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Spatial structure of natural landscapes within the Chornobyl Exclusion Zone

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Abstract: The article demonstrates the results of a study of the landscape structure of the Chornobyl Radiation and Ecological Biosphere Reserve (Ukr.: Chornobylskyi radiatsiino-ekolohichnyi biosfernyi zapovidnyk – ChREBR). Because of radioactive pollution, a sharp drop in human activity, and the granting of the territory the status of a protected object, the process of area rewilding took on certain characteristics and led to the return of ecosystems' natural processes. The studies cover a 7-year period from 2016 to 2022, i.e., from the moment this territory was granted protected status. That territory was abandoned by people more than 37 years ago and the former rural and urban landscapes have either already been transformed or are in the process of being transformed into natural ones. The scale of forest massifs has changed during the previous seven years, which has caused increased pasture overgrowth. huge forest massifs have been lost because of enormous forest fires and floods, particularly along the Pripet and Uzh rivers. Semi-natural successions occur in the gardens, and wooden homes are almost extinct. From orbit, a number of communities no longer resemble settlements. They are cloaked in bushes and trees instead. For places that have been ploughed, the same holds true. The last seven years show that change is happening more slowly than in the decades before. The pattern of natural processes in ecosystems, including periodic fires, the blocking of reclamation channels, and other factors, is the primary driver of changes in the composition of the land cover.

Keywords: reserve, forest, natural restoration, agricultural land, vegetation cover, flooding

INTRODUCTION

The Chornobyl Exclusion Zone (CEZ) now belongs to one of the most unique objects of the nature reserve fund: the Chornobyl Radiation and Ecological Biosphere Reserve (Ukr.: Chornobylskyi radiatsiino-ekolohichnyi biosfernyi zapovidnyk – ChREBR) (Fedonyuk *et al.*, 2020). After the meltdown of nuclear reactor No. 4 of the Chornobyl[1] nuclear power plant (NPP) on April 26, 1986, cities on surrounding lands within a radius of 30 km were evacuated due to the dangerously high level of release of radioactive particles into the atmosphere (Anspaugh, Catlin and Goldman, 1988). Since then, the area has remained uninhabited, and all activities have been moved beyond the 30-kilometre zone. The exclusion zone was abandoned for some time, except for measures that prevented the further release and spread of radioactive substances (González 2013; Romanchuck, Fedonyuk and Fedonyuk, 2017). Currently, the development of the exclusion zone is completely devoted to "natural scenarios". Human intervention in the transformation of former technological landscapes into natural ones is completely limited. However, studying and observing the development of the landscapes in this zone is of great interest. Given the contamination of part of the territory by radioactive fallout in 1986, as well as the fact that part of the territory was under Russian occupation in the spring of 2022 (mining, remnants of

[1] Also referred to as "Chernobyl" (Rus.: Chernobylskaya atomnaya elektrostantsiya – Chernobyl NPP) as the nuclear power plant was built and the accident took place in the Ukrainian SSR, Soviet Union, therefore Chernobyl Exclusion Zone.

explosive substances), the study of this area is possible only with the use of remote sensing data.

Huge tracts of agricultural land, forests, and urban landscapes were among the places that were left neglected for a very long time after the Chornobyl nuclear power plant accident because of the refusal to use radioactively contaminated areas (Santos *et al*., 2019). The area has given rise to a region full of potential for the study of natural restoration and rewilding of ecosystems linked to man-made disasters because of its isolation (Didukh *et al*., 2023). All of these factors effectively transformed the exclusion zone into one of the largest wildlife sanctuaries and refuges on earth (Perino *et al*., 2019), initially legally and later officially (Polozhennia, 2017), opening up new opportunities for ecosystem restoration research. The majority of the region that now makes up the contemporary ChREBR slowly became covered in vegetation throughout the course of its 37-year isolation, and many species, particularly animals, made a comeback to the areas that had been destroyed (Romanchuck, Fedonyuk and Fedonyuk, 2017; Fedonyuk *et al*., 2020; Trouwborst and Svenning 2022). The Reserve's area is very large, so remote sensing is thought to be a key technology for assessing the restoration and development of the landscape as a whole and its individual parts (Skydan *et al*., 2022a). A wide variety of tools and databases are available for in-depth analysis and study, as well as geospatial distribution (Fedonyuk *et al*., 2020). The uniqueness of ecosystem changes can be considered in relation to other elements influencing the processes taking place in the ecosystems of the Chornobyl zone (Beresford *et al*., 2021; Fedoniuk *et al*., 2021; Sevruk *et al*., 2021), such as radioactive deposits and forest fires (Evangeliou *et al*., 2014; Ager *et al*., 2019; Connor *et al*., 2020). It will also make it possible to examine the growth of vegetation in evacuated urban settings and abandoned agricultural sites in more detail (Laćan, McBride and Witt De, 2015).

