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THE FUTURE OF THE KAKHOVKA RESERVOIR AFTER ECOCIDE: AFFORESTATION AND ECOSYSTEM SERVICE RECOVERY THROUGH EMERGENT WILLOW AND POPLAR COMMUNITIES

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Background. The destruction of the Kakhovka Dam during Russia's invasion of Ukraine triggered one of the most severe environmental disasters in Eastern Europe in recent decades. The abrupt draining of the reservoir eliminated essential aquatic habitats, resulting in a collapse of aquatic biodiversity, significant disruption of hydrological cycles, and widespread contamination. The subsequent colonization of the exposed flats, predominantly by two tree species, fails to compensate for the lost diversity of the former aquatic ecosystem. While the abrupt drainage resulted in the degradation of aquatic habitats and posed long-term public health risks, the newly exposed terrestrial substrates have also facilitated spontaneous ecological succession. The most prominent colonisers of the dried-out bottom are hybrid willows (*Salix* × *rubens*) and black poplars (*Populus nigra*), which have rapidly formed dense pioneer stands. These emergent ecosystems now play a critical role in carbon sequestration, soil stabilisation, and microclimate regulation. Understanding the dynamics and ecosystem services of these formations is essential for developing sustainable restoration strategies for the post-war landscape.

Materials and Methods. Field surveys were conducted in April 2025 on the exposed bed of the former Kakhovka Reservoir, near Khortytsia Island. A total of 158 plots were evaluated in terms of tree presence, morphometric parameters, and environmental conditions. The height and diameter of *Salix* × *rubens* and *Populus nigra* trees were measured, and their biomass was estimated using geometric models. Soil pH, temperature, moisture and electrical conductivity were recorded at each plot. Ecological niche parameters were calculated using generalised additive models (GAMs). The carbon sequestration potential was estimated based on total biomass and converted into a monetary value using EU ETS carbon pricing.

Results and Discussion. *Salix* × *rubens* and *Populus nigra* exhibited high colonization rates on the exposed reservoir bed, establishing pioneer stands that exhibited distinct spatial patterns. *Salix* × *rubens* dominated moist, concave microsites, whereas *Populus nigra* was found on elevated, drier areas. Analysis of generalized additive models indicated that stands of *Salix* × *rubens* develop on soils with moderately acidic to near-neutral pH (optimum ≈ 7.25; tolerance range 6.43–8.03), elevated moisture (optimum ≈ 10.42 %), warmer temperatures (optimum ≈ 17.82 °C), and moderate electrical conductivity (optimum ≈ 0.38 dS m^{-1}), whereas *Populus nigra* exhibits broader ecological plasticity: pH optimum ≈ 7.12 (tolerance 3.83–7.67), lower moisture (≈ 5.98 %), cooler conditions (≈ 12.80 °C), and low electrical conductivity (≈ 0.03 dS m^{-1}). The species exhibited significant differences in ecological tolerance and biomass accumulation. Allometric models revealed distinct growth strategies, with *P. nigra* developing thicker stems. The maximum carbon sequestration potential was observed at intermediate stand densities, with *P. nigra* providing a greater economic value per hectare. These findings emphasise the ecological significance of spontaneous afforestation and advocate for nature-based restoration methods over the technical reconstruction of reservoirs.

Conclusion. The spontaneous afforestation of the former Kakhovka Reservoir bottom by *Salix* × *rubens* and *Populus nigra* demonstrates the strong regenerative capacity of floodplain ecosystems. These pioneer stands provide essential ecosystem services, including carbon sequestration, soil stabilization, and habitat provision. Species-specific ecological preferences and growth patterns determine their spatial distribution and carbon offset potential. The estimated economic value of early-stage carbon capture is considerable, particularly for *P. nigra*. These findings support the conservation of emergent willow-poplar communities and emphasize the importance of integrating nature-based solutions into post-war landscape planning instead of pursuing technical restoration of the destroyed reservoir infrastructure.

Keywords: Kakhovka Reservoir, ecocide, willow-poplar forests, *Salix* × *rubens*, *Populus nigra*, spontaneous succession, carbon sequestration, ecosystem services, floodplain restoration

INTRODUCTION

Russia's war against Ukraine has resulted in significant environmental and public health consequences (Leal Filho, *et al*., 2024a; Leal Filho, *et al*., 2024b). As of the end of 2024, total environmental damages were estimated to exceed $56.4 billion, encompassing chemical contamination of air, water, and soil, as well as the mining of 30 % of Ukraine's territory. Approximately 30 % of protected areas have been impacted by shelling, wildfires, deforestation, and other forms of degradation. The occupation of the Zaporizhzhia Nuclear Power Plant and the destruction of the Kakhovka Dam have created risks of long-term environmental disasters that threaten human health (Hryhorczuk *et al*., 2024). Russia's military aggression has also caused extensive damage to water infrastructure and river systems, including targeted attacks on dams, reservoirs, and wastewater treatment facilities. These actions have resulted in massive floods, water contamination, disruption of water supply, and degradation of ecosystems, adversely affecting both human health and the environment (Gleick *et al*., 2023). The destruction of the Kakhovka Dam resulted in a significant ecological disaster, including the release of over 90,000 tons of toxic sediments from the reservoir's bottom and the collapse of aquatic and riparian ecosystems. Optical satellite imagery captured extensive flooding along the Dnipro River following the dam breach, inundating settlements such as Oleshky, Kardashynka, and Hola Prystan (Xu *et al*., 2024). The sudden release of a massive volume of water led to ecosystem degradation, biodiversity loss, water pollution, disruption of access to drinking water, infrastructure damage, and the forced displacement of populations (Chen *et al*., 2024). Although this release was momentary, its consequences will have long-lasting effects.

The contamination had a detrimental effect on the Dnipro River, the Black Sea, and the adjacent floodplain ecosystems, resulting in harm to biodiversity, particularly to fish and bird populations. Furthermore, the contamination created long-term risks to public health and environmental safety (Shumilova *et al*., 2025). The environmental disaster has had a profoundly negative impact on the biodiversity of marine, estuarine, and freshwater ecosystems in the northern Black Sea region. The release of 19.9 billion cubic meters of freshwater, along with associated pollutants, inundated more than 100,000 hectares of land, leading to the destruction of numerous populations and habitats. Although certain species and ecosystems have exhibited indications of recovery, pervasive issues pertaining to habitat degradation, disruption, and pollution persist, thereby underscoring the necessity for long-term monitoring and restoration initiatives (Kvach *et al*., 2025). The abrupt draining of the Kakhovka Reservoir has exposed substantial areas of the reservoir's former bed, leading to soil erosion, the loss of fertile topsoil, and alterations to the regional hydrological regime. These processes have had a detrimental effect on agricultural land, resulting in diminished productivity and long-term ecological consequences for the region (Novakovska *et al*., 2025). The desiccation of the reservoir has also led to an increase in average air temperature by 2 °C or more, and a rise in evapotranspiration rates by 1.41–2.04. There has been an intensification of water deficits across 58.2 % of the dried basin and adjacent surrounding areas. It is estimated that a substantial portion of the area is currently experiencing stressful natural climatic conditions (Pichura *et al.*, 2024a; Pichura *et al.*, 2024b).

