhstan reveals a wide range of medicinal, wild, closely related crop and forage plants found in the forests of Kazakhstan (Zargar *et al.* 2023; Zeinullina *et al.* 2023). Sustainable plant collection and deforestation will lead to the destruction of the ecosystem structure and the subsequent reduction in the wealth of the quantity and quality of ecosystems that form complex communities in isolated areas with abundant accumulation of soil and biological reserves (Kaizhakparova 2020; Dar *et al.* 2022). One such unique area in Kazakhstan is the Charyn Canyon, which is rich in the biological diversity of forest plant species. The canyon is a large geographical object stretching 154 km along the Charyn River, Southeast Kazakhstan. The canyon is part of the Charyn National Park, a natural monument composed of sedimentary rocks, which is about 12 million years old. The height of the steep mountains of the canyon reaches 150-300 masl. The canyon was formed about 25 million years ago in the Tertiary period when there was a large lake in this place. The slopes were formed as a result of both the processes of rock destruction (denudation) and the sedimentation of rocks (marls - white limestone rocks; Sharapkhanova *et al.* 2024). In the river floodplain, on an area of 5 thousand hectares, there is a relict grove of *Fraxinus sogdiana* Bunge. Research scientists assume this species grew here 5 million years ago; the grove survived the Ice Age (Aldibekova *et al.* 2021; Shynybekov *et al.* 2023). Now, the individuals are 300-400 years old; their trunks are 3-4 times larger than their circumference. The grove is included in the list of natural monuments and under state protection. The plant richness and biodiversity of Charyn Canyon have long supported local communities by providing materials, food, ornamental plants, and medicines. Cultural practices and traditional healing methods highlight the deep bond between residents and local flora. This connection emphasizes the need for conservation, as biodiversity loss disrupts the ecological balance and erodes cultural heritage. Therefore, preserving these plants is critical for their environmental value and continued role in traditional practices and the region's cultural identity. Physiological parameters like photosynthetic activity help assess plant health and resilience in the canyon. We measured Fo, Fv, Fm, and the Fv/Fm ratio to evaluate Photosystem II (PSII) efficiency, focusing on *F. sogdiana* and *Populus* L. species. These measurements indicate how well these species cope with environmental stress and anthropogenic pressures. UAV mapping with a multispectral sensor provided a broader view of vegetation health and distribution. Vegetation indices such as NDVI, GNDVI, and OSAVI revealed essential details about vegetation density, canopy conditions, and the effects of deforestation and grazing. The urgency of conservation is highlighted by the fact that many endemic plant species in Kazakhstan's isolated regions, including Charyn Canyon, face extinction. Habitat loss and exploitation are the main threats, underscoring the need for immediate action to prevent further decline. The complex link between environmental challenges and plant biodiversity demands a comprehensive conservation approach. This study aims to investigate and assess the biodiversity of plant species in the *Populus* grove within Charyn Canyon, focusing on critical species' current status and distribution to emphasize their ecological importance and vulnerability. Understanding these factors is essential for creating effective conservation strategies that preserve these unique species and their cultural significance.

MATERIALS AND METHODS

Study area

The study area is the main central part of the Charyn Canyon within the Charyn Ash Grove, the only location in Kazakhstan where relict Sogdian ash trees, *F. sogdiana* grow. The total area of the grove is about 5,000 hectares, although the ash trees themselves grow on just over 800 hectares. The forest stretches for 22 km. The Charyn River and its tributaries cut through the thicket of trees, creating an incredible landscape. Fig. 1 shows a map of the distribution of the poplar grove. The diversity of the Charyn Canyon flora provides a habitat for various plant species. This natural area has unique vegetation adapted to harsh conditions. About 1,000 species of higher vascular plants belonging to 436 genera and 92 families have been registered on the Charyn State National Park territory.

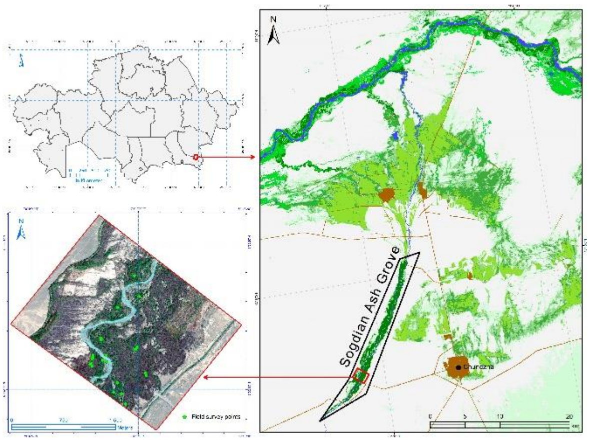

Fig. 1. Map of the location of the *Fraxinus sogdiana* Bunge grove within the Charyn Canyon (Kazakhstan).

Large taxonomic groups related to the leading ten significant families, include Asteraceae Bercht. & J.Presl, Fabaceae Lindl., Poaceae Barnhart, Brassicaceae Burnett, Rosaceae Juss., Boraginaceae Juss., Lamiaceae Martinov, Chenopodiaceae Burnett, Caryophyllaceae Juss., Scrophulariaceae Juss., Apiaceae Lindl., Ranunculaceae Juss., Liliaceae Juss., Alliaceae Herb. and others. The main ecosystems, which are rich in floristic diversity, are concentrated in the floodplain of the Charyn River and form multi-structural terraces with the dominant tree species, *F. sogdiana* (Sogdian ash). Plant communities growing together with Sogdian ash formed an "ash grove" in the Charyn Canyon National Park, a unique territory within the Charyn Canyon. It is characterized by high, narrow rock spires, columns, and stepped floodplain terraces. These formations have been subject to wind and water erosion for millions of years, resulting in the Ash Grove acquiring its characteristic appearance and stable list of plant species. Although Ash Canyon is primarily a geographical feature, the plant life in this area is typical of the flora found in the Charyn Canyon. This includes plants adapted to the semi-arid and continental climate of Kazakhstan. The climate in the grove is sharply continental. The average annual temperature is about +5 °C; the coldest month is January, - 6 °C and the warmest is July, about + 27 °C (Nigmatova *et al.* 2021).

