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War and the Artificial Pine Plantations of the Oleshky Sands: On the Threshold of a New Reality

Yurii Moskalenko, Maria Nitochko, Sergii Pliushch

Black Sea Biosphere Reserve, NAS of Ukraine (Hola Prystan, Ukraine)

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correspondence to

Yurii Moskalenko; Black Sea Biosphere Reserve, NAS of Ukraine, 1 Lebedyna Street, Hola Prystan 75600, Ukraine; e-mail: strix@strix.ks.ua

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abstract

The aim of this study was to assess the scale of pyrogenic losses of artificial pine plantations in the Oleshky Sands during the three years following the onset of the region's occupation as a result of the armed aggression of the Russian Federation against Ukraine, as well as to evaluate their potential ecological consequences. Using Sentinel-2 remote sensing data and machine-learning methods based on an artificial neural network, we modelled the distribution of pine plantations as of 23 February 2022 and 12 February 2025. A comparison of these results revealed that, over the study period, the pine plantations of the Oleshky Sands experienced unprecedented decline and fragmentation due to fires, losing around 30,000 ha, or 64.3% of their pre-invasion extent. In absolute terms, the greatest losses occurred on the Oleshkivska and Kozacholaherska arenas, where 8.818 thousand ha and 5.896 thousand ha of pine stands burned, respectively. In relative terms, the most severely affected were the artificial forests of the Kinburn Peninsula, where 4.808 thousand ha of pine plantations — amounting to 86.1% of their area as of early 2022 — were destroyed by fire within three years of the full-scale invasion. The cumulative pyrogenic losses incurred over previous decades in peacetime, together with those of the occupation period, have resulted in the semi-natural pine-forest ecosystem that developed during the second half of the twentieth century losing its dominant role in the landscapes of the Oleshky Sands. It is assumed that such extensive forest loss will trigger profound restructuring of the region's ecosystems, including successional dynamics, the spatial organisation of plant and animal communities, hydrological regimes, and soil chemical properties. The article outlines several potential directions of these transformations. The findings allow the formulation of hypotheses regarding future changes in the Oleshky Sands, including those that can be verified through remote-sensing monitoring. The latter primarily concern the rate of deadwood decay on burned sites, spontaneous vegetation recovery, and the development and spread of deflation processes. Establishing a systematic monitoring framework to test these hypotheses, followed by broader post-deoccupation research into the environmental consequences of the war, will form the basis for developing an adaptive management strategy for the Oleshky Sands aligned with conservation objectives.

Війна і штучні соснові насадження Олешківських пісків: на порозі нової реальності

Юрій Москаленко, Марія Ніточко, Сергій Плющ

Резюме. Метою дослідження було визначення масштабів пірогенних втрат штучних соснових насаджень Олешківських пісків за три роки від початку окупації регіону внаслідок збройної агресії Російської Федерації проти України та їх можливих наслідків для природи досліджуваного регіону. На основі даних дистанційного зондування Sentinel-2 та з використанням методів машинного навчання заснованого на штучній нейронній мережі змоделювали поширення соснових насаджень станом на 23 лютого 2022 р. та на 12 лютого 2025 р. Порівнюючи отримані результати встановили, що за досліджуваний проміжок часу соснові насадження Олешківських пісків внаслідок пожеж зазнали безпрецедентного скорочення та фрагментації, втративши близько 30 тис. га або 64.3 % від їх площі на момент початку повномасштабного вторгнення. У абсолютних значеннях найбільших втрат зазнали сосняки Олешківської та Козачолагерської арен, де згоріло відповідно 8.818 тис. га та 5.896 тис. га. У відносних значеннях найбільше постраждали штучні ліси Кінбурнського півострова, де за три роки від початку повномасштабного вторгнення вигоріло 4.808 тис. га сосняків або 86,1 % від їх площі станом на початок 2022 р. Сукупні ж пірогенні втрати сосняків за попередні кілька десятиліть у мирний час та протягом досліджуваного періоду окупації регіону призвели до того, що квазіприродна екосистема соснових насаджень, що сформувалася протягом другої половини 20 ст., остаточно втратила панівну роль у ландшафтах Олешківських пісків. Припускається, що таке масштабне скорочення соснових лісів матиме наслідком глибоку перебудову екосистем досліджуваного регіону, у тому числі сукцесійної динаміки, просторової організації рослинних і тваринних угруповань, гідрологічного режиму, хімічних властивостей ґрунтів тощо. У статті у загальних рисах обговорюються деякі можливі напрями таких змін. У підсумку зроблено висновок, що на основі отриманих даних можна формулювати гіпотези щодо подальших змін Олешківських пісків, у т. ч. такі, що піддаються верифікації через моніторинг дистанційними методами. Серед останніх найперше слід вказати гіпотези, які стосуються швидкості розпаду мертвої деревини на згарищах, їх спонтанного заростання та розвитку і поширення дефляційних процесів. Організація системного моніторингу для їх перевірки з наступним розширенням спектра досліджень наслідків війни після деокупації регіону стануть основою для вибудовування стратегії менеджменту Олешківських пісків з урахуванням природоохоронних цілей.

Ключові слова: Олешківські піски, штучні соснові насадження, вплив війни на довкілля, дефляція, постпірогенна сукцесія, дистанційне зондування Землі.

Адреса для зв'язку: Юрій Москаленко; Чорноморський біосферний заповідник НАН України, вул. Лебедина 1, Гола Пристань 75600, Україна; e-mail: strix@strix.ks.ua.

Introduction

Sandy-landscape geosystems are commonly regarded as among the most vulnerable types of natural systems (Kotenko *et al.*, 1999), and the Oleshky Sands provide a compelling example of this. In less than half a century of economic exploitation, their landscape underwent drastic transformation. Deforestation and, in particular, pasture degradation caused by excessive sheep grazing led to sand deflation, and by the 1830s the problem of stabilising the sands had already become evident (Gordienko, 1969). Although it had been clear since the mid-nineteenth century that halting livestock grazing within the Oleshky Sands would be the most effective measure to counter deflation, such an approach was inconceivable at the time, as it directly conflicted with the immediate economic interests of the local population (Military..., 1849). Other approaches to sand stabilisation proved ineffective, leaving the issue unresolved even a century later.