The environmental consequences include the destruction of natural habitats, loss of flora and fauna, disruption of the hydrological regime, and contamination of water resources. Water habitats were adversely affected by a sudden decline in water levels, while terrestrial habitats suffered due to the shockwave generated by the dam's collapse and the subsequent substantial alteration of the hydrological regime in the areas surrounding the Dnipro River. Some of these effects are expected to persist for over a decade, allowing this event to be classified as an act of ecocide (Chernogor *et al*., 2024). The disaster caused significant human casualties, economic losses, and environmental damage, including the destruction of irrigation systems that previously supported agricultural productivity worth approximately $1.5 billion (Yang *et al*., 2024). A substantial deterioration in the sanitary, chemical, and microbiological quality of water was observed (Trokhymenko *et al*., 2023). The risk zone is characterised by the presence of four chemical plants, of which one has been flooded and three remain vulnerable. These facilities have the potential to emit hazardous substances, which, when considered in conjunction with flooding and ongoing military operations, generate multifaceted risks to the environment and public health. The total number of individuals exposed to potential contamination of water and soil has exceeded 42,000, resulting in significant consequences for both human well-being and ecological integrity. The authors posit that such an occurrence constitutes ecocide, defined as the deliberate destruction of the natural environment in a manner that endangers life (Gan *et al*., 2024). The United Nations (UN) estimates that 700,000 people were deprived of access to potable water (Sanina & Lyuta, 2023). An environmental disaster of this scale has broad legal consequences and is often considered ecocide (Babin *et al*., 2023; Malysheva & Hurova, 2024; Gavrysh, 2024). In June 2021, the expert group Stop Ecocide International presented a draft amendment to the Rome Statute of the International Criminal Court that would officially recognise ecocide as the fifth international crime, alongside genocide and war crimes (Branch & Minkova, 2023). "The Independent Expert Panel convened by Stop Ecocide International" defines ecocide as "unlawful or wanton acts committed with knowledge that there is a substantial likelihood of severe and either widespread or long-term damage to the environment being caused by those acts" (Independent Expert Panel for the Legal Definition of Ecocide, 2021). The dam's destruction constitutes a violation of international treaties, such as the Convention on the Protection of the Environment during Armed Conflict. Those responsible for this act should be held accountable through international judicial institutions (Malysheva & Hurova, 2024). The deliberate destruction of critical water infrastructure, which resulted in severe ecological and humanitarian consequences, may be regarded as a breach of international humanitarian law. This opens avenues for prosecution through the International Criminal Court (Maruf, 2024).

One of the most notable phenomena following the disaster was the rapid overgrowth of the exposed reservoir bed, predominantly by willows (*Salix* sp.). Within one year after the catastrophe, willows in areas with rich organic deposits exceeded 4 meters in height, while those in sandy soils were considerably smaller (Vyshnevskyi & Shevchuk, 2024a). This observation indicates the high viability of willow seeds and their capacity to rapidly colonize newly available habitats. As noted by V. Pichura *et al*. (2024), these new plantations are unable to restore the pre-dam microclimatic conditions that existed prior to the destruction of the Kakhovka Dam, since the buffering effects of a large water body cannot be replicated by early-successional woody stands. The risk of forest fires in the region has increased, driven by both climate change and an ongoing military activity (Pichura *et al.*, 2024a). The formation of new river channels and lakes has also been observed, alongside the partial restoration of the natural hydrological regime, which now depends in part on the water discharges from the upstream Dnipro Hydropower Station. During periods of high discharge, significant portions of the former reservoir area become inundated once again (Vyshnevskyi & Shevchuk, 2024a). In the immediate aftermath of the disaster, intense water mixing occurred, resulting in a significant decrease in surface water temperatures at the Dnipro estuary. Subsequently, water temperatures in the lower Dnipro approached values typical of the pre-dam period. Following the collapse of the Kakhovka Dam, the thermal regime of the lower Dnipro and the area of the former reservoir has shifted toward natural conditions resembling those that existed prior to the construction of the reservoir (Vyshnevskyi & Shevchuk, 2024b). The preliminary findings of vegetation surveys conducted in the aftermath of the June 6, 2023 disaster indicate an exceptionally rapid formation of ecosystems on the former reservoir bed. By the end of the initial growing season, approximately 30 % of the former aquatic area had been colonized by vegetation, predominantly consisting of willow and poplar stands. The most active colonizer of open substrates was the hybrid *Salix* × *rubens* (Didukh *et al*., 2024), where the overwhelming majority of willow individuals were shown to belong to this hybrid rather than to *S. alba* or *S. fragilis*, which exhibited mean growth rates of up to 2.3 cm per day and formed dense, vertically stratified tree stands. A total of 87 plant species were documented in the recently established phytocoenoses, comprising 79 vascular plants, 6 algae, and 2 bryophytes. Among these species was one listed in the Red Data Book of Ukraine (*Carex secalina*), highlighting the area's significant conservation value (Didukh *et al*., 2024).

Ecosystem services encompass a range of material and non-material benefits that people derive directly or indirectly from natural ecosystems (Mengist *et al*., 2020). These services include the production of food and fodder, climate regulation, water purification, and support for biodiversity (Mezeli *et al*., 2020). Assessing these services is crucial for developing effective environmental policies, as it enables the quantitative comparison of the benefits derived from conservation versus economic activities, optimizes the use of natural resources, and aids in planning adaptive measures in response to environmental changes (Keenan *et al*., 2019). Carbon sequestration falls under the category of regulating services, as the fixation and storage of organic carbon by soils and vegetation play a crucial role in mitigating climate variability and maintaining global climate stability (Yin *et al*., 2023). Evaluating the consequences of the destruction of the Kakhovka Reservoir through the lens of ecosystem services is particularly relevant; it enables a quantitative assessment of losses in provisioning services (such as water resources and fish populations), regulating functions (including carbon sequestration, water purification, and flood modulation), supporting processes (like biogeochemical cycles and soil-forming mechanisms), and cultural values (encompassing recreational, educational, and cultural-historical aspects) (Husain *et al*., 2024). This comprehensive approach will aid in the development of effective restoration and adaptation strategies for the affected landscapes, as well as the establishment of long-term policies aimed at countering the impacts of this act of ecocide.

The aim of this study is to identify patterns in the formation of pioneer willow and poplar stands at the bottom of the former Kakhovka Reservoir following its drainage, focusing specifically on the roles of *Salix* × *rubens* and *Populus nigra* in succession processes, their ecological tolerance, and their potential ecosystem services. To achieve this objective, the study will test the following hypotheses:

1. The establishment of primary tree vegetation on the drained reservoir bottom is uneven and influenced by local geomorphological and soil conditions, with *Salix* × *rubens* predominating in moist concave areas and *Populus nigra* thriving on elevated terrains.
2. The morphometric parameters of trees (height and trunk diameter) in newly formed stands exhibit species-specific allometric relationships that can be described by nonlinear models.
3. The ecological preferences and tolerances of *Salix* × *rubens* and *Populus nigra* to soil factors (pH, electrical conductivity, temperature, and moisture) are statistically significant and differentiated, which influences their spatial distribution.
4. Young stands that develop as a result of natural succession are capable of providing substantial carbon sequestration at an early stage, and the economic value of this service is considerable.
5. The developed willow-poplar phytocenoses possess ecological and conservation value, which supports the need to reconsider management decisions regarding the restoration of the reservoir in favour of preserving and maintaining these new ecosystems.

MATERIALS AND METHODS

Field surveys were conducted in early April 2025 in the southern part of Khortytsia Island (Zaporizhzhia Oblast, Ukraine), an area predominantly characterized by floodplain ecosystems. The study focused on newly exposed land surfaces resulting from the catastrophic drainage of the Kakhovka Reservoir, where the water level had dropped by approximately 5 meters. These emergent areas exhibited varied vegetation cover, ranging from unvegetated zones to sites colonized by young willow (*Salix* × *rubens* Schrank) and poplar (*Populus nigra* L.) stands. A total of 158 sampling points were systematically established across this landscape, and their exact coordinates were determined using GPS (Garmin eTrex, ± 5 m) (**Fig. 1**). Sampling points were selected to represent the complete range of floodplain substrates on Khortytsia Island, including organic-rich alluvial soils, silty loams, and sandy bars. The sites included both those with and without willow and poplar stands. This approach facilitated a comprehensive evaluation of each species' ecological tolerance across varying soil conditions.