Floristic Analysis

The route reconstruction methods were used to identify the central locations of significant ecosystems and stable plant communities. Large ecosystems can be divided into the following components: aquatic, coastal-aquatic (right-bank and left-bank), tugai-forest, primary floodplain terrace, secondary floodplain terrace, tertiary floodplain terrace, and coastal-mountain (desert). The floristic properties of plants were analyzed using the method of O. V. Smirnova *et al.* (Shevchenko & Smirnova 2017). In this case, the names of plant species were compared with the "Flora of Kazakhstan" (Pavlov *et al.* 1961), "Illustrated Identifier" (Goloskokov 1972), "Identifier of Plants of Central Asia" (Khasanov 2015), and the International Index of Electronic Database Names (Croft *et al.* 1999). The classification of life forms of species included in the population was assessed using the method of I. G. Serebryakov (Serebrjakov 1962). Traditional methods of geobotanical survey use ecological and morphological indicators to describe populations, such as laying out and marking a test plot, filling out a phytocenosis description form, and other basic methods. *F. sogdiana* individuals were counted by age groups, and their floristic composition was described. The vocabulary of plants was determined according to POWO (POWO 2024). Komarov *et al.* (2003) method was used to describe ontogenesis. The population type was determined using the S.V. Fedorov method. The following age groups were considered: young individuals (of root or seed origin), virginal (large individuals that have not reached the generative period), and young and adult generative. Seedlings and senile individuals were not identified in the natural population at the time of the study.

Physiological method for assessing the condition of plants

Physiological methods for assessing plant health are based on measuring chlorophyll fluorescence and chlorophyll concentration in leaves. One of the critical parameters is minimum fluorescence (Fo), measured in the dark state when the reaction centers of photosystem II are fully open. It reflects the level of unabsorbed light by chlorophyll. Variable fluorescence (Fv) is calculated as the difference between maximum (Fm) and minimum (Fo) fluorescence, which shows the amount of energy used in photosynthesis (Cendrero-Mateo *et al.* 2016). These parameters were related using two devices: The first device, the SKM-300, is a compact chlorophyll content meter in plants. The measurement is based on chlorophyll fluorescence. The sensor measures variable fluorescence for wavelengths 735 nm and 700 nm. The chlorophyll content is determined by the ratio of these values, expressed in mg m^{-2} with a thickness of + / - 1 mg m^{-2}. The second device, the OS30p +, is a modulated fluorimeter with a calibrated red actin LED lamp designed to provide automatic measurement of FV / FM parameters and the Strasser protocol OJIP (Opti-Sciences, Inc., 8 Winn Avenue, Hudson NH 03051, USA).

UAV vegetation mapping

By the development of technology, uncrewed aerial vehicles (UAVs) equipped with various optical and laser sensors are widely used to study the spatial distribution of vegetation in forest ecosystems (Tang *et al.* 2015; Torresan *et al.* 2017; Assmann *et al.* 2019; Chehreh *et al.* 2023). The assessment and mapping of the vegetation cover of the Yasenovaya Grove was carried out using an uncrewed aerial vehicle (UAV) with a multispectral sensor from Da-Jiang Innovations (DJI), model: Mavic M3M Enterprise (Kratky & Komarkova 2023). After processing the UAV data in the DJI Terra Pro platform, an ultra-high-resolution aerial photograph (< 5 cm) was obtained in four spectral ranges: green (G) 560 ± 16 nm, red (R) 650 ± 16 nm, red edge (RE) 730 ± 16 nm and near-infrared (NIR) 860 ± 26 nm, covering an area of 275 ha of the Sharyn River floodplain. Spectral indices for assessing the state of vegetation were calculated by mathematical operations between the spectral ranges and are presented in Table 1.

Table 1. Vegetation indices used in this study.

Vegetation Indices	Equation	Reference
Normalized Difference Vegetation Index (NDVI)	(NIR – R) / (NIR +R)	(Rouse *et al.* 1996)
Green Normalized Difference Vegetation Index (GNDVI)	(NIR – G) / (NIR +G)	(Gitelson *et al.* 1996)
Optimized Soil Adjusted Vegetation Index (OSAVI)	(NIR – R) / (NIR +R + 0.16)	(Rondeaux *et al.* 1996)
Chlorophyll Index Red Edge (CIRE)	(NIR – RE) - 1	(Chappelle *et al.* 1992)
Green Chlorophyll Index (GCI)	(NIR – G) - 1	(Xiao *et al.* 2014)
Modified Chlorophyll Absorption in Reflectance Index (MCARI)	(RE − R) − 0.2 x (RE − R)	(Haboudane *et al.* 2004)
Chlorophyll Vegetation Index (CVI)	(NIR x R) / G^2	(Vincini *et al.* 2008)

RESULTS AND DISCUSSION

Floristic analysis of *F. sogdiana* forests

Large ecosystems can be divided into the following components: aquatic, coastal-aquatic (right-bank and left-bank), tugai-forest, primary-floodplain terrace, secondary floodplain terrace, tertiary floodplain terrace, and coastal-mountain (desert). Various aquatic species represent the marine flora of the Charyn River. The height of the river flow along the pyramid section is 700-750 meters above sea level (masl). The river has a high laminar flow, which, in turn, is not favorable for the formation of talon colonies or bottom water crows. The algology of green water crows is limited. The shrub layer develops well. It is 1.5-2 m high and is closed to one form under the canopy of ash and poplar. The dominants of the shrub layer are *Rosa* L., Berberis L., etc. In addition to *Haloxylon* Bunge and *Tamarix* L., other shrubs are also indicated in the canyon, such as *Berberis* spp. and *Rosa* spp., which contribute to the diversity of the plant community. The second shrub line is formed by a dense *Tamarix ramosissima* Ledeb., *Caragana halodendron* (Pall.) Dum.Cours. and *Berberis iliensis* Popov, thinning out towards the center of the riparian forest. The grass cover is rich in species. Closer to the center of the riparian forest, these species of shrubs are replaced by *Rosa iliensis* Chrshan and *R. beggeriana* Schrenk. On the right and left banks woody forms of willow and poplars are abundant, including oleaster, and they turn into ash. The condition is satisfactory, and fallen branches and leaves have formed a dense forest litter. This type of structure makes up the central massif of the riparian forest on the verges of the first floodplain terrace. Olive is a narrow-leaved shrub or small tree with silvery leaves and edible fruits. The species composition of poplars builds a diverse complex with various forms, such as the emergence and cultural attacks on both banks and floodplain terraces with transitions within the sea boundaries. Among the riparian forests, several associations can be distinguished. The natural Red Book *Populus euphratica* Oliv. It was fixed in its presence on the right bank, and *Acer tataricum* L. was included sparsely. Poplar trees such as *Populus diversifolia* Oliv. can be found close to water sources, including the Charyn River. They provide the shade and contribute to the overall biodiversity of the territory. The central poplar-ash community is represented by *P. nigra* f. *pyramidalis* L., *P. thalassica* Kom., and its pyramidal form was used as a forestry crop in the eastern direction, forest clearings, and along the banks. The condition is satisfactory. In Charyn, various grasses within this Canyon area, including *Stipa* L. spp. and *Carex* L. spp., facilitate herbivores' digestion. The herbaceous layer of plants in the riparian forest is not dense and abundant.