The 1950s marked a turning point both in the history of land use in the Oleshky Sands and in efforts to combat deflation. This period was preceded by extensive investigations of the region's natural conditions conducted by numerous scientific expeditions and by the Oleshky Sand-Amelioration Station, established in 1925. Their collective research laid the groundwork for developing and improving silvicultural techniques for growing monoculture pine plantations, which made it possible — within just a few decades (from 1949 to the late 1980s) — to establish artificial pine forests over approximately 70,000 ha of the Oleshky Sands (Shevchuk *et al.*, 2012). The pine stands cultivated here are characterised by low productivity, high fire hazard, inability to self-regenerate, and susceptibility to mass pest outbreaks, all of which, coupled with changes in the hydrological regime, repeatedly resulted in forest dieback (Sirik, 2000; Kolomiyets & Burda, 2007; Mykhailov & Nazarenko, 2007; Shevchuk & Tymoshchuk, 2017; Tymoshchuk, 2019). In essence, the Oleshky Sands became a large-scale long-term experiment that produced an extensive forest ecosystem which, owing to its artificial origin, superficial resemblance to natural systems, and the absence of inherent self-sustaining mechanisms as defined by Reimers (1994), should be classified as semi-natural.

The maintenance of these pine stands was constantly supported by forestry enterprises, including through fire-prevention measures and reforestation of burned areas. Key scientific support for this work was provided by the Steppe Branch of the Ukrainian Research Institute of Forestry and Forest Melioration named after V. M. Vynogradov, whose specialists investigated the full range of factors negatively affecting the pine forests and developed optimal strategies for their preservation and regeneration (Fomin *et al.*, 2017).

Beyond the inherent challenges of establishing and maintaining extensive monoculture pine plantations, this transformation also had significant consequences for the biodiversity of the Oleshky Sands. In many areas where pine plantations were established, there had been no genuine need to combat deflation. For example, deflation was never an issue on the Kinburn Peninsula, and the creation of pine plantations there reflected the broader Soviet tradition of large-scale melioration rather than actual environmental necessity (Kryvulchenko, 2016).

As a result, in some parts of the Oleshky Sands the afforestation programme affected areas originally covered by native sandy vegetation. These natural communities were first damaged through site preparation and planting, and later, as the stands closed, were completely eliminated beneath the tree canopy (Umanets, 1999; Umanets *et al.*, 2002). At the same time, the biodiversity of the artificial pine stands themselves remained extremely poor. Studies of avifauna revealed that bird assemblages of pine plantations were markedly poorer in species composition, diversity, and ecological structure compared to those of natural Oleshky Sands habitats (Moskalenko, 2015). Similar patterns have been documented for other faunal groups (Kotenko, 1997; Kotenko & Kotenko, 2002). The full-scale invasion and occupation of the region resulting from the armed aggression of the Russian Federation against Ukraine should be regarded as a new turning point in the conservation and management of the Oleshky Sands, as war has profoundly disrupted all pre-existing practices, affecting both people and nature (Zagorodniuk, 2023). By early May 2022, when large wildfires engulfed pine plantations on the Kinburn Peninsula and in the Ivanivska and Oleshkivska arenas, the shortage of personnel and resources needed to combat the fires became the first sign of wartime collapse of forestry management. The transformation of the Oleshky Sands into an active war zone in 2022–2023 brought an end to all forms of forest management, including operations conducted by illegal forestry structures established by the occupying authorities.

Despite the ongoing occupation, there is already a pressing need for a professional discussion about the future of the Oleshky Sands, similar to current debates regarding the fate of the Kakhovka Reservoir (Zagorodniuk, 2023; Vasyliuk *et al.*, 2025). To initiate such a discussion meaningfully, at least a general understanding is required of the nature and scale of changes occurring within the pine plantations, as well as their potential consequences. Such understanding will make it possible not only to formulate hypotheses regarding possible scenarios of landscape transformation, but also to organise systematic monitoring to test them, ultimately informing an adaptive management strategy aligned with conservation objectives.

Given that field observations are currently impossible due to the occupation, assessment of the present state of the Oleshky Sands must rely exclusively on remote methods, particularly analyses of land-cover change using satellite imagery. Accordingly, the aim of this study is to quantify the extent of artificial pine-forest losses in the Oleshky Sands based on remote-sensing data and to establish an overall picture of their current condition, serving as a baseline for modelling future transformations of the region's natural and semi-natural landscapes.

Materials and methods

Remote-sensing data and preprocessing

Modelling the loss of pine plantations was carried out using Sentinel-2 remote-sensing data (MSI instrument) (ESA, 2015). For this purpose, two winter scenes were selected — 23 February 2022 and 12 February 2025 — both of which were cloud-free over the study area. Winter scenes were preferred because, during the cold season, green pine stands exhibit more distinct spectral differences from other land-cover types, allowing higher accuracy in their detection during supervised classification.

As geospatial predictors for supervised classification, we selected the components of the Tasselled Cap Transformation (TCT) — Tasselled Cap Brightness (TCB), Tasselled Cap Greenness (TCG), and Tasselled Cap Wetness (TCW) (Shi & Xu, 2019) — as well as the following spectral indices: the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Green–Red Vegetation Index (GRVI), Modified Soil-Adjusted Vegetation Index (MSAVI2) and Normalized Sand Index (NSI). TCT components were derived from Sentinel-2 Level-1C (Top of Atmosphere Reflectance, TOA), while the remaining indices were computed using Sentinel-2 Level-2A (Surface Reflectance, SR) products. Formulae for all geospatial variables used are provided in Table 1.