Up until recently, most of the scientific research in the exclusion zone involved performing field tests, studies, and data collection on the dispersal of radionuclides in space and their effects on people, animals, and plants (Kashparov *et al*., 2003; Romanchuck, Fedonyuk and Fedonyuk, 2017). However, the potential for using remote information has increased recently, which significantly aids in the execution of environmental impact assessment procedures. In this study, we were able to examine and monitor a region with limited access owing to a variety of variables using both current and previous remote sensing data and a machine learning system. First and foremost, this is because a portion of the exclusion zone territory has been mined since 2022 and is still inaccessible for on-the-ground research and analysis. Additionally, this is due to the fact that Russia's military aggression has made a portion of the exclusion zone territory potentially dangerous for its researchers. Remote sensing techniques enable a wide range of new options in this area (Skydan *et al*., 2022b). We have already applied these techniques in the past to monitor the exclusion zone in biodiversity studies, evaluate the effects of fires, create fire hazard forecasts, put out flames, and address other issues (Romanchuck, Fedonyuk and Fedonyuk, 2017; Fedoniuk *et al*., 2022).

Based on the use of satellite data, several thorough studies have been published recently on monitoring the environmental status of the exclusion zone and evaluating the impact of the accident's repercussions on the Chornobyl NPP. There is information on the biological condition of the given region that spans more than 50 years (Landsat missions, Terra and Aqua satellites, etc.). Such information has been employed by several scientists to study environmental data on a worldwide scale to evaluate changes in the temperature, hydrological parameters, afforestation patterns, and the spread of fires among other things (Potapov *et al*., 2015; Matsala *et al*., 2021; Skydan *et al*., 2021; Seydi *et al*., 2022). Gemitzi (2020), in her work, examined the changes in the vegetation cover of the exclusion zone, which was one of the most thorough assessments of the changes in the exclusion zone plant cover.

The geographical layout of the exclusion zone has dramatically changed since the Chornobyl nuclear power plant catastrophe (Justova *et al*., 2013). A specific form of land cover now makes up, in some experts' estimations, nearly 30% of the landscapes in exclusion zones. The 30-kilometre exclusion zone's land cover type has altered in around 20% of the area, according to the analysis of all 18 annual land cover type photos (Gemitzi, 2020). As a result, the neglect of the land in this area resulted in the loss of meadows and the growth of thick and sparse forest areas. As a result, during the past few decades, there has been a noticeable decline in pastures, which is solely attributable to the progressive overgrowth of woody plants (Kalinichenko, Nenashev and Goloveshkin, 2019).

The objective of this study was to examine the alterations in landscape cover within radioactively contaminated areas resulting from the implementation of rewilding practices and the subsequent designation of these areas as protected territories. This investigation employed remote sensing techniques to evaluate the Earth's surface.

By combining the historical Landsat archive with the gradient-boosted regression algorithm, changes in the landscape of this region since 1986 can be inferred. Several factors, such as the abandonment of agricultural land and an uninhabited urban environment, the presence of forest fires, different levels of radioactive pollution, the effects of the Russian military's presence on the territory of the specified object of the nature reserve fund (mining, remnants of explosive devices and substances), etc., make it difficult to develop mechanisms for the geospatial management of these objects. However, we are only concerned with the last seven years, or since the exclusion zone's territory was formally designated as a protected object and added to the nature reserve fund (Skydan *et al*., 2022b).

Thus, in this article, we tried the possibilities of using remote sensing of the Earth in solving the problem of monitoring the exclusion zone landscapes, where access to the territory is difficult due to many reasons (radioactive contamination, consequences of Russian aggression, etc.).