Broadleaf and dark forests formed communities of mesophilic and resistant species. *Clematis orientalis* L. grows in size on trees and shrubs, forming lianas. Various species of wormwood, including *Artemisia turanica* Krasch., are adapted to the region's arid conditions. They have silvery-grey leaves and are used as forage plants for herbivores. The grass cover is rich in species and is represented mainly by mesophilic forbs and cereals, particularly boreal Asian flora, which is in the same layer as shrubs. Ruderal species such as *Xanthium strumarium* L. were observed along the roads and clearings. This area within the canyon is also a wildflower area that blooms during the spring and summer, adding color to the landscape. Some common wildflowers include tulips, irises, and various asters and daisies. On the right bank in the grassy layer, *Iris halophila* Pall., *Glycyrrhiza uralensis* Fisch. ex DC., *Sophora alopecuroides* L., etc., are sporadically found. It would also be worth noting the presence in the flora of the riparian forest of cultivated species of fruit plants *Hippophae rhamnoides* L., *Malus domestica* (Suckow) Borkh., and *Rubus caesius* L. In more shaded and damp places, you can also find mosses and lichens covering stones and tree trunks and several hornbeams *Laetiporus sulphureus* (Bull.) Murrill, *Psathyrella* (Fr.) Quel. and *Coprinopsis* P. Karst. The higher floodplain terraces of the Charyn River differ from the floodplain route in their poor floristic composition. Deserts, turning into screes of the Charyn Canyon, are widespread. Here, desert vegetation is found intrazonally. The most numerous elements of desert vegetation, widespread wormwood deserts with the dominance of *Arthrophytum* Schrenk, are found. The ecological conditions of rocky-gravelly habitats and the absence of developed soil cover create specific conditions for the settlement of plants here. The vegetation cover of these habitats is highly sparse and never forms a closed cover, and its distribution is uneven. Thus, the Charyn Canyon within the ash grove, located Southeast Kazakhstan, is a unique natural territory known for its inimitable rock formations and distinctive flora. The flora of the Charyn Canyon is adapted to the semi-arid and continental climate of the region, characterized by hot summers and cold winters. During the study, an annotated list of the leading representatives of higher vascular plants was compiled: *Elaeagnus angustifolia* L., *Zygophyllum fabago* L., *Populus talassica* Kom., *Glaucium fimbrilligerum* Boiss., *Malus domestica* (Suckow) Borkh., *Melilotus officinalis* (L.) Lam., *Haloxylon ammodendron* (C.A. Mey.) Bunge ex Fenzl, *Salix purpurea* L., *Clematis orientalis* L., *Glycyrrhiza uralensis* Fisch. ex DC., *Pentanema britannicum* (L.) D.Gut.Larr., *Rubus caesius* L., *Clematis orientalis* L., *Rosa beggeriana* Schrenk, *Ceratocarpus arenarius* L., *Hippophae rhamnoides* L., *Rosa iliensis* Chrshan., *Nitraria sibirica* (DC.) Pall., *Centaurea virgata* subsp. *squarrosa* (Willd.) Gugler, *Populus alba* L., *Cynanchum acutum* subsp. *sibiricum* (Willd.) Rech.fil., *Elaeagnus angustifolia* L., *Populus alba* L., *Peganum harmala* L., *Berberis iliensis* Popov, *Caragana halodendron* (Pall.) Dum.Cours., *Iris halophila* Pall., *Equisetum ramosissimum* Desf., *Myricaria bracteata* Royle, *Haloxylon ammodendron* (C.A. Mey.) Bunge ex Fenzl, *Sophora alopecuroides* L., *Reaumuria songarica* (Pall.) Maxim., *Tamarix ramosissima* Ledeb., *Xanthium strumarium* L., *Sophora alopecuroides* L., *Clematis songorica* Bunge, *Populus euphratica* Olivier, *Rosa beggeriana* Schrenk, *Acer tataricum* subsp. *semenovii* (Regel & Herder) A.E. Murray, *Tamarix ramosissima* Ledeb., *Alhagi pseudalhagi* (M.Bieb.) Desv. ex Wangerin, *Caragana balchaschensis* (Kasn. ex Kom.) Pojark., *Oenanthe pleschanka* Lepechin, *Glaucium elegans* Fisch. & C.A. Mey., *Reaumuria songarica* (Pall.) Maxim., *Nanophyton iliense* U.P. Pratov, *Suaeda physophora* Pall. (Table 2). These plant species represent the diverse flora found in the Charyn Canyon and adjacent areas of Kazakhstan, which is characterised by a variety of desert, steppe, and coastal vegetation adapted to the region's semi-arid climate and unique environmental conditions. The floristic composition includes xerophytic and halophytic species characteristic of arid and saline habitats. Most of them are adapted to extreme environmental conditions, such as water shortages and high salt content in the soil. Based on the provided data on the geographical location, family, life form, and ecological group of plants, the following estimates can be made: approximately half of the plants are xerophytes, indicating a significant proportion of arid conditions in this region. This is confirmed by plants such as Anabasis brevifolia C.A. Mey. and Peganum harmala L., which are well adapted to arid conditions. Another significant proportion of plants are mesophytes, requiring moderate moisture. This indicates the presence of areas with more favorable conditions for plants with moderate water requirements, such as Clematis orientalis L. and Sophora alopecuroides L. Halophyte plants such as Sphaerophysa salsula (Pall.) DC. and Sphaerophysa salsula (Pall.) DC. indicates the presence of areas with saline soils. This may indicate the proximity of salt marshes or water bodies with increased mineralization. The presence of hydrophytes such as *Rumex hydrolapathum* (Scop.) Huds. and *Lactuca undulata* Ledeb. suggests the presence of humid zones or ponds, although such plants are less common. Herbaceous plants dominate the area (about 50%), indicating a grassy cover and tolerance to various environmental conditions. Shrubs and trees also occupy a significant proportion, indicating complex plant community structures.