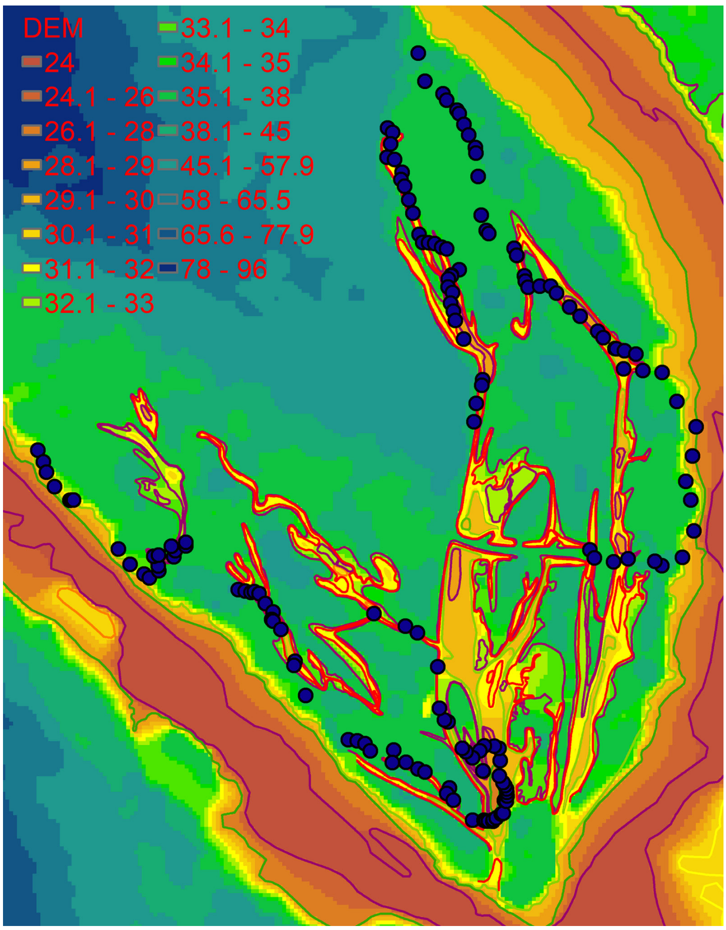

Fig. 1. Locations of sampling points in the area affected by the catastrophic water level decline following the destruction of the Kakhovka Reservoir. The color palette shows the Digital Elevation Model (DEM). The sites include areas without tree cover, as well as areas colonized by young willow (*Salix* × *rubens* Schrank) and poplar (*Populus nigra* L.)

Salix × *rubens* Schrank (*S. fragilis* × *S. alba*) is a widespread hybrid willow that is commonly found in disturbed floodplain habitats across Europe. Following the drainage of the Kakhovka Reservoir, *S.* × *rubens* emerged as the dominant pioneer species on the exposed bottom. At the beginning of the growing season, before leaf emergence and the development of other taxonomically informative traits, morphological differentiation between *Salix* × *rubens* and *S. alba* is not possible (De Cock *et al*., 2003). Therefore, we relied on the findings of Didukh *et al*. (2024), who classified these stands in analogous biotopes as *S.* × *rubens*, while acknowledging a possible minor admixture of pure *S. alba*.

At each point, we recorded the presence or absence of woody vegetation, categorizing sites into three groups: without woody vegetation (n = 84), colonized by young willow (n = 44), and colonized by young poplar (n = 53). In addition to vegetation assessments, we measured key environmental variables at each location, including soil pH, electrical conductivity (EC), soil moisture content, and soil temperature. These measurements were obtained using standardized field protocols and calibrated instruments to ensure data accuracy and consistency. The apparent electrical conductivity (EC) of the soil was measured in situ using a HI 76305 sensor (Hanna Instruments, Woonsocket, RI, USA) connected to the portable device HI 993310. Measurements were taken at a depth of 0–5 cm and repeated three times at each sampling point. The soil moisture content was measured using an MG–44 soil moisture meter (Ukraine), with readings taken at a depth of 5–7 cm. This device has a measurement resolution of 0.1 % and an associated error margin of 1 %. Soil pH and temperature were measured in situ using a YY-1033 soil pH meter, which allows simultaneous recording of pH and temperature values directly in the field. Tree surveys were conducted within square plots measuring 1×1 m. All woody plants rooted within the plot boundaries were recorded. For five randomly selected individuals per plot, we measured the stem diameter at collar height (in millimeters) and the total stem height (in meters). Stem diameter was measured using a digital caliper (MICROTECH), while tree height was measured with a measuring tape.

These floodplain plots predominantly consist of one to two species, with occasional herbaceous individuals whose combined biomass is negligible at this successional stage. Consequently, all phytomass and ecosystem service calculations are based exclusively on *Salix* × *rubens* and *Populus nigra*.

To estimate the stem biomass (dry matter) of young willow (*Salix* × *rubens*) and poplar (*Populus nigra*) trees, we applied a geometric model that assumes a cylindrical stem shape. This approach is appropriate for early growth stages when the stem has not yet developed pronounced tapering. Stem biomass was calculated according to the following equation (Khodakarami *et al*., 2022):

$$\text{Stem biomass (kg)} = \pi \cdot (D / 2000)^2 \cdot H \cdot WD \cdot K_c \cdot 1000,$$

where: D is the stem diameter at the collar height (in millimeters), H is the stem height (in meters), WD is the wood density (g/cm³), K_c – form factor (dimensionless), accounting for deviation from a perfect cylinder, 1000 is the conversion factor from grams to kilograms. Species-specific constants used in this study were: for *Salix* sp.: WD = 0.34 g/cm³, K_c = 0.55; for *Populus* sp.: WD = 0.42 g/cm³, K_c = 0.50. The formula converts diameter from millimeters to meters, calculates the cylindrical volume, and adjusts for wood density and stem shape. To estimate the total biomass of young trees, we assumed that the stem, crown (branches and leaves), and roots represent fixed proportions of the total biomass. According to the biomass component distribution, the stem accounts for 56 %, the crown for 24 %, and the root system for 20 % of the total tree biomass (Ximenes *et al.*, 2008). Based on this assumption, total biomass was calculated as:

$$\text{Total biomass (kg)} = \text{Trunk biomass} / 0.56.$$

This approach enables estimation of the whole-tree biomass using only trunk biomass data obtained through geometric modeling or direct measurement. The method is particularly useful in early growth stages when the tree morphology is simple and destructive sampling is limited.

The following procedure outlines the calculation of the economic value of carbon sequestration as an ecosystem service, based on Total biomass (kg per m^2, dry matter). Carbon price is the market value of one tonne of CO_2. As of May 2025, the carbon emission price within the European Union Emissions Trading System (EU ETS) ranges from €64 to €75 per tonne of CO_2. For the purposes of this study, a reference value of €70 per tonne of CO_2 was adopted to estimate the carbon content in biomass:

$$C = \text{Total biomass} \cdot 0.47,$$

where 0.47 is the average carbon content in dry wood biomass (Eggleston *et al.*, 2006).

Convert Carbon to CO_2-equivalent using molecular weight ratio: 44/12 = 3.667:

$$CO_2 = C \cdot 3.667.$$

Calculate the monetary value of sequestered CO_2:

$$\text{Value (€)} = CO_2 \cdot (\text{Carbon price per tonne} / 1000)$$

Alternatively, the complete formula is:

$$\text{Value (€/m}^2\text{)} = \text{Total biomass (kg per m}^2\text{, dry matter)} \cdot 0.47 \cdot 3.667 \cdot (\text{Carbon price} / 1000),$$

or

$$\text{Value (€/ha)} = 17.24 \cdot \text{Total biomass (kg per m}^2\text{, dry matter)} \cdot \text{Carbon price}.$$

To assess species responses along environmental gradients, we applied a generalized additive model (GAM) approach using the *mgcv* package in R (Wood, 2011). Species abundance data for *Salix × rubens* and *Populus nigra* were modeled separately against each environmental variable using GAMs with a Poisson error distribution and a penalized spline smoother (s(x, k = 5)), with smoothing parameter estimation via restricted maximum likelihood (REML). A gamma value of 2.0 was applied to reduce overfitting. To estimate ecological niche parameters, fitted response curves were used to identify three descriptors: (1) Optimum is the environmental value at which the predicted abundance was maximal; (2) Tolerance range is the environmental interval where predicted abundance was ≥50 % of the maximum; and (3) Tolerance width is the length of this interval (van der Veen *et al.*, 2021). For each GAM model, predictions were made across 200 evenly spaced values of the environmental variable. The optimum was determined as the x-value corresponding to the maximum predicted abundance. The tolerance range was identified by extracting the minimum and maximum x-values for which predicted abundance exceeded 50 % of the maximum. These niche descriptors were calculated for each species across all considered gradients: soil pH, electrical conductivity, soil water content, and soil temperature. All analyses were performed in R 4.x (R Core Team, 2023). Visualizations were generated using base R plotting functions.