MATERIALS AND METHODS

STUDY AREA

The Chornobyl Radiation and Ecological Biosphere Reserve (ChREBR) is situated between N51.084 and N51.351, and E29.262 and E30.384 in the Kyiv Oblast in northern Ukraine. (Fig. 1). The research area is located between 93 and 200 m a.s.l., has an average annual temperature of +8.2°C, and receives an average of 619 mm of precipitation. On the roughly 2,600 km^2 territory of the Chornobyl Exclusion Zone (CEZ), which includes the now-

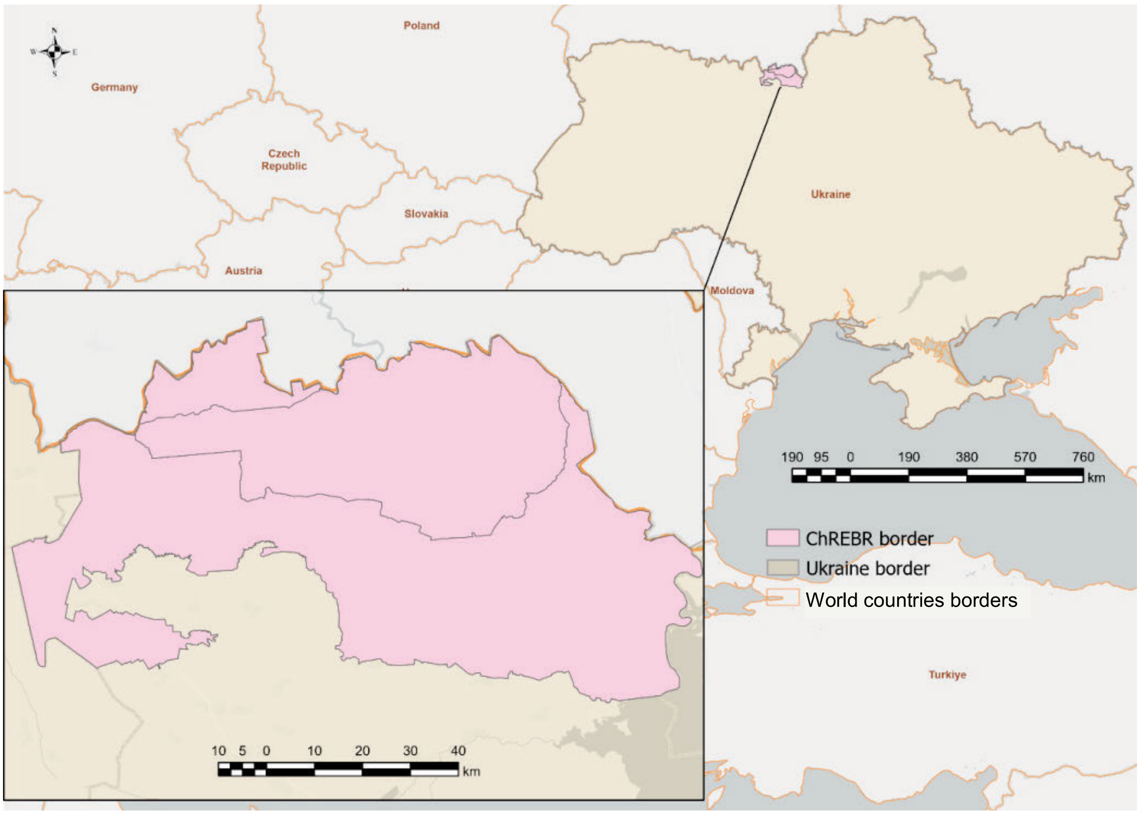

Fig. 1. Location of the Chornobyl Radiation and Ecological Biosphere Reserve (ChREBR); source: own study

decommissioned nuclear power plant situated in the eastern part of the exclusion zone along the northwestern part of the cooling pond, is the ChREBR (Melnichuk *et al*., 2020; DAZV, 2022).

Chornobyl and Pryp'yat, two functioning towns, are also included in the zone; they are situated 15 km south and somewhat to the northwest of the power plant, respectively. The CEZ, which contains a particular type of woody plant community encompassing around two-thirds of the region, is part of the mixed forest zone of the East European Plain. The Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth.), black alder (*Alnus glutinosa* (L.) Gaertn.), and European oak (*Quercus robur* L.) are the predominant tree species in the ChREBR (Davids and Tyler, 2003).