Table 2. Main key plant species.

latitude	longitude	Family	Scientific Name	Life form	Environmental group
43.54292	79.28273	Amaranthaceae Juss.	*Anabasis brevifolia* C.A.Mey.	Bush	Xerophyte
43.54422	79.28151	Amaranthaceae Juss.	*Anabasis eriopoda* (C.A. Mey.) Benth. ex Volkens	Bush	Mesophyte
43.54898	79.27988	Amaranthaceae Juss.	*Ceratocarpus arenarius* L.	Herbaceous plant	Xerophyte
43.54046	79.26625	Amaranthaceae Juss.	*Haloxylon ammodendron* (C.A. Mey.) Bunge ex Fenzl	Tree	Mesophyte
43.5197	79.24746	Amaranthaceae Juss.	*Iljinia regelii* (Bunge) Korovin	Herbaceous plant	Xerophyte
43.54432	79.28147	Amaranthaceae Juss.	*Suaeda dendroides* (C.A. Mey.) Moq.	Liana	Xerophyte
43.5724	79.2979	Amaranthaceae Juss.	*Suaeda physophora* Pall.	Bush	Xerophyte
43.54266	79.28331	Apocynaceae Juss.	*Cynanchum acutum* subsp. *sibiricum* (Willd.) Rech. fil.	Tree	Mesophyte
43.51949	79.2057	Asteraceae Bercht. & J.Presl	*Cancrinia discoidea* (Ledeb.) Poljakov ex Tzvelev	Herbaceous plant	Xerophyte
43.53373	79.27192	Asteraceae Bercht. & J.Presl	*Centaurea virgata* subsp. *squarrosa* (Willd.) Gugler	Herbaceous plant	Mesophyte
43.54053	79.26643	Asteraceae Bercht. & J.Presl	*Lactuca tatarica* (L.) C.A. Mey.	Bush	Xerophyte
43.54	79.29093	Asteraceae Bercht. & J.Presl	*Lactuca undulata* Ledeb.	Herbaceous plant	Hydrophytes
43.54241	79.28396	Asteraceae Bercht. & J.Presl	*Pentanema britannicum* (L.) D.Gut.Larr.	Herbaceous plant	Halophyte
43.52462	79.25886	Asteraceae Bercht. & J.Presl	*Xanthium strumarium* L.	Herbaceous plant	Mesophyte
43.5115	79.23618	Berberidaceae Juss.	*Berberis iliensis* Popov	Bush	Mesophyte
43.55568	79.30499	Berberidaceae Juss.	*Berberis vulgaris* L.	Bush	Mesophyte
43.51973	79.20292	Brassicales Bromhead	*Lachnoloma lehmannii* Bunge	Herbaceous plant	Xerophyte
43.54428	79.28148	Capparaceae Juss.	*Capparis spinosa* var. *herbacea* (Willd.) Fici	Herbaceous plant	Mesophyte
43.54395	79.28683	Caprifoliaceae Juss.	*Lonicera iliensis* Pojark.	Bush	Mesophyte
43.51993	79.20349	Convolvulaceae Juss.	*Convolvulus fruticosus* Pall.	Herbaceous plant	Mesophyte
43.55443	79.30177	Convolvulaceae Juss.	*Convolvulus tragacanthoides* Turcz.	Herbaceous plant	Xerophyte
43.58542	79.30804	Cynomoriaceae Endl. ex Lindl.	*Glaucium elegans* Fisch. & C.A. Mey.	Parasite	Xerophyte
43.54402	79.27652	Elaeagnaceae Adans.	*Elaeagnus angustifolia* L.	Herbaceous plant	Xerophyte
43.52397	79.25781	Elaeagnaceae Adans.	*Hippophae rhamnoides* L.	Bush	Mesophyte
43.51932	79.20433	Ephedraceae Dumort.	*Ephedra equisetina* Bunge	Bush	Mesophyte
43.54329	79.28765	Ephedraceae Dumort.	*Equisetum ramosissimum* Desf.	Herbaceous plant	Mesophyte
43.58949	79.31284	Fabaceae Lindl.	*Caragana balchaschensis* (Kasn. ex Kom.) Pojark.	Herbaceous plant	Xerophyte
43.54437	79.28031	Fabaceae Lindl.	*Caragana halodendron* (Pall.) Dum.Cours.	Bush	Halophyte
43.55428	79.30225	Fabaceae Lindl.	*Gleditsia triacanthos* L.	Bush	Halophyte
43.54775	79.29646	Fabaceae Lindl.	*Glycyrrhiza uralensis* Fisch. ex DC.	Herbaceous plant	Xerophyte
43.5208	79.26252	Fabaceae Lindl.	*Sophora alopecuroides* L.	Bush	Mesophyte