RESULTS

The locations with the presence of *Salix × rubens* accounted for 27.8 % of all surveyed plots, while *Populus nigra* was present in 33.5 % of the plots. In 29.1 % of cases, both tree species co-occurred at the same locations. The co-occurrence of *Salix* and *Populus* individuals was significantly non-random ($\chi^2 = 10.22$, $df = 1$, $P = 0.0014$). These species co-occurred less frequently than expected under the assumption of independence, suggesting a negative association between their presence at the same sites. When co-occurring, the population densities of the two tree species exhibited a negative correlation ($r = -0.42$, $P = 0.04$). The proportion of the surveyed plots occupied by trees (i.e., with the presence of either *Salix × rubens* or *Populus nigra*) did not deviate significantly from a random expectation. A chi-square goodness-of-fit test comparing the observed number of occupied (74) and unoccupied (84) plots with an expected 1:1 ratio yielded $\chi^2 = 0.63$, $P = 0.426$. This indicates that the distribution of trees among plots did not differ from a random allocation, suggesting no overall preference or avoidance of colonization at the landscape scale.

The population characteristics of *Salix × rubens* and *Populus nigra* in the overgrown areas formed after the destruction of the Kakhovka Reservoir reveal notable differences in density and stem dimensions (**Table 1**). *Salix × rubens* exhibited a higher mean density (23.6±3.1 individuals·m^{-2}) compared to *Populus nigra* (12.2±1.1 individuals·m^{-2}). Welch's *t*-test ($t = 3.47$, $P = 0.0010$) indicates a statistically significant and non-random difference in colonization success between the two species. Mean tree height was similar between species, ranging from 1.9±0.1 m in *Populus nigra* to 2.0±0.1 m in *Salix × rubens*, and the difference was not statistically significant according to Welch's *t*-test ($t = 0.71$, $P = 0.481$). Stem diameter at collar height showed slightly higher values in *Populus nigra* (8.7±0.5 mm) than in *Salix × rubens* (7.9±0.6 mm), but the difference was not statistically significant (Welch's *t*-test: $t = -1.02$, $P = 0.308$). Minimum and maximum values indicate substantial variation in local conditions influencing early-stage establishment.

Table 1. **Descriptive statistics of population density, stem height, and stem diameter of *Salix × rubens* and *Populus nigra* at sites within the overgrown areas formed after the destruction of the reservoir**

Variable	Valid N	Mean±st. error	Minimum	Maximum
Salix × rubens				
Tree density, individuals·m^{-2}	44	23.6±3.1	1	85
Tree height, m	44	2.0±0.1	0.1	3.7
Tree diameter at collar height, mm	44	7.9±0.6	0.8	17.8
Populus nigra				
Tree density, individuals·m^{-2}	53	12.2±1.1	1	30
Tree height, m	53	1.9±0.1	0.2	3.7
Tree diameter at collar height, mm	53	8.7±0.5	1.7	16.0

A Gaussian mixture of three distributions provided a statistically significant fit to the distribution of *Salix × rubens* tree density (Kolmogorov–Smirnov test: D = 0.08, $P = 0.94$) (**Fig. 2**). The first component of the mixture accounted for 48.5 % of the total

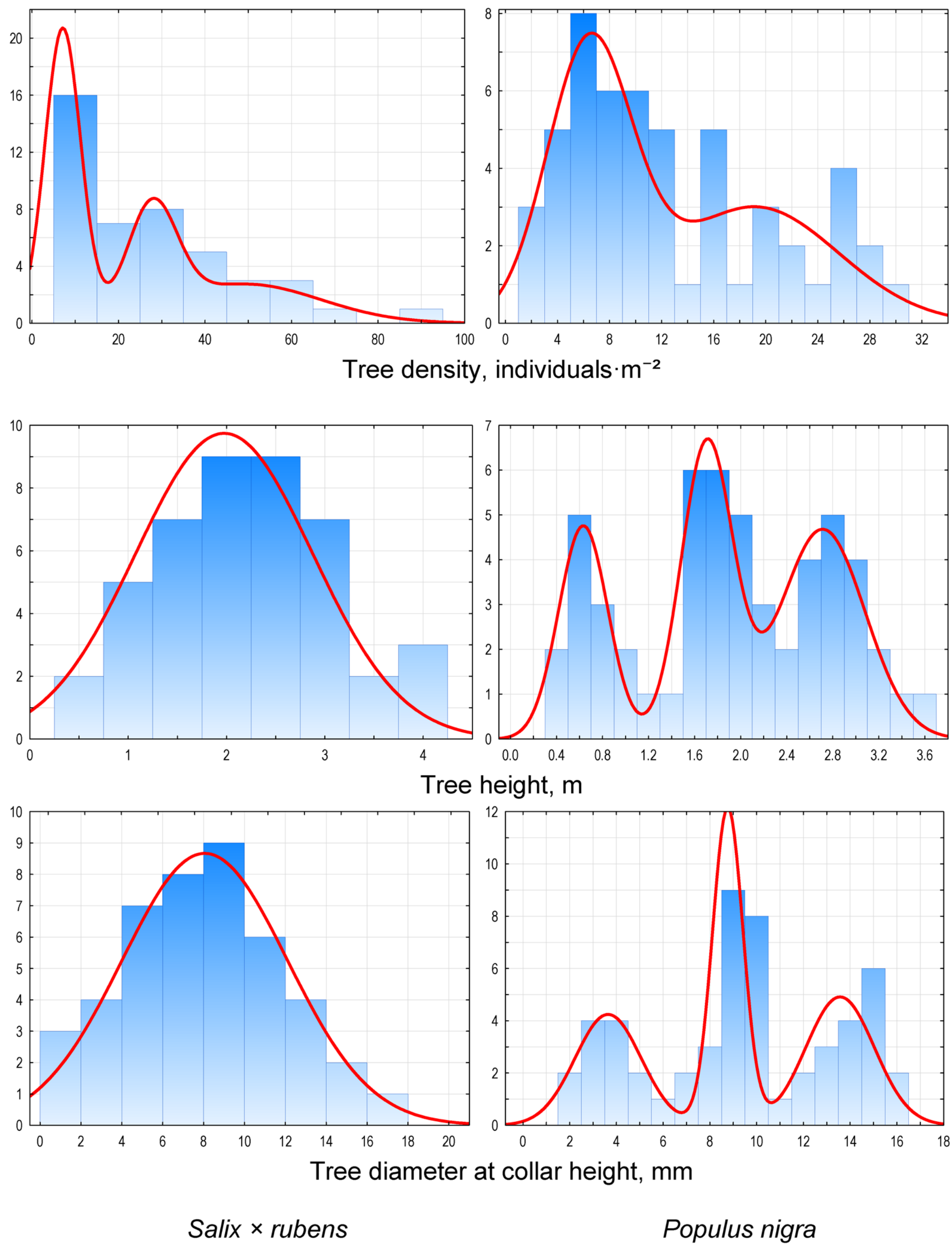

Fig. 2. Histograms of the distribution of population density, stem height, and stem diameter of *Salix × rubens* and *Populus nigra*. On the x-axis, values of the measured morphometric traits are plotted (with specific trait names and units indicated beneath each panel), and on the y-axis, the frequency (number of individuals) is shown