Table 1. **Formulae for calculating the components of the tasselled cap transformation and the spectral indices**

Таблиця 1. **Формули розрахунку компонентів перетворення «ковпак з китицею» та спектральних індексів**

Indices	Formulae for calculating	Source
TCB	0.351 * B2 + 0.3813 * B3 + 0.3437 * B4 + 0.7196 * B8 + 0.2396 * B11 + 0.1949 * B12	Shi & Xu, 2019
TCG	–0.3599 * B2 – 0.3533 * B3 – 0.4734 * B4 + 0.6633 * B8 + 0.0087 * B11 – 0.2856 * B12	Shi & Xu, 2019
TCW	0.2578 * B2 + 0.2305 * B3 + 0.0883 * B4 + 0.1071 * B8 – 0.7611 * B11 – 0.5308 * B12	Shi & Xu, 2019
NDVI	(B8 – B4) / (B8 + B4)	Lemenkova & Debeir, 2023
NDWI	(B3 – B8) / (B3 + B8)	Lemenkova & Debeir, 2023
GRVI	(B3 – B4) / (B3 + B4)	Motohka *et al.*, 2010
MSAVI2	0.5 * (2 * B8 + 1 – sqrt((2 * B8 + 1)2 – 8 * (B8 – B4)))	Lemenkova & Debeir, 2023
NSI	(B3 + B4) / (log(B11))	Secu *et al.*, 2022

Note: B2, B3, B4, B8 and B11 refer respectively to the 2nd, 3rd, 4th, 8th and 11th spectral bands of Sentinel-2 remote-sensing data.

Almost all stages of predictor preparation from satellite imagery for subsequent supervised classification were performed using the Google Earth Engine (GEE) cloud platform (Gorelick *et al.*, 2017). These included retrieving the selected remote sensing scenes from the “Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-1C (TOA)” (for TCT computation) and “Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-2A (SR)” collections (for all other spectral indices), applying scale factors, calculating the geospatial variables, reducing high-frequency noise with a 3×3-pixel median filter, per-band mosaicking, clipping results to the Oleshky Sands region, and exporting the outputs as GeoTIFF rasters at 10-m spatial resolution. All processing steps were implemented via a custom GEE JavaScript API script, which is provided in the supplementary materials.

Sample preparation

A dataset of 10,000 points for modelling pine-forest distribution as of early 2022 was generated in QGIS using the “Random points inside polygons” tool. Given that the area of pine plantations is approximately three times smaller than the total area of the Oleshky Sands, random sampling across the entire sand-dune region would have produced a markedly imbalanced dataset, with far fewer pine points than non-pine points. To avoid this, the sample was generated within a custom multipolygon created from georeferenced forest-plantation plans outlining the boundaries of the forest fund, supplemented with polygons delineating pine stands outside forest-fund lands. Each point was attributed in QGIS with one of two classes: “Pinus” if it fell within a pine stand, and “nonPinus” otherwise. The classification of points was based on a Sentinel-2 colour composite from 23 February 2022. In the resulting sample, the “Pinus” class comprised 4,037 points and the “nonPinus” class 5,963 points. This same sample was reused for modelling pine-forest distribution for the winter of 2024/2025, after reassigning the class attribute from "Pinus" to "nonPinus" for points corresponding to pine stands burned between 2022 and 2024. Because the number of "Pinus" points after this adjustment (1,445 points) became much smaller than the number of "nonPinus" points (8,555 points), a class-balancing procedure was applied to avoid dominance of the majority class during model training and to improve the detection of the minority class. To achieve this, an random undersampling procedure was used [Haibo & Garcia 2009], reducing the number of "nonPinus" points so that they exceeded the number of "Pinus" points by only a factor of two.

Supervised classification

A single-hidden-layer artificial neural network (ANN) designed for binary classification was used as the classification algorithm. The model was implemented in R version 4.5.1 (R Core Team, 2021) using the nnet package (v.7.3-20) (Venables & Ripley, 2002).

Following established best practice (Lones, 2024), the ability of the models to generalise was assessed using independent test samples that were not involved in model training or hyperparameter tuning. The training, validation, and test subsets were selected using spatial blocking, because random sampling across the entire spatial domain would, due to spatial autocorrelation, inflate estimates of model performance (Roberts *et al.*, 2017). Using the blockCV package (v. 3.1.5) (Valavi *et al.*, 2019), both datasets were divided into six spatial blocks. One block from each dataset was randomly selected as an independent test set used for the final model evaluation. Points in the remaining blocks served as training data, including for hyperparameter optimisation via cross-validation implemented using the caret package (v. 7.0.1) (Kuhn, 2008). Hyperparameter tuning involved identifying optimal values for the number of hidden-layer neurons (tested values: 2–8) and the L2 regularisation parameter (decay; tested values: 0.0001, 0.001, 0.01, 0.1, 0.2, 0.3, 0.4, 0.5). Thus, 64 hyperparameter combinations were evaluated for each model. The selection criterion was the area under the ROC curve (AUC), computed using the pROC package (v. 1.18.5) (Robin *et al.*, 2011).

Final model evaluation on the test samples employed AUC together with the following performance metrics: Accuracy, Balanced Accuracy, Cohen's Kappa, Sensitivity, Specificity, Positive Predictive Value, and Negative Predictive Value (Sokolova & Lapalme, 2009; Kuhn, 2008). Additional R packages used for data import, processing, and visualisation included terra (v. 1.8-50) (Hijmans, 2025), sf (v. 1.0-21) (Pebesma, 2018), dplyr (v. 1.1.4) (Wickham *et al.*, 2023), NeuralNetTools (v. 1.5.3) (Beck, 2018), and ggplot2 (v. 3.5.2) (Wickham, 2016). All R code listings used in the workflow are provided in the supplementary materials.