43.54274	79.28346	Fabaceae Lindl.	*Sphaerophysa salsula* (Pall.) DC.	Herbaceous plant	Halophyte
43.54273	79.28342	Iridaceae Juss.	*Iris halophila* var. *sogdiana* (Bunge) Skeels	Bush	Halophyte
43.54405	79.28386	Iridaceae Juss.	*Iris halophila* Pall.	Bush	Mesophyte
43.54385	79.28398	Lamiaceae Martinov	*Mentha arvensis* L.	Herbaceous plant	Mesophyte
43.54681	79.29059	Nitrariaceae Lindl.	*Nitraria sibirica* (DC.) Pall.	Tree	Mesophyte
43.54815	79.27963	Nitrariaceae Lindl.	*Peganum harmala* L.	Herbaceous plant	Xerophyte
43.45373	79.26845	Oleaceae Hoffmanns. & link	*Fraxinus sogdiana* Bunge	Tree	Mesophyte
43.51992	79.20253	Orobanchaceae Vent.	*Cistanche salsa* (C.A. Mey.) Beck	Parasite	Halophyte
43.60964	79.35471	Papaveraceae Juss.	*Glaucium fimbrilligerum* Boiss.	Herbaceous plant	Xerophyte
43.55436	79.30192	Papaveraceae Juss.	*Glaucium squamigerum* Kar. & Kir.	Herbaceous plant	Xerophyte
43.57253	79.29802	Papaveraceae Juss.	*Reaumuria songarica* (Pall.) Maxim.	Herbaceous plant	Xerophyte
43.51957	79.20371	Plumbaginaceae Juss.	*Limonium michelsonii* Lincz.	Herbaceous plant	Halophyte
43.54789	79.28761	Polygonaceae Juss.	*Rumex hydrolapathum* (Scop.) Huds.	Herbaceous plant	Hydrophytes
43.54932	79.29154	Ranunculaceae Juss.	*Clematis orientalis* L.	Liana	Mesophyte
43.54439	79.28124	Ranunculaceae Juss.	*Clematis songorica* Bunge	Bush	Xerophyte
43.55926	79.30682	Ranunculaceae Juss.	*Ranunculus sceleratus* L.	Herbaceous plant	Mesophyte
43.54878	79.2973	Rosaceae Juss.	*Malus domestica* (Suckow) Borkh.	Tree	Mesophyte
43.54658	79.2862	Rosaceae Juss.	*Rosa beggeriana* Schrenk	Tree	Mesophyte
43.54411	79.28855	Rosaceae Juss.	*Rosa iliensis* Chrshan.	Bush	Xerophyte
43.54275	79.2836	Rosaceae Juss.	*Rosa laxa* Retz.	Liana	Xerophyte
43.5493	79.29698	Rosaceae Juss.	*Rubus caesius* L.	Bush	Xerophyte
43.54392	79.27649	Salicaceae Mirb.	*Populus alba* L.	Tree	Mesophyte
43.5208	79.26252	Salicaceae Mirb.	*Populus euphratica* Olivier	Herbaceous plant	Xerophyte
43.54413	79.27652	Salicaceae Mirb.	*Populus nigra* L.	Bush	Xerophyte
43.54222	79.28436	Salicaceae Mirb.	*Populus talassica* Kom.	Bush	Xerophyte
43.54752	79.28897	Salicaceae Mirb.	*Salix purpurea* L.	Bush	Mesophyte
43.54396	79.28855	Sapindaceae Juss.	*Acer tataricum* subsp. *semenovii* (Regel & Herder) A.E.Murray	Bush	Halophyte
43.5428	79.28281	Solanaceae Juss.	*Lycium dasystemum* Pojark.	Bush	Mesophyte
43.55444	79.30214	Tamaricaceae Link.	*Myricaria bracteata* Royle	Tree	Mesophyte
43.57253	79.29802	Tamaricaceae Link.	*Nanophyton iliense* U.P.Pratov	Bush	Xerophyte
43.53473	79.41715	Tamaricaceae Link.	*Tamarix ramosissima* Ledeb.	Bush	Halophyte
43.54219	79.28432	Zygophyllaceae R.Br.	*Zygophyllum fabago* L.	Herbaceous plant	Mesophyte

Plants are evenly distributed throughout the area, with few clusters. This shows a high level of biodiversity across sites and no single species dominating a particular area. Various environmental conditions characterize the area, including arid, temperate, humid regions and saline soils. This creates a rich biodiversity in which xerophytic and mesophytic plants dominate according to the arid and semi-arid conditions of the area.

Results of physiological parameters (PP) of two large tree species

Fo (Minimum Fluorescence) is the fluorescence level measured in plants in the dark state (i.e., after dark adaptation, when all the main centers of photosystem II are open). It reflects the state of unabsorbed light by chlorophyll. Fv (Variable Fluorescence) is the difference between the maximum and minimum fluorescence (Fv = Fm – Fo). This value indicates a significant level of energy used in the photosynthetic process. Fm (Maximum Fluorescence) is the fluorescence level observed under saturated illumination (when the switched-on centers of photosystem II are entirely closed). This value is associated with plants' high photosynthetic capacity. Fv/Fm (Ratio of Variable to Maximum Fluorescence) indicates the efficiency of photosystem II (PSII). Usually, in healthy plants, this value varies from 0.75 to 0.85. Lower values may cause stress or damage to the photosynthetic apparatus. Fv/Fo: the ratio of variable fluorescence to a minimum; an indicator of the efficiency of PSII's photochemical activity; efficiency indicator of PSII photochemical activity. A lower Fv/Fo value can indicate stress in the plant. The mg m^{-2} (Chlorophyll content): the study is carried out in milligrams of chlorophyll per square meter of square leaf. This indicator reflects the pigment's density, which affects the photosynthesis efficiency. The data contains results for two tree species: *Fraxinus* and *Populus*. Table 3 presents values for the following parameters: Fo, Fv, Fm, Fv/m, Fv/o, and mg m^{-2}, as well as statistics such as mean (mean), standard deviation, minimum values (min), quartiles (25%, 50%, 75%) and maximum values (max).

Table 3. Physiological indices of photosynthetic activity in *Fraxinus* and *Populus* species.

Physiological indicators	**Fo**	**Fv**	**Fm**	**Fv/m**	**Fv/o**	**mg m^{-2}**	**Fo**	**Fv**	**Fm**	**Fv/m**	**Fv/o**	**mg m^{-2}**
Species	***Fraxinus***						***Populus***					
mean	168.8	636.9	805.8	0.78	3.78	384.7	149.2	625.3	774.5	0.79	4.25	440.1
std	11.4	97.7	98.8	0.02	0.61	38.261	21.4	154.8	156.5	0.06	1.03	77.4
min	156.0	520.0	682.0	0.735	2.78	306.0	118.0	299	479.0	0.624	1.661	332.0
25%	161.0	540.2	717.0	0.768	3.33	371.5	138.0	572.0	715.0	0.803	4.078	370.0
50%	163.5	611.0	789.0	0.786	3.694	395.0	143.0	647.0	785.0	0.821	4.601	446.0
75%	173.2	736.7	898.2	0.809	4.270	408.0	152.0	733.0	885.0	0.828	4.822	503.0
max	193.0	773.0	962.0	0.828	4.831	452.0	185.0	830.0	1015.0	0.834	5.029	535.0