with a mean of 7.1±4.1 individuals·m^{-2}, the second component represented 24.2 % with a mean of 27.8±5.7 individuals·m^{-2}, and the third component comprised 27.3 % with a mean of 49.3±17.4 individuals·m^{-2}. A Gaussian mixture of two distributions provided a statistically significant fit to the distribution of *Populus nigra* tree density (Kolmogorov–Smirnov test: D = 0.10, *P* = 0.66). The first component of the mixture accounted for 54.3% of the total with a mean of 6.4±3.3 individuals·m^{-2}, and the second component represented 45.7% with a mean of 19.2±6.4 individuals·m^{-2}. The distributions of *Salix × rubens* heights and diameters can be statistically reliably described by a normal law (Kolmogorov–Smirnov test: D = 0.06, P = 0.99 and D = 0.10, P = 0.74, respectively). A Gaussian mixture of three distributions provided a statistically significant fit to the distribution of *Populus nigra* heights (Kolmogorov–Smirnov test: D = 0.06, *P* = 0.98). The first component of the mixture accounted for 22.8 % of the total with a mean of 0.7±0.2 m, the second component represented 35.0 % with a mean of 1.7±0.2 m, and the third component comprised 42.1 % with a mean of 2.7±0.4 m. A Gaussian mixture of three distributions provided a statistically significant fit to the distribution of *Populus nigra* stem diameter (Kolmogorov–Smirnov test: D = 0.05, *P* = 0.99). The first component of the mixture accounted for 27.0 % of the total with a mean of 3.7±1.3 mm, the second component represented 38.2 % with a mean of 8.8±0.7 m, and the third component comprised 34.8 % with a mean of 13.6±1.5 m.

The relationship between stem diameter at collar height and tree height was strongly linear for both *Salix × rubens* and *Populus nigra* (**Fig. 3**). In both cases, Pearson's correlation coefficient was *r* = 0.99 (*P* <0.001), indicating an almost perfect positive correlation between the two variables. The regression equations suggest a slightly steeper height increase per unit stem diameter in *Salix × rubens* ($Y = 0.24 \cdot X$) compared to *Populus nigra* ($Y = 0.21 \cdot X$), although both relationships reflect consistent allometric patterns during early growth stages. The difference in the slope of the relationship between stem diameter and tree height between *Salix × rubens* and *Populus nigra* was statistically significant (interaction term: β = -0.031, *t* = -6.90, *P* <0.001), indicating distinct allometric scaling between the species. The significantly lower slope observed in *Populus nigra* (compared to *Salix × rubens*) suggests a more robust stem development relative to height, which may reflect a more pyramidal growth form in young poplar individuals.

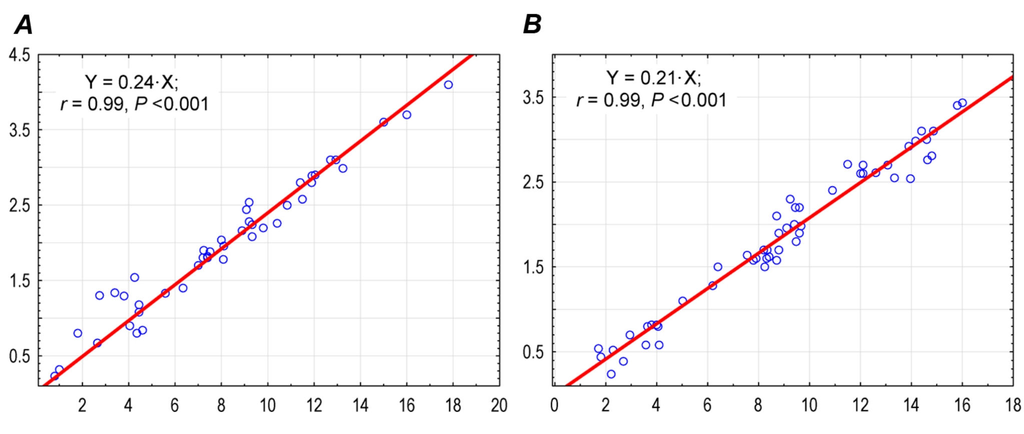

Fig. 3. Relationship between stem diameter and tree height in *Salix × rubens* (***A***) and *Populus nigra* (***B***). The x-axis represents tree diameter at collar height (mm), and the y-axis represents tree height (m)

The surveyed plots exhibited a considerable variation in environmental conditions (**Table 2**). Soil pH ranged from 2.98 to 9.20, with a mean value of 6.44±0.10, indicating a broad gradient from acidic to alkaline soils. Electrical conductivity (EC) varied between 0.01 and 2.20 dS/m, with a mean of 0.32±0.04 dS/m, reflecting predominantly low salinity levels. Soil water content ranged from 0.40 % to 16.74 %, with an average of 8.96±0.34 %, while soil temperature showed a narrower range, from 9.82 °C to 20.92 °C, and a mean of 14.52±0.18 °C. These gradients provided a heterogeneous microenvironment for assessing species-specific responses.

Table 2. **Descriptive statistics of environmental variables (N = 158)**

Variable	Mean±st.error	Minimum	Maximum
pH	6.44±0.10	2.98	9.20
EC, dSm/m	0.32±0.04	0.01	2.20
Soil water content, %	8.96±0.34	0.40	16.74
Soil temperature, °C	14.52±0.18	9.82	20.92

The response curves fitted using generalized additive models (GAMs) revealed species-specific preferences and tolerances along environmental gradients (**Fig. 4**). *Salix* × *rubens* showed clear unimodal responses with distinct optima for all tested gradients, particularly soil temperature and water content. *Populus nigra* exhibited broader and more variable response shapes, especially under alkaline conditions and in drier soils, suggesting wider ecological plasticity under certain conditions.

Table 3. **Response model parameters for *Salix* × *rubens* and *Populus nigra* along gradients of soil reaction, electrical conductivity, soil water content, and soil temperature**

Species	Gradient	Optimum	Tolerance limits (range)		Tolerance width
			Low	High	
Salix × *rubens*	pH	7.25	6.43	8.03	1.60
Populus nigra		7.12	3.83	7.67	3.84
Salix × *rubens*	EC, dSm/m	0.38	0.01	0.93	0.92
Populus nigra		0.03	0.01	1.07	1.06
Salix × *rubens*	Soil water content, %	10.42	7.63	13.29	5.67
Populus nigra		5.98	3.19	10.26	7.06
Salix × *rubens*	Soil temperature, °C	17.82	12.65	18.68	6.03
Populus nigra		12.80	10.42	17.61	7.19

The corresponding niche parameters (**Table 3)** quantify the modeled optima and tolerance ranges for each species. For example, *Salix* × *rubens* showed a narrower tolerance to pH (6.43–8.03) and soil temperature (12.65–18.68 °C), while *Populus nigra* displayed broader tolerance ranges for both variables. Tolerance widths for soil water content were comparable, though *Populus nigra* tended to occur in slightly drier conditions (optimum: 5.98 %) than *Salix* × *rubens* (optimum: 10.42 %). These differences suggest distinct ecological strategies, with *Salix* × *rubens* favoring more mesic and thermally stable microsites, while *Populus nigra* displays greater resilience across more heterogeneous conditions.