Post-processing of classification results

Binary raster outputs were converted to vector format in QGIS using the "Polygonize" tool, after which polygons corresponding to non-pine areas were removed. Post-classification cleaning was then applied to reduce classification artefacts: polygons smaller than 500 m^2 were removed, and internal holes below the same threshold were filled. Subsequent processing differed between the 2022 and 2025 pine-distribution vectors. The 2022 dataset was processed twice using the "Intersection" tool: first with a shapefile of the Oleshky Sands arenas boundaries as the mask, and second with the shapefile of forest-fund boundaries (supplemented with pine patches outside forest-fund areas). The 2025 pine-distribution vector was intersected with the cleaned 2022 pine layer. This resulted in two vector layers cleaned of artefacts and containing attribute information on the arenas to which each polygon belonged. Polygon areas were then calculated using the field calculator, and the attribute tables were exported for further analysis in R. To analyse the nature of pine-forest losses, we computed not only the total area of pine plantations (both per-arena and across the entire Oleshky Sands), but also several landscape-pattern metrics at the patch level. These included total number of pine patches (NP), mean patch area (AREA_MN), standard deviation of patch area (AREA_SD), the largest patch index (LPI), and the coefficient of variation of patch area (AREA_CV) (Wang *et al.*, 2014).

Results

During model preparation, both point datasets were partitioned into spatial blocks, as shown in Fig. 1. The test set for the 2022 model was randomly selected as the block containing 2,718 points located within Block 4 (Fig. 1a), while for the 2025 model the test set consisted of 3,688 points located within Block 1 (Fig. 1b). Hyperparameter calibration showed that, for the model based on the 2022 data, the optimal architecture consisted of seven neurons in the hidden layer and an L2-regularisation value of 0.1. For the 2025 model, the best-performing configuration included five neurons in the hidden layer with the same L2-regularisation value of 0.1. The neural-network architectures for both models are in Fig. 2.

The confusion matrices obtained from the test datasets are shown in Fig. 3, and the model performance metrics derived from them are presented in Table 2. Figure 4 shows the ROC curves and corresponding AUC values with 95 % confidence intervals for both models.

Overall, assessment across all reported performance metrics showed that both models were able to reliably distinguish between the Pinus and nonPinus classes.

Table 2. **Values of selected model performance metrics calculated from the confusion matrices**
Таблиця 2. **Значення деяких метрик якості моделей, обчислених за матрицями переплутування**

Performance metrics	Model based on data as of 23 February 2022	Model based on data as of 12 February 2025
Accuracy	0.9588 (95% CI: 0.9506, 0.966)	0.9599 (95% CI: 0.9531, 0.966)
Kappa	0.9097	0.8353
Sensitivity	0.9386	0.9196
Specificity	0.9698	0.9661
Positive Predictive Value	0.9445	0.8051
Negative Predictive Value	0.9665	0.9875
Balanced Accuracy	0.9542	0.9428

The modelled maps of pine-forest distribution across the Oleshky Sands are shown in Fig. 5, and the spatial-structure metrics derived from them are provided in Table 3. As these results show, over the three years following the full-scale invasion, wildfires decreased the total area of pine plantations by approximately 30 thousand hectares, or 64.3 %. Among all arenas, the greatest absolute losses occurred in the Oleshky (8.818 thousand ha) and Kozacholagerska (5.896 thousand ha) arenas — those that had initially contained the largest pine-forest areas.

Table 3. **Area of pine plantations and selected landscape metrics based on modelling as of 23 February 2022 and 12 February 2025.**

Таблиця 3. **Площа соснових насаджень та значення окремих метрик їх просторової структури за даними моделювання станом на 23 лютого 2022 р. та 12 лютого 2025 р.**

Arenas	Year	Total area, ha (%)	NP	AREA_MN, ha	AREA_SD, ha	LPI, %	AREA_CV, %
Kakhovska	2022	686 (100)	75	9.15	32.7	33.1	357
	2025	459 (66.9)	115	3.99	17.9	33.0	448
Kozacholaherska	2022	10756 (100)	750	14.34	83.3	11.8	581
	2025	4860 (45.2)	1656	2.93	16.8	5.8	573
Oleshkivska	2022	14775 (100)	2422	6.1	35.9	3.6	589
	2025	5957 (40.3)	2937	2.03	13.5	5.8	664
Chalbaska	2022	4996 (100)	829	6.03	44.8	19.5	744
	2025	1552 (31.1)	1006	1.54	7.9	10.2	511
Zburivska	2022	6489 (100)	306	21.2	161.0	41.2	759
	2025	1822 (28.1)	714	2.55	10.3	6.8	405
Ivanivska	2022	3358 (100)	401	8.38	46.1	22.8	550
	2025	1211 (36.1)	454	2.67	12.6	15.8	471
Kinburn Peninsula	2022	5582 (100)	1001	5.58	35.3	16.1	633
	2025	774 (13.9)	935	0.83	3.6	11.6	431
Total:	2022	46642 (100)	5784	8.06	59.0	5.73	732
	2025	16636 (35.7)	7817	2.13	12.7	2.08	597

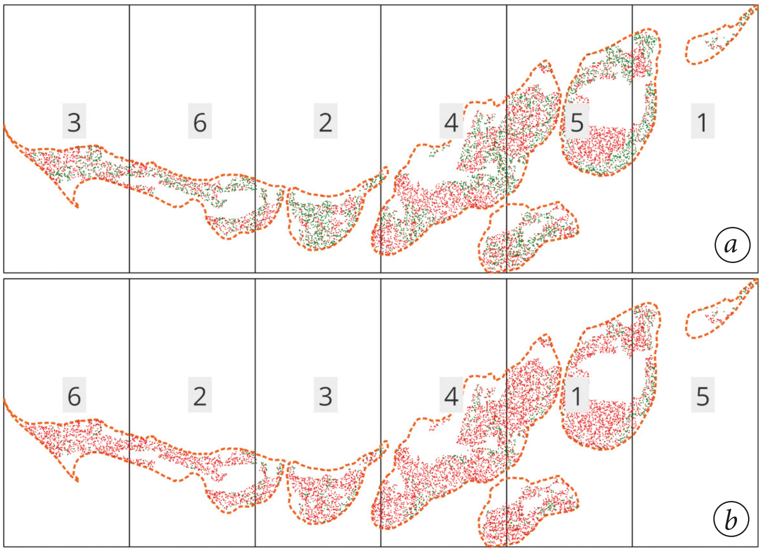


Fig. 1. Scheme and numbering of spatial blocks for splitting the dataset into training and test subsets: (a) for data as of 23 February 2022; (b) for data as of 12 February 2025.