The average values of the photosynthetic parameters (PP) Fo, Fv, and Fm are slightly higher for *Populus* than for *Fraxinus*. For example, the average Fo value is 149.22 for *Populus* and 168.83 for *Fraxinus*. However, the *Fraxinus* range of values is slightly smaller, indicating more stable results for this species. *Populus* shows a higher variability of the parameters (higher standard deviation values), indicating more pronounced individual differences between the measured plants than *Fraxinus*. The average values for the efficiency coefficients Fv/m and Fv/o are higher for *Populus* (0.79 and 4.25) than for *Fraxinus* (0.78 and 3.78). This may indicate that *Populus* has a slightly higher efficiency of energy use during photosynthetic processes. Table 3 shows that *Fraxinus* has a higher standard deviation for specific photosynthetic parameters, suggesting a more comprehensive range of values and variability among individual plants than *Populus*. For example, the standard deviation for *Fraxinus* in parameters such as Fv (97.7) and Fm (98.8) is relatively high compared to *Populus* (Fv: 154.8, Fm: 156.5). This indicates that while *Fraxinus* has generally stable average values, there is still considerable individual variation within the species. Thus, contrary to the initial interpretation, *Populus* appears to have slightly less variability in specific parameters, potentially indicating more consistent performance across the measured samples. This revised perspective suggests that while *Populus* may demonstrate a marginally higher average photosynthetic efficiency, *Fraxinus* exhibits broader variability, which could imply adaptation to a range of conditions or individual plant responses. The average chlorophyll mass per unit leaf area in *Populus* is 440.11 mg m^{-2}, significantly higher than that of Fraxinus, which is 384.78 mg m^{-2}. This may indicate that *Populus* leaves contain more chlorophyll, which may affect the photosynthesis rate. The scatter of chlorophyll mass values (standard deviation) is also higher in *Populus* than in *Fraxinus*, indicating a more comprehensive range of values in this species. *Populus* shows higher average values for most photosynthetic parameters, which may indicate a better adaptation of this species to the measurement conditions or its higher photosynthetic activity. On the other hand, *Fraxinus* shows more stable results and minor fluctuations in photosynthesis parameters among the studied samples.

UAV mapping results

A representative aerial mapping area of 275 hectares covers the characteristic landscapes typical of an ash grove in the Sharyn River's floodplain zone. The vegetation conditions, including the dominant tree species, *Fraxinus* and *Populus*, were studied using proven vegetative indices: NDVI, GNDVI, OSAVI, CIRE, GCI, MCARI, and CVI (Fig. 2)

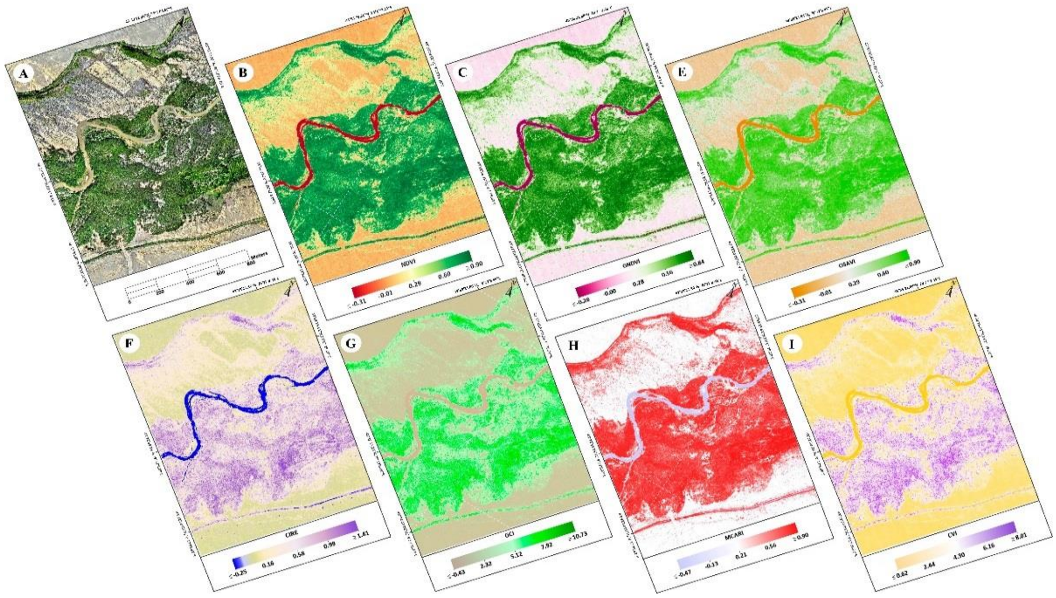

Fig. 2. VI calculation results of Charyn Ash Grove region; A. Ortho mosaic RGB; B. NDVI; C. GNDVI; E. OSAVI; F. CIRE; G. GCI; H. MCARI; I. CVI.

Each vegetation index we selected has advantages and disadvantages in the conditions of complex relief and vegetation cover of forest areas. The most popular index, NDVI, is well suited for a general assessment of vegetation density, especially over large areas, and its adaptability makes it a versatile tool. However, it can be influenced by soil background. In contrast, OSAVI is less affected by soil, enhancing its adaptability and making it a reliable alternative in various conditions (Kleinsmann *et al.* 2023). GNDVI, CIRE, and GCI provide a more accurate assessment of chlorophyll content and photosynthetic activity, which makes them useful for studying the health of forests with a high green mass (Saravia *et al.* 2022). CVI and MCARI provide high accuracy in assessing photosynthetic activity, especially in complex forest ecosystems (Kurbanov *et al.* 2021). The VI statistics for two dominant tree species (*Fraxinus* and *Populus*) show differences in favor of *Populus* in the mean values, while the maximum VI values are predominantly higher for *Fraxinus*. For instance, the average values of the studied vegetation indices, except for CIRE, were 30% higher in *Populus*, while the maximum values in this species were 14% lower than in *Fraxinus* (Table 4). The observed differences in VI values between the two species are probably due to their biological and morphological adaptations to the environment. *Populus* is more adapted to rapid growth and prefers low terraces by the increased moisture levels. At the same time, *F. sogdiana* can live on medium and high terraces, demonstrating high resistance to stress conditions.

Correlation of VI and PP

Pearson correlation analysis was used to assess the linear relationship between vegetation indices (VI) and physiological parameters (PP; Schober *et al.* 2018). Physiological parameters measured in the field and VI values calculated using UAV data show similar trends, which require further confirmation through correlation analysis. A strong positive correlation is observed within VI: NDVI - OSAVI (r = 0.95) and MCARI - OSAVI (r = 0.96) with a significance value of $p < 0.0001$. All VI have a positive relationship with each other, with an average value of r = 0.85 ($p = 0.005$). The correlation between PP values is different, if, between variable fluorescence (Fv) and maximum fluorescence (Fm), a high correlation is observed with a value of r = 0.99 ($p < 0.0001$). At the same time, the minimum fluorescence (Fo) shows an absolute negative correlation with PP: Fv/o (r = -0.46), Fv/m (r = -0.44), and chlorophyll content mg m^{-2} (r = -0.27) with a medium degree of significance (p = 0.08) (Fig. 3A).