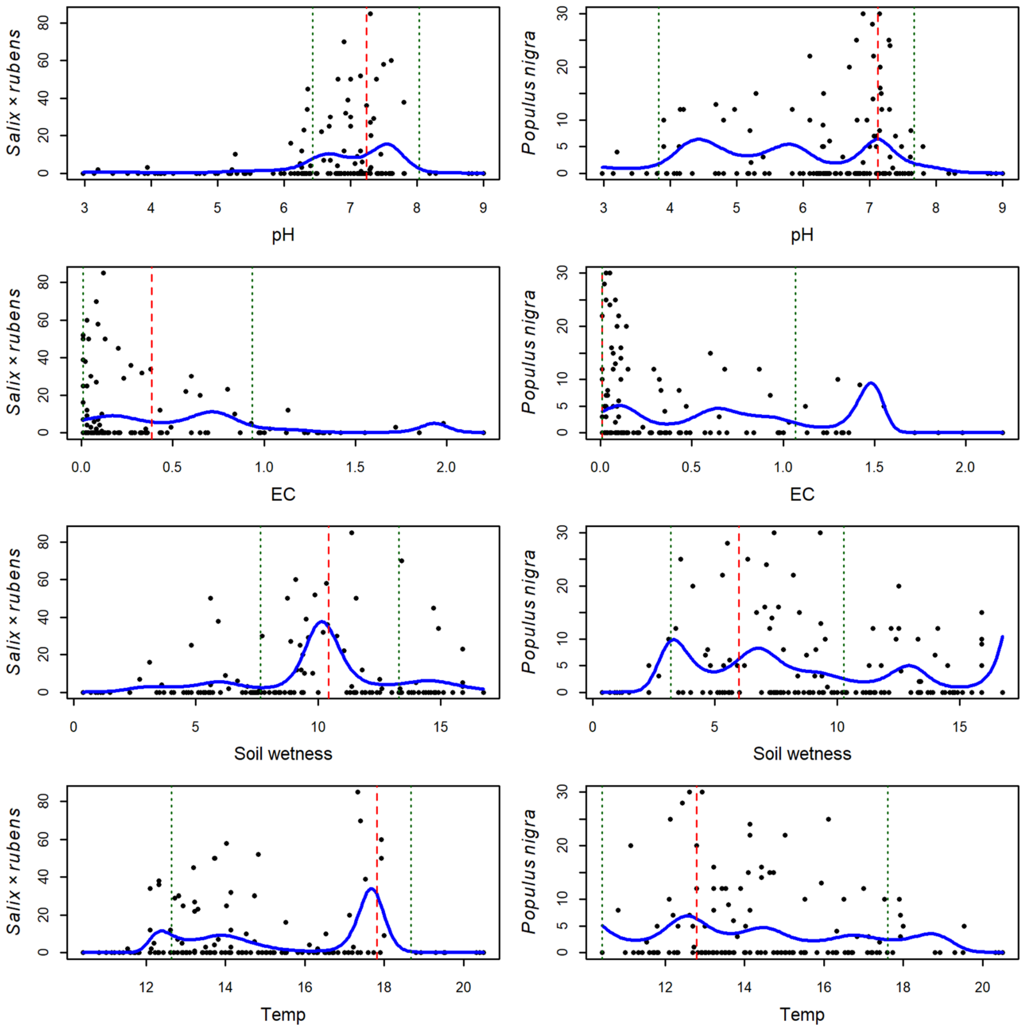

Fig. 4. Response models for *Salix* × *rubens* and *Populus nigra* along gradients of soil reaction (pH), electrical conductivity (EC), soil water content (Soil wetness), and soil temperature (Temp), fitted using a generalized additive model (GAM) approach

The estimated carbon dioxide sequestration value demonstrated non-linear relationships with stand density in both species (**Fig. 5**). For *Salix* × *rubens* (***A***), sequestration value increased sharply with density, reaching a maximum at approximately 30 individuals·m^{-2}, beyond which the value declined, suggesting potential density-related limitations. In contrast, *Populus nigra* (***B***) showed a more gradual increase in sequestration value, peaking at around 25 individuals·m⁻², followed by a moderate decline. These patterns reflect species-specific differences in biomass accumulation dynamics and potential trade-offs between density and per-individual carbon uptake efficiency. The red line represents a fitted distance-weighted least squares approximation that captures the general trend of the data.

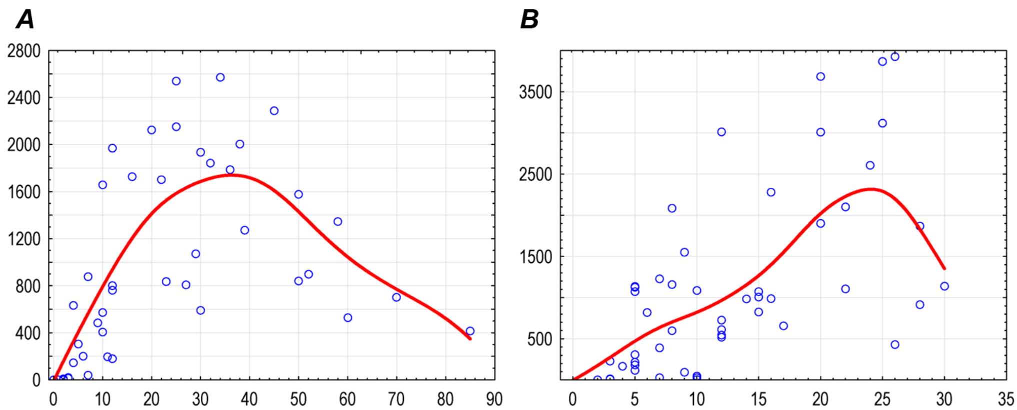

Fig. 5. Carbon dioxide sequestration value of *Salix* × *rubens* (***A***) and *Populus nigra* (***B***) as a function of stand density: the *x*-axis represents stand density (individuals·m^{-2}), and the *y*-axis represents the carbon dioxide sequestration value (€ per ha). The red line indicates an approximation using the distance weighted least squares fitting method

The maximum carbon dioxide sequestration value for *Populus nigra* was approximately 1.75 times higher than that of *Salix* × *rubens*, suggesting a greater economic potential for carbon capture per unit area under optimal stand density.

DISCUSSION

After the destruction of the Kakhovka Hydroelectric Power Plant on June 6, 2023, the territory of the former Kakhovka Reservoir underwent significant natural changes. The reservoir has practically disappeared, turning into a network of river branches and lakes that are close to natural conditions (Vyshnevskyi & Shevchuk, 2024a). The sudden drop in water levels caused by the breach of the dam destroyed existing aquatic ecosystems, but simultaneously exposed new terrestrial areas. This initiated a succession process, whereby herbaceous, shrubby, and woody plant species began to colonise these open surfaces. Among the woody species, *Salix* × *rubens* and *Populus nigra* were the most prominent colonisers. *S.* × *rubens* exceptional colonization success can be attributed to several key traits: prolific seed production with rapid germination; high light demand at the seedling stage; and the ability to disperse via both wind and receding water. Within three weeks of exposure, densities of seedlings exceeded 90 per m². By the end of the first growing season, individuals reached heights of over 3 meters. They had documented growth rates of 2.3 cm per day. These rates surpassed those of cultivated energy willows. In moist, nutrient-rich microsites, second-year individuals attained heights of up to 4.7 m. These characteristics establish *S.* × *rubens* as a vital structural element in emergent floodplain forests (habitat type G1.11: Riverine Salix Woodland), which are protected under the Bern Convention and offer essential ecosystem services, such as carbon sequestration, soil stabilisation, and microclimate regulation (Didukh *et al.*, 2024).

Salix × *rubens* and *Populus nigra* frequently co-occur but exhibit distinct ecological preferences that drive their spatial niche differentiation. *Salix* × *rubens* typically establishes on flat or concave landforms, often directly adjacent to the waterline. It may also colonize more distant surfaces provided they are horizontal or slightly depressed. In contrast, elevated microtopographic features such as convex slopes or hilltops are more often colonized by *Populus nigra*. These geomorphological distinctions clearly demarcate the respective habitat zones of the two species. Both species show a marked preference for sandy soils, as evidenced by the soil electrical conductivity (EC) values near the lower end of the spectrum, corresponding to nutrient-poor, coarse-textured substrates with low salt concentrations and high air porosity. However, *Populus nigra* appears more tolerant of elevated EC levels. This may be attributed to its occurrence closer to the original riverbanks, where soils tend to contain higher clay content, resulting in increased conductivity.

The newly exposed post-reservoir landscapes exhibit substantial heterogeneity in their environmental characteristics. For instance, the pH of desiccated lakebed sediments varies widely, ranging from 2.98 to 9.20. Alkaline conditions are particularly common in sandy substrates along the Dnipro's banks. These alluvial soils are extremely nutrient-poor due to prolonged sediment deposition under hydrological influence. Currently, in addition to nutrient deficiency, these areas are also subject to extreme temperature fluctuations, which further constrain plant establishment. Nevertheless, extensive patches are now vegetated by either *Salix* × *rubens* or *Populus nigra*. For both species, soil pH above 7.8–8.0 appears to be a limiting factor, with highly alkaline conditions generally unsuitable for tree colonization. This may reflect direct physiological stress or be a proxy for other environmental constraints that accompany the formation of such alkaline sandy soils.