Рис. 1. Схема і нумерація просторових блоків для розділення вибірки на навчальну та тестову: (a) для даних за 23 лютого 2022 р.; (b) для даних за 12 лютого 2025 р.

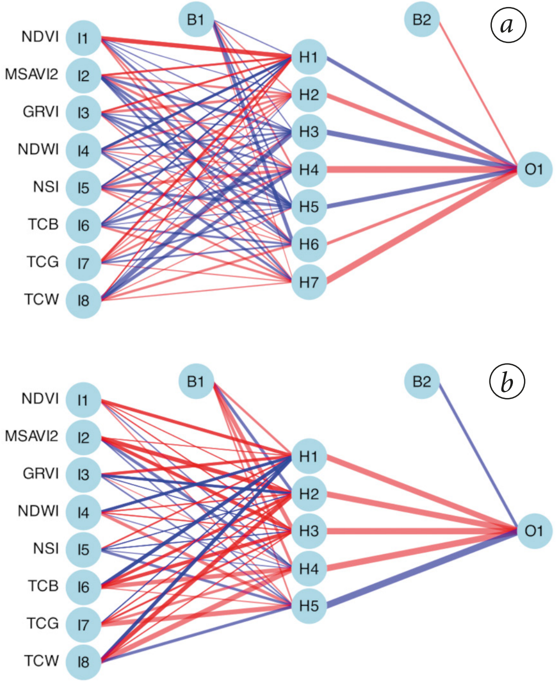
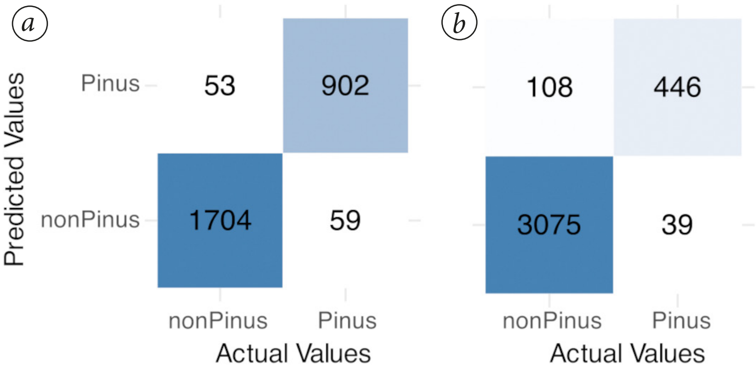


Fig. 2. Neural network architecture diagram: (a) for the model based on data as of 23 February 2022; (b) for the model based on data as of 12 February 2025.

Рис. 2. Схема архітектури нейромереж: (a) для моделі за даними за 23 лютого 2022 р.; (b) для моделі за даними за 12 лютого 2025 р.



(a)

Predicted Values	nonPinus	Pinus
Pinus	53	902
nonPinus	1704	59

(b)

Predicted Values	nonPinus	Pinus
Pinus	108	446
nonPinus	3075	39

Fig. 3. Confusion matrices on the test subsets: (a) for the model based on data as of 23 February 2022; (b) for the model based on data as of 12 February 2025.

Рис. 3. Матриці переплутування, які були отримані на тестових вибірках: (a) для моделі за даними за 23 лютого 2022 р.; (b) для моделі за даними за 12 лютого 2025 р.

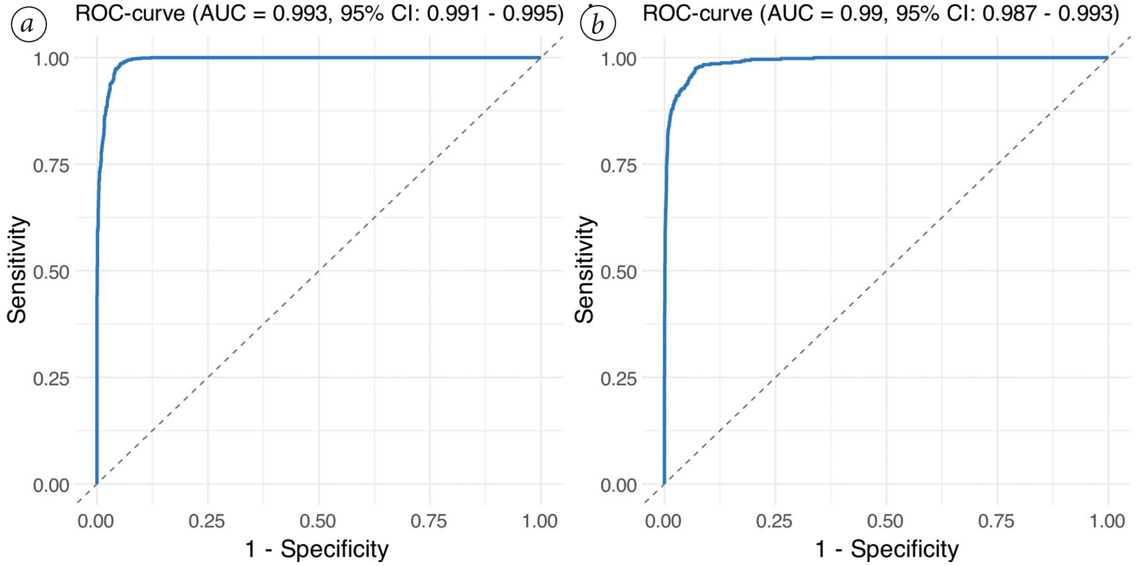


Fig. 4. ROC curve plots: (a) for the model based on data as of 23 February 2022; (b) for the model based on data as of 12 February 2025.

Рис. 4. Діаграми ROC-кривих: (a) для моделі за даними за 23 лютого 2022 р.; (b) для моделі за даними за 12 лютого 2025 р.

Fig. 5. Distribution of pine plantations within the Oleshky Sands based on modelling: (a) as of 23 February 2022; (b) as of 12 February 2025. Arenas of the Oleshky Sands: 1 — Kakhovska; 2 — Kozacholaherska; 3 — Oleshkivska; 4 — Chalbaska; 5 — Zburivska; 6 — Ivanivska; 7 — Kinburn Peninsula.