Table 4. Vegetation indices values (min, max, and mean) of *Fraxinus* and *Populus* species.

VI	NDVI	GNDVI	OSAVI	CVI	MCARI	GCI	CIRE	NDVI	GNDVI	OSAVI	CVI	MCARI	GCI	CIRE
Species	***Fraxinus***							***Populus***						
Min	0.108	0.194	0.108	1.032	-0.125	0.480	-0.099	-0.041	0.006	-0.041	0.962	-0.280	0.012	-0.077
Max	0.955	0.931	0.955	21.61	0.952	26.76	3.343	0.947	0.920	0.947	16.92	0.955	22.96	2.561
Mean	0.731	0.683	0.731	4.562	0.738	4.754	0.778	0.822	0.738	0.822	4.584	0.854	6.171	0.731
Std	0.101	0.083	0.101	1.316	0.113	1.861	0.254	0.056	0.069	0.056	1.399	0.042	2.194	0.264

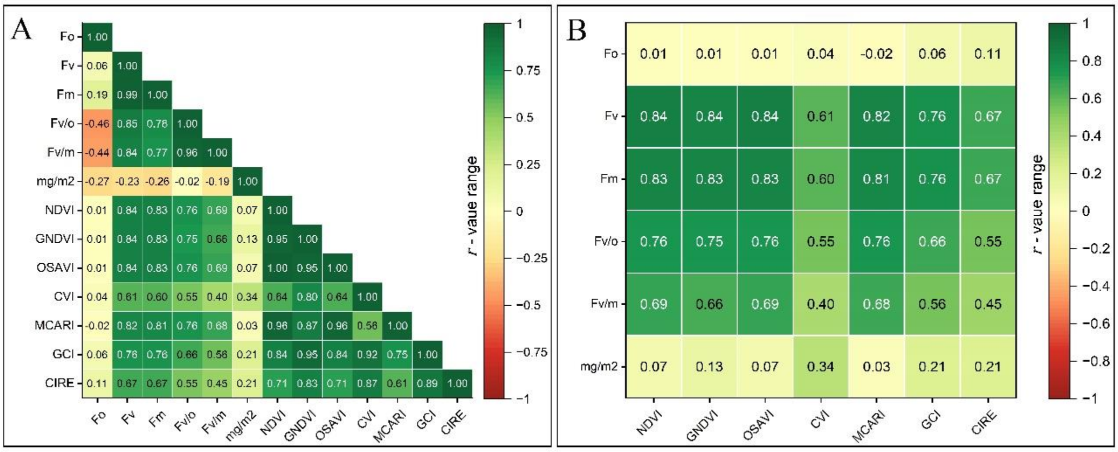

Fig. 3. Correlation matrix: A. for all 13 variables; B. between PP and VV. The value of the correlation coefficient *r* represents the direction and strength of the linear relationship between the input and output feature, which range from −1 to +1, and the corresponding color is from green to red).

The interdependence between individual PP and VI indices is of greater interest to our study. The obtained results of the correlation matrix show predominantly positive values, although Fo and chlorophyll content indices (mg m^{-2}) exhibit a negative or no relationship with the vegetative index. Fv and Fm show an excellent linear relationship with VI parameters: NDVI, GNDVI, OSAVI, and MCARI with an average value of r = 0.83 ($p < 0.0001$), while the correlation between the CVI, GCI, and CIRE indices was significant (r = 0.83; $p < 0.005$; Fig. 3B). Thus, the physiological parameters and vegetation indices demonstrate predominantly positive relationships, which makes them practical tools for monitoring plant health. However, the weak correlation of chlorophyll content (mg m^{-2}) with fluorescence parameters and vegetation indices underscores the need for additional parameters, highlighting the importance of further research for an accurate assessment of the physiological state of plants.

DISCUSSION

Research in other parts of Central Asia, such as Turkmenistan and Uzbekistan, also highlights the importance of conserving rainforests to maintain regional biodiversity. In these regions, forests provide genetic resources for various species adapted to extreme climatic conditions and play an essential role in stabilizing ecosystems. Our study supports this, which shows that *Fraxinus* forests support a wide range of flora and fauna, from rare plants to animals, making them essential for maintaining ecosystem connections. Fraxinus stress observed in *Fraxinus* is high anthropogenic pressure, including uncontrolled logging and grazing. These factors contribute to habitat degradation and a decrease in the genetic diversity of rare plant species. Continuation of these processes may lead to a further reduction in the area of the relict forest and the loss of many species adapted to the isolated conditions of the Charyn Canyon. This is also confirmed by studies in other regions where anthropogenic impacts lead to decreased biodiversity and degraded ecosystems (Orazov *et al.* 2022; Koblanova *et al.* 2024). A study of the biodiversity of *Fraxinus* forests in the Charyn Canyon showed significant differences in the state of populations against anthropogenic factors. Photosynthetic activity parameters indicate the stability of photosynthesis in *Fraxinus*, but the Fv/Fm coefficient variation from 0.735 to 0.828 indicates stress in individuals. For *Populus*, this indicator was higher, up to 0.834, which means better adaptation of this species to the environment.

These data are consistent with previous studies, where *Populus* also showed higher photosynthetic efficiency under stress conditions such as drought and anthropogenic impact. Charyn Canyon is a unique ecosystem with over 1,500 plant species, of which 17 are listed in the Red Book of Kazakhstan. This emphasizes the importance of preserving this region to maintain biodiversity. Our study confirms that the *Fraxinus* relict grove, which covers approximately 800 hectares of the 5,000-hectare area, is vital in maintaining ecosystem processes and species diversity, providing habitat for various other plants and animals. The study also found that 62 animal species, including rare species such as the bearded vulture and golden eagle, inhabit the area, demonstrating the close relationship between the region's plant and animal life (Cendrero-Mateo *et al.* 2016). Thus, the biological diversity of the Charyn Canyon, including its rare and endemic species, is under threat due to the destructive impact of human activities. Essential measures to protect relict forests, such as enhanced conservation and restoration of ecosystems, are needed to prevent the loss of this unique biodiversity. The introduction of sustainable natural resource management programs and improved monitoring of ecosystem conditions will contribute to the conservation of the *Fraxinus* forests and the entire biodiversity of the region. Thus, our results confirm the importance of preserving *F. sogdiana* forests as a critical element for maintaining ecosystem stability and biodiversity of the Charyn Canyon. These measures will also help protect critical genetic resources for future ecology, agriculture, and pharmaceutical research, making protecting these forests a priority for the region. The findings of this study provide a detailed insight into the physiological health and ecological status of the *Fraxinus* forests in the Charyn Canyon. The photosynthetic parameters measured, including minimum fluorescence (Fo), variable fluorescence (Fv), and maximum fluorescence (Fm), revealed notable differences between *Fraxinus* and *Populus* species in their ability to adapt to environmental stress.