Extremely acidic soils are rare in the steppe zone of Ukraine, but were found in certain former water bodies with thick bottom layers of decomposing organic material. These formed under anaerobic conditions in shallow, vegetation-rich ponds that heated significantly in summer. The result is soil acidity that strongly suppresses vegetation growth. For *Salix* × *rubens*, these highly acidic environments are particularly extreme, with limited colonization observed. Optimal conditions for this species generally require soil pH not lower than 6. In contrast, *Populus nigra* is markedly more acid-tolerant, with its lower threshold for establishment extending to soils with pH as low as 3.8.

In terms of moisture preferences, *Salix* × *rubens* is a more stenotopic and hydrophilic species, while *Populus nigra* exhibits eurytopic behaviour with greater drought tolerance. The species show an asymmetric response to the moisture gradient, which correlates well with geomorphological site preferences. Areas close to bodies of water with flat or concave microrelief tend to have relatively stable and high soil moisture. In contrast, convex slopes that are further from the water surface, both horizontally and vertically, experience fluctuating and often limited water availability. The observed temperature patterns are most likely related to the density of tree stands and the angle of surface exposure. Dense stands of *Populus nigra* create shaded microhabitats with relatively lower soil surface temperatures. In contrast, the more open-canopy structure of *Salix* × *rubens* stands permits increased solar radiation, resulting in greater surface warming.

It is important to emphasize that the restoration of willow-poplar biotopes on the former bed of the Kakhovka Reservoir is occurring not through technical reclamation but via spontaneous successional processes, which demonstrate an exceptional potential for natural recovery. This nature-based approach serves as a strong argument against reconstructing the reservoir, which could destroy already established ecosystems of high ecological and economic value. As noted by other researchers, newly forming habitats of the *G1.11 Riverine Salix woodland* type hold a high conservation status under the Bern Convention and should be preserved and supported as part of the sustainable ecological recovery of southeastern Ukraine (Didukh *et al*., 2024).

The establishment of willow and poplar stands contributes not only to the re-establishment of vegetation cover but also initiates a broad range of ecosystem functions: carbon fixation, soil stabilization, hydrological regulation, microclimate moderation, and provision of habitat for a wide array of faunal species. These forests, particularly in their early developmental stages, are characterized by high rates of transpiration and photosynthesis, giving them significant climate-regulating potential. Furthermore, due to their robust root systems, these tree species contribute to soil structuring and may act as biofilters, reducing eutrophication pressures and accumulation of heavy metals.

Our findings show that *Salix × rubens* prefers moist, low-salinity, and thermally stable microsites, whereas *Populus nigra* displays broader ecological tolerance and is capable of colonizing drier, nutrient-poor substrates. This functional differentiation allows them to occupy distinct niches within the same ecosystem and enhances the stability of plant communities in heterogeneous environments. Our results align with H. Guilloy *et al*. (2011), who demonstrated that Salix alba seedlings require more stable soil moisture and are more sensitive to moisture deficits, whereas *Populus nigra* exhibits higher tolerance to soil-water fluctuations and establishes more effectively on drained or sandy substrates (Guilloy *et al*., 2011).

The young *Salix × rubens* and *Populus nigra* stands forming on the exposed sediments of the former Kakhovka Reservoir exhibit substantial potential for carbon sequestration, even at early successional stages. Based on biomass measurements and species-specific parameters, the maximum estimated monetary value of sequestered CO_2 for *Populus nigra* exceeded that of *Salix × rubens* by approximately 1.75 times. This difference is attributable to the larger average biomass of individual trees and the more stable performance of *Populus nigra* populations across a wider range of environmental conditions. The observed nonlinear relationship between stand density and total CO_2 sequestration indicates the existence of a density optimum beyond which carbon capture efficiency declines. This pattern may be linked to resource competition or morphological constraints that limit biomass accumulation at high densities. For *Salix × rubens*, peak sequestration efficiency was observed at approximately 30 individuals·m^{-2}, while for *Populus nigra* it was around 25 individuals·m^{-2}. These findings highlight the importance of stand structure in determining carbon offset potential.

The assessment of carbon sequestration capacity in young willow and poplar forests has not only ecological, but also economic significance in the context of contemporary carbon market mechanisms. Given the current price of €64–75 per tonne of CO_2 under the EU Emissions Trading System (EU ETS), even the early stages of tree vegetation recovery can deliver substantial ecosystem services in the form of carbon footprint compensation. This opens up opportunities for developing financial incentives to support natural regeneration by integrating ecosystem services into environmental policy and spatial planning frameworks. Despite the destructive consequences of the reservoir's collapse, the event has created a unique window for natural floodplain ecosystem restoration. The emergence of self-generating willow-poplar forests on the newly exposed land demonstrates nature's remarkable regenerative capacity, even in heavily transformed anthropogenic landscapes. These ecosystems provide vital climate-regulating functions, including carbon sequestration, thermal load reduction, hydrological stabilization, and biodiversity enhancement. In the context of global climate challenges, the role of such regenerating ecosystems must be recognized as a critical element of sustainable development at both national and regional levels. The carbon sequestration potential of these forests makes them essential for achieving Ukraine's climate targets and fulfilling its international commitments under the Paris Agreement. Conversely, an uncritical return to the idea of reconstructing the reservoir or restoring hydraulic infrastructure could lead to the loss of newly formed, high-value habitats.

Decisions regarding the future of this territory must be based not only on infrastructure or economic considerations, but also on the recognition of ecosystem services already emerging. There is a point of view according to which the restoration of the Kakhovka Reservoir after the war is considered a key element in the restoration of irrigated agriculture in the Southern Steppe of Ukraine, particularly in the Kherson region. The authors emphasise the need to reconstruct hydraulic structures, such as the Kakhovka Hydroelectric Power Plant, in a modernised format, which involves assessing the infrastructure and implementing the necessary upgrades to ensure reliable operation in the post-war conditions. This approach includes the integration of environmental considerations into restoration efforts, such as soil conservation practices and the protection of natural habitats. Thus, the future of the Kakhovka Reservoir after the war envisages its restoration in line with modern environmental and technical requirements (Lavrenko *et al.*, 2024). Some experts acknowledge that natural restoration processes are already underway in the former reservoir area: new ecosystems are forming, including floodplain forests of willow and poplar trees, which contribute to the restoration of biodiversity. However, they emphasise that these natural changes cannot fully compensate for the losses in energy, water supply, and agriculture that the reservoir provided (Vyshnevskyi & Shevchuk, 2024c), which is difficult to agree with. The integration of a nature-based approach into spatial planning, acknowledgment of carbon sequestration potential, and support for successional dynamics can form the foundation for a restoration model that combines ecological resilience with climate responsibility and long-term sustainability.

The results of this study hold significant practical importance for ecological planning, the restoration of degraded areas, and the development of nature-oriented approaches to landscape management in the region of the former Kakhovka Reservoir. The identified patterns of spatial distribution and ecological tolerance of *Salix × rubens* and *Populus nigra* can be utilized to predict succession trajectories and optimize land reclamation measures without relying on costly technical interventions. Evaluating the carbon sequestration potential of newly established tree stands enables their inclusion in the ecosystem services assessment framework and supports a well-founded stance on climate-oriented land use. Specifically, calculating the economic value of CO_2 sequestration provides a basis for attracting financial mechanisms to support natural restoration efforts, such as carbon financing schemes or government environmental compensation programs. These findings can inform the development of regional sustainable development plans, spatial planning schemes, and decisions regarding the feasibility of restoring hydraulic infrastructure in the former reservoir area. The established phytocenoses of type G1.11 Riverine Salix woodland, which possess internationally recognized nature conservation status, can be integrated into projects aimed at creating new protected areas or zones of ecological stability within the Emerald Network.