Рис. 5. Поширення соснових насаджень в межах Олешківських пісків за даними моделювання: (a) станом на 23 лютого 2022 р.; (b) станом на 12 лютого 2025 р. Арени Олешківських пісків: 1 — Каховська; 2 — Козачолагерська; 3 — Олешківська; 4 — Чалбаська; 5 — Збур'ївська; 6 — Іванівська; 7 — Кінбурнський півострів.

In the Kakhovska arena, which had the smallest initial pine-forest area (686 ha), only 227 ha of pine stands were destroyed. Across the remaining arenas, absolute losses ranged from 2.147 to 4.808 thousand ha. In relative terms, pine-forest loss varied considerably among arenas. The smallest proportion of burnt pine stands (33.1 % of the initial area) occurred in the Kakhovska arena, likely due to the fragmentation of local forests by settlement zones, which may have reduced the number of artillery strikes and facilitated more effective suppression of fires. The most severe losses occurred on the Kinburn Peninsula, where 86.1 % of pine forests disappeared between February 2022 and February 2025. The Zburivska and Chalbaska arenas ranked second and third in proportional losses, with 71.9 % and 68.9 % of pine stands destroyed, respectively. In all other arenas, losses ranged from 54.8 % to 63.9 %.

The spatial-pattern metrics clearly illustrate that, alongside the dramatic reduction in total area, pine stands became markedly more fragmented during the study period. As shown in Table 3, the total number of pine patches (NP) increased nearly 1.4-fold, while their mean area (AREA_MN), standard deviation of area (AREA_SD), and largest patch index (LPI) decreased by factors of 3.8, 4.6 and 2.8, respectively. The coefficient of variation of patch area (AREA_CV) also decreased, indicating a reduced spread of patch sizes, though its absolute value remains high — typical of mosaic natural landscapes.

In summary, wildfires across the Oleshky Sands resulted in substantial reductions in pine-forest area and a marked increase in their fragmentation.

Discussion

Because of their monocultural structure and the specific environmental conditions of the region, the pine plantations of the Oleshky Sands belong to the highest fire-hazard class, requiring a permanent mobilisation of considerable human and material resources to prevent wildfires (Shevchuk & Tymoshchuk, 2015). Although fires in these plantations were not uncommon even after the first closed-canopy stands appeared, they became a major factor driving substantial reductions in forest area only from 1990 onwards, when the first large-scale fire on the Oleshkivska arena occurred, affecting approximately 0.8 thousand hectares of forest stands (Shevchuk & Tymoshchuk, 2015). A series of extensive fires in the region led to a reduction of pine-forest area to approximately 46.6 thousand hectares by the beginning of the full-scale invasion, according to our remote-sensing-based estimates (Table 3). Total losses between 1984 and 2021 amounted to roughly 23.8 thousand hectares (Moskalenko, 2021). The underlying cause was clear: the forestry sector — according to Popkov (1997), one of the most unprofitable in Ukraine — was structurally unable, under the conditions of the economic collapse of the 1990s and subsequent transition to a market economy, to maintain the full spectrum of fire-prevention measures required for the most fire-prone forest types.

The cessation of all forest-management activities due to the full-scale invasion and occupation drastically accelerated the destruction of pine stands by fire. Over the three years of occupation, fires directly or indirectly caused by military action destroyed an area of pine plantations roughly one-and-a-half times larger than the accumulated losses of the previous three decades. It is important to stress that this is not the end of the decline: throughout the preparation of this article, during 2025, the study area remained an active combat zone and its forests continued to burn regularly.

Thus, regardless of how the situation in the region develops, it can already be stated that the semi-natural pine-forest ecosystem has irreversibly lost its dominant role in the landscapes of the Oleshky Sands. This will inevitably lead to large-scale landscape restructuring, including profound changes in habitat types and associated biotic communities. It is therefore essential to develop an understanding of the initial conditions and major drivers of this transformation.

Unfortunately, successional processes on the burned areas formed after the destruction of pine stands on the Oleshky Sands remain poorly studied. One of the few examples of such research examined post-fire demutation on recent burned areas on the Kinburn Peninsula (Kolomiiets & Burda,

Fig. 6. A fragment of Compartment 6 of the Ivanivske Forestry with completely burnt pine stands on a high-resolution satellite image dated 30 July 2024 (image source: Google Earth Pro). Coordinates of the centre of the depicted fragment: 46.4511° N, 32.0796° E.

Рис. 6. Фрагмент 6 кварталу Іванівського лісництва з повністю вигорівшими сосновими насадженнями на супутниковому знімку високої роздільності від 30 липня 2024 р. (джерело знімка: Google Earth Pro). Координати центру зображеного фрагмента: 46.4511° Пн.ш. 32.0796° Сх.д.

2007). The authors showed that within 3–7 years, spontaneous recovery of plant species typical of psammophytic steppe with small patches of broadleaved woodland in depressions — communities present before anthropogenic transformation — had already begun.

In his study, Moskalenko (2021) analysed long-term NDVI dynamics as a proxy for vegetation regeneration rates on burned areas of pine stands in the Oleshky Sands. He concluded that in most cases spontaneous revegetation proceeds relatively rapidly, whereas only in certain areas — with unfavourable soil and hydrological conditions and without nearby patches of preserved psammophytic steppe vegetation that could serve as seed sources (e.g., the southern part of the Kozacholagerska arena or the centre of the south-western half of the Oleshkivska arena) — deflation processes may prevail and regeneration proceeds slowly.