STUDY METHODS

The following steps were taken to complete the geospatial evaluation of changes in the structure of natural landscapes as a protected area of the CEZ: data collecting, data processing, and statistical analysis. Retrospective analysis of land cover based on a dense time series of space images differs from the task of constructing a similar map for one specific year in that there is a need for consistency between data from adjacent years at the pixel level. According to the results of the simulation, one crucial aspect is, for instance, to prevent or greatly reduce the occurrence of scenarios where one pixel is categorised differently more than twice over the course of several years. The "forest–grass–forest" chains within 3–5 years for one pixel are an example of such illogical circumstances. The open landscape was wrongly predicted precisely because the image for such a year had significant patches of unfiltered cloudiness, shadows from clouds, plumes of smoke from forest fires, etc. Since the territory was given protected status eight years ago, that is why that time frame was chosen for the research.

Collecting data. The primary data source for this project was created using the "Dynamic World V1" product on the Google Earth Engine platform (Google LLC, American multinational technology company, USA) (Gorelick *et al*., 2017). Dynamic World is a 10-m near-real-time (NRT) land use/land cover (LULC) dataset that includes class probabilities and label information for nine classes. Our study was based on annual data from 2016 to 2022 (Brown *et al*., 2022).

Processing data. ArcGIS Pro was used to carry out additional data processing, turning the data into a format that could be used there, and carrying out several spatial analyses to find changes in land use and cover. Further processing of the data was done in ArcGIS Pro, converting the data into a format that can be used in ArcGIS Pro and then performing a series of spatial analyses to detect changes in land cover and land use. ArcGIS Pro is geographic information system (GIS) software developed and maintained by Esri (Esri, no date). GIS software is used to collect, store, manage, analyse, and visualise spatial data. The spatial analysis that was performed in ArcGIS Pro included the following:

– land cover change detection: this analysis was used to detect land cover changes for the period 2016–2022;
– land use change detection: this analysis was used to detect land use changes from 2016 to 2022;
– spatial analysis of land cover and land use change: this analysis was used to identify trends in land use development and land use change.

Data analysis. Further processing of digital information was carried out in the programming language R and Excel. This involved a graphical analysis of the data to identify trends in land cover and land use change. Statistical analysis performed in R and Excel included descriptions of land cover distribution and land use change data and the identification of trends in land use development and change.

RESULTS

GENERAL DYNAMICS

The natural complexes of the Chornobyl Radiation and Ecological Biosphere Reserve (ChREBR), as well as the exclusion zones, are characterised by a mosaic of landscapes and include forests, meadows, and swamps, which form a natural environment typical of the Polissia of Ukraine. Since the accident at the Chornobyl nuclear power plant, the landscape structure of the exclusion zone has changed significantly. According to the estimates of some researchers, about 30% of the landscapes in the Chornobyl Exclusion Zone (CEZ) have changed to belong to a certain class of land cover (Gemitzi, 2020; Matsala *et al.*, 2021). During the last decades, there has been a significant decrease in pastures, former agricultural lands, and urbanised areas, which is entirely related to the gradual overgrowth of shrubs and woody plants.

The designation of the ChREBR as a protected area in 2016 helped to further stabilise the remediation and unhindered rewilding of the exclusion zone's territory. Its goal is to maintain the biosphere's most common natural complexes in their pristine condition. As a result, the earlier phases of land abandonment in this region resulted in the progressive transformation of abandoned villages and agricultural territories as well as the spread of dense and sparse forest regions at the expense of pastures. Figure 2 represents the landscape configuration in 2022.

Many specialists foresaw rapid development of the natural renewal of tree species on formerly agricultural fields and the rise of forest cover in the exclusion zone to 90% and above in the immediate aftermath of the catastrophe (Evangeliou *et al.*, 2016). Nevertheless, in cases where the grass mat experienced disruption due to fire, flooding, or the presence of wild animals, the process of spontaneous regeneration of tree species occurred, provided that there were available seed sources. Recent research, for instance, shows that the exclusion zone's total forest cover increased from 41% in 1986 to 59% in 2020, indicating a significant potential for natural forest regeneration (Matsala *et al.*, 2021). The expansion of forests on formerly agricultural land, which has been especially quick since 2000, explains the rise in forests.