The higher variability in the photosynthetic parameters of *Populus*, as indicated by the more significant standard deviation for Fv (154.8 for *Populus* vs 97.7 for *Fraxinus*), suggests that this species is more responsive to environmental changes. At the same time, *F. sogdiana* shows more stable but potentially less adaptable photosynthetic performance. The UAV-based vegetation mapping also provided valuable spatial data. NDVI (Normalized Difference Vegetation Index) values ranged from 0.108 to 0.955 for *Fraxinus*, with an average value of 0.731, indicating moderate vegetation density. For *Populus*, NDVI values ranged from -0.041 to 0.947, with an average value of 0.822, reflecting a generally healthier and denser canopy. This difference was consistent across other indices, such as GNDVI and OSAVI, where *Populus* consistently outperformed *Fraxinus*, with average values of 0.738 and 0.731, respectively, compared to 0.683 and 0.731 for *F. sogdiana*. The correlation analysis between vegetation indices and physiological parameters further supports the close relationship between photosynthetic efficiency and vegetation health. For instance, NDVI and OSAVI were strongly correlated with Fv and Fm, with correlation coefficients of 0.95 and 0.96, respectively ($p < 0.0001$). This high correlation highlights the potential of using UAV-based vegetation indices as reliable physiological health indicators, allowing for efficient large-scale monitoring of forest conditions (Torresan *et al.* 2017). The study's results also highlighted the significant anthropogenic threats facing the *Fraxinus* forests. Uncontrolled grazing and illegal logging have led to habitat degradation, contributing to the stress observed in *Fraxinus* populations. The absence of younger generative individuals in the population points to a lack of natural regeneration, which could have severe long-term consequences for the survival of this relict species. Environmental scientists, conservationists, and policymakers must intervene and prevent further forest degradation, thereby preserving its genetic diversity and ecosystem stability. Conservation efforts should focus on reducing human impact, mainly through regulating grazing and preventing illegal logging.

Additionally, restoration efforts, such as the reforestation of degraded areas and the protection of critical habitats, are essential for ensuring the long-term health of the *Fraxinus* forests. The data from UAV mapping and physiological assessments provide a strong foundation for developing targeted conservation strategies. In conclusion, the *Fraxinus* forests in the Charyn Canyon represent a crucial ecological and cultural resource but are under significant threat. The physiological and UAV-based data collected in this study reveal the extent of environmental stress on these forests and underscore the need for immediate conservation measures. Advanced technologies, such as UAV mapping and traditional physiological assessments, offer a comprehensive approach to monitoring and protecting this unique ecosystem. By integrating these methods, we can develop more effective strategies for preserving the biodiversity of the Charyn Canyon for future generations.

CONCLUSION

The *Fraxinus* forests of Charyn Canyon represent a vital component of Kazakhstan's biodiversity, crucial in maintaining regional ecological balance. This study has highlighted the significance of these relict forests for their environmental and historical value and their ability to support diverse plant and animal species, including endangered species. Physiological measurements carried out, such as Fo, Fv, Fm, and Fv/Fm, revealed that while the photosynthetic activity of *Fraxinus* is generally stable, some individuals are experiencing stress, with Fv/Fm ratios ranging from 0.735 to 0.828. In contrast, *Populus* species showed a higher Fv/Fm ratio of up to 0.834, indicating a better adaptation to environmental stress.

The UAV-based vegetation mapping further supported these findings, showing that *Populus* consistently exhibited higher vegetation indices, such as NDVI and GNDVI, than *Fraxinus*. These differences reflect the canopy's overall health and *Populus* resilience under the same environmental conditions. However, the unique role of *Fraxinus* as a relict species makes it irreplaceable in the region's ecosystem. The primary threats to these forests, including deforestation and uncontrolled grazing, are accelerating habitat degradation and reducing genetic diversity. The *Fraxinus*'s lack of natural regeneration severely threatens the species' long-term survival, particularly the absence of younger generative individuals. Immediate conservation actions are essential to preserving these ecosystems. Measures should include stricter grazing regulation, prevention of illegal logging, and active restoration efforts, such as reforestation and habitat rehabilitation. Moreover, continuous monitoring using advanced technologies, such as UAV mapping and physiological assessments, will allow for more effective management strategies. In conclusion, the *Fraxinus* forests of Charyn Canyon are ecologically and culturally significant and represent a critical resource for maintaining biodiversity in Central Asia. Preserving these forests is essential for protecting rare species and ensuring ecological stability for future generations. The findings from this study provide a strong foundation for developing targeted conservation strategies that will help safeguard these unique ecosystems.

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Abbreviations: CIRE – Chlorophyll Index Red Edge, used for precise chlorophyll measurement. CVI – Chlorophyll Vegetation Index estimates overall chlorophyll and photosynthetic activity. Fm – Maximum fluorescence is observed under saturated illumination when PSII is closed, indicating potential fluorescence output. Fo – Minimum fluorescence, measured in the dark-adapted state when PSII reaction centres are open, reflecting baseline fluorescence. Fv – Variable fluorescence, calculated as the difference between maximum (Fm) and minimum fluorescence (Fo), representing energy available for photosynthesis. Fv/Fm – Ratio of variable to maximum fluorescence, indicating PSII efficiency. Fv/Fo – Ratio of variable to minimum fluorescence, indicating PSII efficiency in converting light to chemical energy. GCI – Green Chlorophyll Index, estimates vegetation chlorophyll. GNDVI – Green Normalized Difference Vegetation Index, sensitive to chlorophyll content. Mg/m^2 – Milligrams of chlorophyll per square meter, indicating leaf chlorophyll concentration. MCARI – Modified Chlorophyll Absorption in Reflectance Index, assesses leaf chlorophyll in dense vegetation. NDVI – Normalized Difference Vegetation Index, calculated as (NIR - Red) / (NIR + Red), used to assess vegetation health. OSAVI – Optimized Soil Adjusted Vegetation Index, reduces soil influence in vegetation assessments. PSII – Photosystem II, a critical photosynthetic complex that absorbs light and drives electron transport. UAV – uncrewed aerial vehicle.

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