However, it is important to stress that burned areas formed after the full-scale invasion differ in one significant respect. Previously, burnt pine stands were rapidly (typically within 1–2 years after a fire) harvested and removed by forestry enterprises. Now, at least 30 thousand hectares of burned areas with large quantities of standing deadwood (Fig. 6) have accumulated across the Oleshky Sands, and because of ongoing hostilities this material will not be removed. Moreover, even after de-occupation, burned area clearance will remain impossible for a long time owing to mine contamination, the destruction of forestry infrastructure and large-scale depopulation of the region. Since there is no prior experience of long-term observation of such burned areas, the course of their regeneration remains uncertain. Based on our own preliminary observations of individual fire-damaged pine trees, we can assert that dead trees will rapidly be colonised by xylophagous insects and xylophilous fungi. Accelerated decay of the lower parts of trunks (below the soil surface, under conditions of higher moisture) will lead within the first few years to their collapse, producing extensive windthrows. Early stages of this process were already visible in high-resolution satellite imagery two years after the fires of 2022. The spontaneous decomposition of windthrown wood will likely be slow under the region's arid climate, although secondary fires that burn accumulated deadwood may accelerate the process. In any case, these processes will constitute a long-term component of the successional dynamics of burned areas in the Oleshky Sands.

Because the pine plantations of the Oleshky Sands were established to halt deflation, a key question now arises: what is the likelihood of renewed aeolian activity following the loss of such vast forested areas? Forestry experts had repeatedly warned that the appearance of large treeless areas after the massive fires of the 1990s and 2000s could reactivate deflation (Kuzyk, 2008; Shevchuk *et al.*, 2009; Nazarenko *et al.*, 2020). Lubskiy *et al.* (2023), using a multi-decadal Landsat dataset, even interpreted the pyrogenic elimination of artificial pine stands as a process of desertification — a conclusion that is, however, incorrect due to methodological and conceptual shortcomings of their study[1]. At the same time, long-term NDVI analyses indicate that in most cases burned areas on the Oleshky Sands do not pose a serious deflation risk (Moskalenko, 2021). This is expected, since the decline of pastoralism in the region removed the key factor driving sand deflation. Under current conditions, with no removal of deadwood from burned areas, the development of deflation processes is even less likely. In our view, extensive windthrows will serve as barriers to sand movement, providing an anti-deflation function while their gradual decomposition will create a temporal buffer during which the early phases of spontaneous sand stabilisation can begin.

One component of the spontaneous revegetation process will be the spread of woody species. This will primarily involve the typical r-strategist *Betula borysthenica*, whose rapid formation of groves on burned areas of the Oleshkivska arena has been observed previously (Moskalenko, 2021). Pyrogenic elimination of large pine areas removes barriers to long-distance seed dispersal of this species and simultaneously opens patches with suitable soil conditions for colonisation. Studies of spontaneous regeneration of Scots pine on the wood-steppe sections of the Black Sea Biosphere Reserve (Umanets & Pliushch, 2017) suggest that on lower-lying microrelief elements with favourable soil conditions, *Pinus sylvestris* is also likely to regenerate from seed, with surviving fragmented stands serving as seed sources.

Soil-chemical changes induced by fire will also influence the course of spontaneous succession. It is known that the typically acidic soil reaction beneath pine stands shifts towards near-neutral conditions on burned areas (Zibtsev *et al.*, 2022).

Another important consideration is the spatial heterogeneity that develops on post-fire sites: burned areas contain a fine-scale mosaic of areas differing in burn severity, ash deposition, deadwood accumulation and remaining patches of unburnt forest litter. This creates a small-scale pyrogenic habitat mosaic that strongly influences subsequent successional trajectories. We therefore expect a multi-directional pattern of vegetation recovery and the emergence of a mosaic of successional stages: some patches will be rapidly colonised by pioneer psammophytes, while others will remain less productive for prolonged periods due to preserved forest litter or allelopathic effects of fire-damaged pine. The presence of large quantities of standing deadwood and windthrows — which will not be removed because of military and mine hazards — will further reinforce landscape structural heterogeneity. Ultimately, a stable mosaic of psammophytic steppe, meadow, and woody–shrub communities is expected to emerge, reflecting the interplay of pyrogenic, edaphic, microclimatic and biotic factors. Overall, this is likely to enhance structural resilience in contrast to the previous monocultural plantations.

The loss of pine stands over such a vast area will also alter evapotranspiration regimes, likely reducing water-loss components of the hydrological balance and potentially creating conditions for changes in groundwater levels. As far back as the early 20th century, Academician H. M. Vysotsky warned that creating continuous forest plantations on sands would lead to groundwater decline — a prediction later confirmed by practice (Zibtsev *et al.*, 2022). For example, long-term observations at

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[1] In this work, an error was made in calculating one of the desertification indicators — TCB. First, this indicator was calculated for all remote-sensing datasets from different Landsat sensors using a single formula, whereas the TCT coefficients are derived individually for each sensor (the formula applied was derived for the TM sensor, while the study also used remote-sensing data from TM+ and OLI sensors). Second, TCB was calculated using atmospherically corrected data (i.e. SR), whereas the TCT coefficients are generally derived for use with uncorrected remote-sensing data (i.e. TOA). At a conceptual level, the natural and historical conditions of the Oleshky Sands were not taken into account in this study, as areas afforested with artificial pine plantations were included in the analysis. A correct conclusion about the presence or absence of desertification processes in the Oleshky Sands can only be drawn by examining the dynamics of desertification indicators on non-afforested areas, as well as on burned areas, while excluding pre-fire periods for the latter. Including pine plantations — whose vegetation, by definition, contains far higher chlorophyll levels than the natural and semi-natural psammophytic steppe vegetation of the Oleshky Sands — obscures true trends in desertification indicators.

the “Dalekyi Karabai” hydrological station (Oleshkivska arena) showed that under pine plantations the mean annual groundwater level fell from −119 cm in 1956 to −270 cm in 2002, and during the dry early 1990s dropped to −318 cm in 1996 (Shevchuk *et al*., 2005). Under current conditions, the opposite trend — gradual groundwater rise — appears plausible. Another aspect to be considered when modelling the consequences of ecosystem restructuring is the impact on protected areas. Pine plantations surrounding the wood-steppe sections of the Black Sea Biosphere Reserve, namely the Solonoozerna, Ivano-Rybalchanska and Volyzhin Forest sections (total area 5,600 ha) largely isolated these areas from adjacent territories by forming a continuous belt of unsuitable habitat for many species (Seliunyna & Moskalenko, 2004). This substantially limited the reserve’s potential to support biodiversity in surrounding unprotected landscapes. At the same time, the reserve’s wood-steppe sections experienced negative impacts from these plantations.