From 192,784 to 181,177 ha of forest covered the exclusion zone during the study period (Tab. 1). Scots pine stands are the predominant forest species in the exclusion zone. The mortality of pines and firs in the region known as "Red Forest" was the most dramatic manifestation of the radiobiological response of plants.

A peculiar centre of nature has emerged (together with the Drevlianskyi Nature Reserve (Ukr.: Drevlianskyi pryrodnyi zapovidnyk – DPZ), the Poliskyi Nature Reserve (Ukr.: Poliskyi pryrodnyi zapovidnyk – PPZ), and the Polesie State Radiation-Ecological Reserve (Bel.: Palyeski dzyarzhawny radyyatsyyna-ekalahichny zapavyednik – PDREZ) (on the side of Belarus) in the conditions of an anthropogenic radionuclide anomaly, which must be preserved as a huge territory with a special status of heritage.

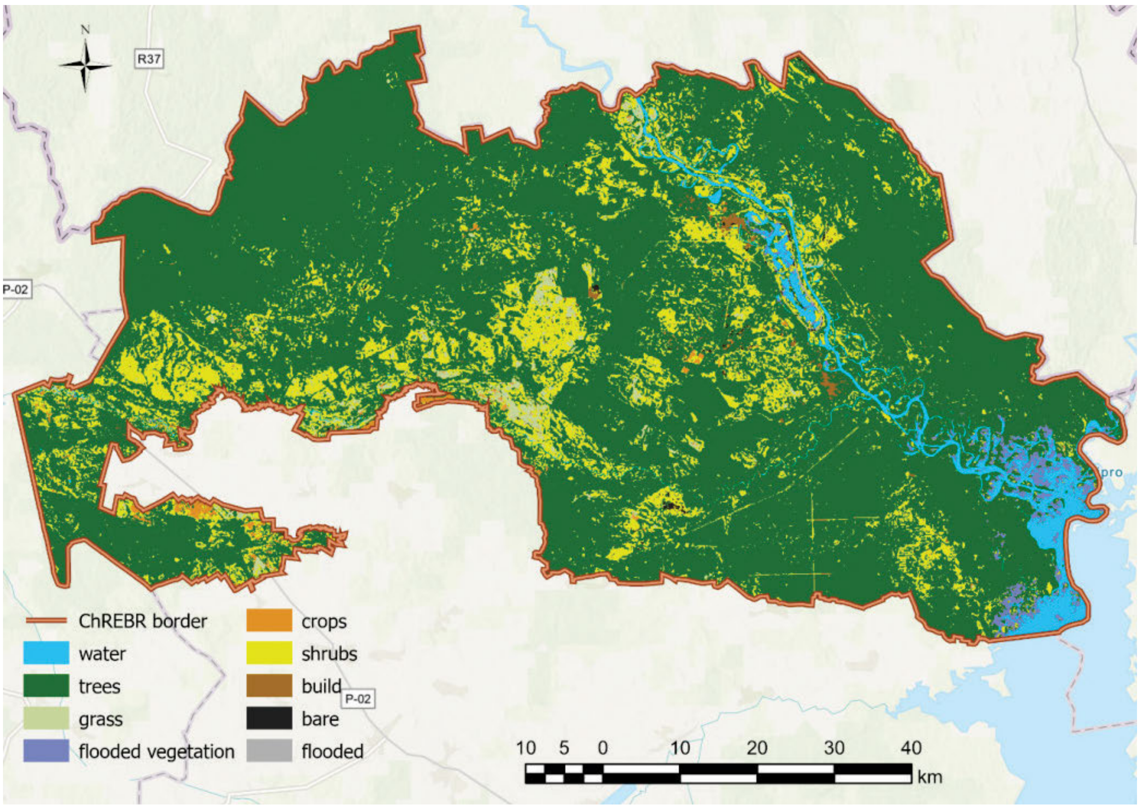

Fig. 2. The Chornobyl Radiation and Ecological Biosphere Reserve's (ChREBR) landscape structure as of 2022; source: own study