Carbon sequestration, soil stabilization, and primary biomass production are particularly important in the context of floodplain ecosystem restoration, and directly inform management decisions for the former reservoir bed. Additionally, emergent willow–poplar stands should be considered for their capacity to provide various ecosystem functions, including hydrological regulation, sediment retention, microclimate amelioration, nutrient cycling, and habitat provision. These functions warrant quantification in future studies to achieve a comprehensive assessment of ecosystem service recovery. Further research should concentrate on the long-term monitoring of succession processes at the bottom of the former Kakhovka Reservoir. This includes examining changes in the species composition and stratification structure of tree stands, biomass growth rates, the ontogenetic development of dominant species, and the stability of established phytocenoses under various microecological conditions. Of particular relevance is the study of the dynamics of the hybrid complex *Salix* × *rubens* and potential scenarios for changes in the genetic structure of populations during natural reproduction. It is essential to broaden the range of taxa studied, particularly herbaceous species and bryophytes, to evaluate the completeness of secondary vegetation formation and identify bioindicators of community stability. A significant area of focus is the integration of data on soil microbiota, which will enhance our understanding of the interactions between woody vegetation and microbial communities under conditions of altered hydrology and soil chemistry. Promising research avenues include investigating the carbon balance in newly established forest ecosystems, with an emphasis on modeling sequestration capacity in the medium and long term, as well as developing spatial-dynamic models to predict the structure of phytocenoses in response to climatic factors. Finally, the socio-ecological aspect is crucial: examining management scenarios for this territory from the perspective of ecosystem services, sustainable land use, and biodiversity conservation, which should be incorporated into decision-making processes at both national and regional levels.

CONCLUSION

Colonization of the drained bottom of the Kakhovka Reservoir during the initial stages of succession occurred remarkably quickly, being primarily facilitated by pioneering stands of *Salix* × *rubens* and *Populus nigra*. A distinct spatial separation between these species was observed, attributed to the geomorphological features of the microrelief and soil characteristics. The morphometric parameters of the trees indicated the presence of species-specific allometric relationships, reflecting different ecological growth strategies. The application of generalized additive models confirmed that under the floodplain conditions of Khortytsia Island, *S.* × *rubens* prefers moist, slightly saline, and thermally stable conditions, while *P. nigra* exhibits a broader tolerance to variations in soil acidity, electrical conductivity, and moisture. The assessment of carbon sequestration potential revealed that young stands are capable of accumulating significant amounts of carbon even in the early stages of development, and the economic value of this ecosystem service can be considerable. The results obtained are of practical importance for decision-making regarding the ecological and spatial management of the former reservoir area, particularly considering the preservation of the established phytocenoses as a component of nature-oriented restoration.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: the authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Human Rights: this article does not contain any studies with human subjects performed by any of the authors.

Animal studies: all institutional and national guidelines for the care, maintenance, and use of laboratory animals were followed.

AUTHOR CONTRIBUTIONS

Conceptualization, [O.Z.]; methodology, [O.K.; O.L.]; investigation, [H.T.; O.L.; O.K.; O.Z.]; data analysis, [H.T.; O.Z.]; writing – original draft preparation, [O.K.; O.Z.]; writing – review and editing, [O.K.]; visualization, [O.Z.]; supervision, [O.K.]; project administration, [O.K.]; funding acquisition, [–].

All authors have read and agreed to the published version of the manuscript.

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МАЙБУТНЄ КАХОВСЬКОГО ВОДОСХОВИЩА ПІСЛЯ ЕКОЦИДУ: ЗАЛІСНЕННЯ ТА ВІДНОВЛЕННЯ ЕКОСИСТЕМНИХ ПОСЛУГ ЗА ДОПОМОГОЮ НОВОУТВОРЕНИХ УГРУПОВАНЬ ВЕРБИ І ТОПОЛІ

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Обґрунтування. Зруйнування Каховської греблі під час російського вторгнення в Україну спричинило одну з найтяжчих екологічних катастроф у Східній Європі за останні десятиліття. Раптове осушення водосховища оголило великі площі колишніх водних екосистем, що призвело до скорочення біорізноманіття, порушення гідрологічних циклів і до широкомасштабного забруднення. Хоча наслідки включають деградацію середовищ існування та довгострокові ризики для здоров'я населення, новоутворені землі також сприяли спонтанній екологічній сукцесії. Найбільш помітними колонізаторами висохлого дна є гібридні верби (*Salix* × *rubens*) та чорні тополі (*Populus nigra*), які швидко утворили густі піонерні угруповання. Ці нові екосистеми відіграють важливу роль у поглинанні вуглецю, стабілізації ґрунту й регулюванні мікроклімату. Розуміння динаміки й екосистемних послуг цих утворень є важливим для розробки стратегій сталого відновлення післявоєнного ландшафту.

Матеріали та методи. Польові дослідження було проведено у квітні 2025 р. на оголеному дні колишнього Каховського водосховища, поблизу острова Хортиця. Усього оцінено 158 ділянок за наявністю дерев, морфологічними параметрами та умовами навколишнього середовища. Виміряно висоту і діаметр дерев *Salix* × *rubens* та *Populus nigra*, а їхню біомасу оцінено за допомогою геометричних моделей. На кожній ділянці було зафіксовано pH, температуру, вологість і електропровідність ґрунту. Параметри екологічної ніші розрахували за допомогою узагальнених адитивних моделей (GAM). Потенціал поглинання вуглецю оцінили на основі загальної біомаси та перетворили у грошову вартість за допомогою системи торгівлі викидами ЄС (EU ETS).

Результати й обговорення. *Salix* × *rubens* і *Populus nigra* продемонстрували високі темпи колонізації на відкритому дні водосховища, утворивши піонерні угруповання з чіткими просторовими структурами. *Salix* × *rubens* домінував на вологих, увігнутих мікроділянках, тоді як *Populus nigra* виявили на піднесених, більш сухих ділянках. Аналіз узагальнених адитивних моделей показав, що угруповання *Salix* × *rubens* сформувалися на ґрунтах із помірно кислими та близькими до нейтральних реакціями (pH оптимум ≈ 7,25; діапазон толерантності 6,43–8,03), підвищеною вологістю (оптимум ≈ 10,42 %), вищою температурою (оптимум ≈ 17,82 °C) та помірною електропровідністю (оптимум ≈ 0,38 дСм/м), тоді як *Populus nigra* демонструє ширшу екологічну пластичність: оптимум pH ≈ 7,12 (толерантність 3,83–7,67), нижчу вологість (≈ 5,98 %), прохолодніші умови (≈ 12,80 °C) і низьку електропровідність (≈ 0,03 дСм/м). Види продемонстрували значні відмінності в екологічній толерантності й накопиченні біомаси. Алометричні моделі виявили чіткі стратегії росту, причому *P. nigra* розвивав товстіші стебла. Максимальний потенціал поглинання вуглецю спостерігали за середньої щільності насаджень, причому *P. nigra* забезпечував більшу економічну цінність на гектар. Ці результати підкреслюють екологічне значення спонтанного лісовідновлення та свідчать на користь природних методів відновлення замість технічної реконструкції водосховищ.

Висновок. Спонтанне лісовідновлення дна колишнього Каховського водосховища *Salix* × *rubens* і *Populus nigra* демонструє сильну регенераційну здатність заплавних екосистем. Ці піонерні угруповання надають важливі екосистемні послуги, включаючи поглинання вуглецю, стабілізацію ґрунту і формування біотопів. Екологічні переваги й особливості росту окремих видів визначають їхній просторовий розподіл і потенціал поглинання вуглецю. Економічна цінність поглинання вуглецю на ранніх стадіях є значною, особливо для *P. nigra*. Ці результати підтверджують доцільність збереження новоутворених вербових і тополевих угруповань та свідчать про важливість інтеграції природних рішень у післявоєнне планування ландшафту замість технічної реконструкції зруйнованої інфраструктури водосховища.

Ключові слова: Каховське водосховище, екоцид, вербово-тополеві ліси, *Salix* × *rubens*, *Populus nigra*, спонтанна сукцесія, поглинання вуглецю, екосистемні послуги, відновлення заплави

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