For example, during the late 1980s, when wild boar (*Sus scrofa*) numbers increased significantly, the species concentrated in pine plantations bordering the reserve’s wood-steppe sections and caused severe damage to populations of rare orchids (Orchidaceae) by foraging on reserve lands (Seliunyna & Umanets, 1987). Similarly, elevated breeding numbers of the Eurasian goshawk (*Astur gentilis*) in the surrounding pine plantations negatively affected several corvid species within the reserve. The decline or disappearance of corvids — providers of nests — in turn led to marked reductions or local disappearance of the eurasian hobby (*Falco subbuteo*), common kestrel (*Falco tinnunculus*), red-footed falcon (*Falco vespertinus*) and long-eared owl (*Asio otus*) (Moskalenko, 2015). The fragmentation of pine plantations around the reserve’s wood-steppe sections caused by recent fires (Fig. 7) will undoubtedly alter ecological linkages between them and surrounding territory. Similar changes are expected for ecosystems of the Oleshky Sands National Nature Park (11,671.06 ha), whose sites lie within the Kozacholagerska and Chalbaska arenas. Substantial transformations will also occur in ecosystems of the Ivory Coast of Sviatoslav National Nature Park, 9,848.14 ha of which are located on the Kinburn Peninsula. Most of this area (9,205.2 ha, or 93.5 %) belonged to the forest fund at the time of the park’s establishment and was largely covered by pine plantations, of which only 13.9 % survived on the peninsula in general by early 2025 (Table 3).

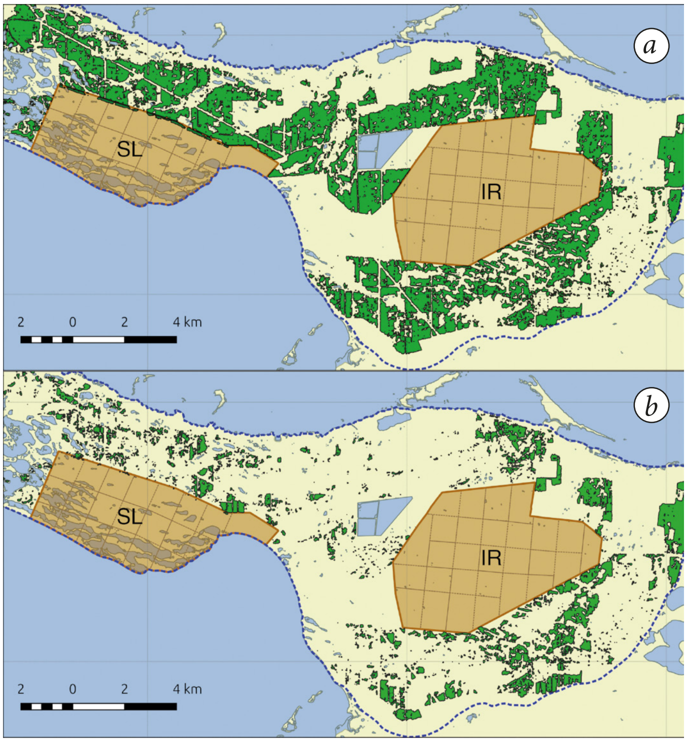

Fig. 7. Distribution of pine stands around the Solonoozerna (SL) and Ivano-Rybalchanska (IR) sections of the Black Sea Biosphere Reserve based on modelled data: (a) as of 23 February 2022; (b) as of 12 February 2025.

Рис. 7. Поширення соснових насаджень навколо Солоноозерної (SL) та Івано-Рибальчанської (IR) ділянок Чорноморського біосферного заповідника за даними моделювання: (a) станом на 23 лютого 2022 р.; (b) станом на 12 лютого 2025 р.

Finally, assessments of the current state of the Oleshky Sands, modelling of future development scenarios, and planning of adaptive post-war management should consider not only the regional scale but also the global context — particularly the region's role in climate regulation. The loss of artificial pine plantations over such a vast area means that decades of carbon accumulation in woody biomass were effectively nullified in a very short time. Thus, the unreliability of artificial pine stands under the conditions of the Oleshky Sands in terms of sequestering carbon dioxide — one of the principal contributors to the greenhouse effect — provides an additional argument against their restoration. In contrast, the recovery of grassland ecosystems, where soils play the dominant role in carbon storage, seems to be a much more appropriate strategy in line with global objectives of reducing greenhouse-gas emissions and safeguarding ecosystem carbon stocks.

Conclusions

Over the three years since the beginning of the full-scale invasion, the artificial pine plantations of the Oleshky Sands have undergone an unprecedented reduction in area as a result of fires directly or indirectly caused by military action. This is certain to result in systemic ecological consequences operating across multiple spatial and temporal scales. The monocultural plantations established during the second half of the twentieth century have effectively lost their dominant role in the landscape structure, which will trigger a profound reorganisation of the region's ecosystems, including changes in successional dynamics, the spatial organisation of plant and animal communities, the hydrological regime, soil chemical properties and more. Unfortunately, the study area remains occupied and continues to lie within an active combat zone, making direct field research impossible. Even after de-occupation the accessibility of the area to researchers will remain severely limited for a long time due to landmine contamination. Nevertheless, the results obtained already allow us to formulate hypotheses about possible future transformations of the Oleshky Sands, including those that can be verified through remote-sensing-based monitoring. Among such hypotheses, the most immediate concern the rate of deadwood decomposition on burned areas, the course of spontaneous revegetation, and the development and spread of deflation processes.

Supplementary materials

Supplementary materials for this article are available in the Zenodo repository at https://doi.org/10.5281/zenodo.17790480. They include shapefiles of the modelled distribution of pine stands within the Oleshky Sands as of 23 February 2022 and 12 February 2025, as well as the JavaScript and R code used for the preparation and analysis of the data underlying this study.

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Declarations

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Conflict of interests. The authors have no conflicts of interest to declare that are relevant to the content of this article.

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