Table 1. Dynamics of changes in the landscape structure of the Chornobyl Radiation and Ecological Biosphere Reserve (in %)

Land cover class	Year						
	2016	2017	2018	2019	2020	2021	2022
Water	2.861	2.865	3.726	3.324	3.324	3.204	3.596
Forest	81.976	83.617	85.639	83.100	83.767	83.467	80.673
Grass	1.862	2.571	2.126	1.059	1.548	0.946	1.491
Flooded vegetation	1.769	1.431	0.776	1.175	1.248	0.910	1.192
Crops	0.148	0.212	0.316	0.277	0.352	0.286	0.579
Shrub and scrub	11.296	9.221	7.341	10.921	9.647	10.843	12.319
Built	0.048	0.039	0.037	0.033	0.033	0.027	0.023
Bare	0.041	0.045	0.039	0.111	0.080	0.318	0.126

Source: own study.

VEGETATION CHANGES

As the researchers note, intensive processes of overgrowth (afforestation) of the meadows and fallows of the CEZ with woody vegetation have been noted over the last ten years (Gemitzi, 2020). The species richness of the vegetation cover of the CEZ after the Chornobyl disaster is quite high (ChREBR, no date). Over the past seven years, forested areas in the Reserve have decreased by 3,298 ha. At the same time, significant variations in forested areas have been noted over the years; for example, in 2018, 192,7 ha of forested areas were recorded, and by 2022, >11 thous. ha of forests had been lost (Tab. 2).

The exclusion zone's vegetation changed significantly because of the fires. For instance, based on the information we obtained, adjustments were made to around 25% of the fire-affected areas in 2020. Among these, there are 62.2% of woods, 20.3% of fallow land, 11.5% of marshes, 2.5% of burns, and 1% of abandoned plantations (Skydan *et al.*, 2022a). A satellite data study also revealed that the fires damaged grassy and tree-shrub vegetation that had overgrown highways, areas beneath power lines, river floodplains, and reclamation channels. The area of the Reserve increased by 2.25 thous. ha during the past seven years (Tab. 1) due to an increase in areas covered by shrubs and scrubs. When evaluating the changes in vegetation cover due to forest fires, we came to the conclusion that forest fires destroy most of the tree cover within the burned areas while the shrub cover increases. A significant portion of the pre-fire footage included in the 2020 imagery is to blame for the small modification in vegetation cover for the April 2020 wildfire. Most likely, the loss of tree cover from communities leads to the development of shrub cover, opening new opportunities for the growth of other forms of vegetation. Fallows and grasslands were the least affected by the fires. Typically, the fire on such area spreads quickly, destroying only dry vegetation and sparing the root system. Herbaceous and shrubby species are frequently observed to spread out first in the area following wildfires due to two reasons: firstly, the increased sunlight availability, and secondly, there is no tree canopy to provide shade. In pre-fire areas practically everywhere in the Reserve, Scots pine is the primary forest-forming species. The major barrier to the natural renewal of pine is a thick grass cover, which grows quickly as the area cleared of trees receives more light (Adámek *et al.*, 2015).

Grass vegetation over the seven-year period showed negative dynamics (0.8 thous. ha), which is obviously also

Table 2. Rates of land cover changes in the landscapes of the Chornobyl Radiation and Ecological Biosphere Reserve compared to the previous year (in %)

Land cover class	Year					
	2017	2018	2019	2020	2021	2022
Water	0.1272	30.0783	−10.8003	0.0204	−3.6256	12.2402
Forest	2.0027	2.4179	−2.9646	0.8027	−0.3590	−3.3470
Grass	38.0263	−17.3102	−50.1629	46.1485	−38.9006	57.5954
Flooded vegetation	−19.1056	−45.7884	51.5275	6.1724	−27.0428	30.9841
Crops	43.1364	49.1162	−12.3878	27.3473	−18.9768	102.7375
Shrub and scrub	−18.3694	−20.3862	48.7592	−11.6638	12.3936	13.6198
Built	−18.7522	−3.4097	−11.9157	1.3991	−18.6016	−14.6509
Bare	10.7869	−13.6910	184.0556	−28.3663	299.7611	−60.2316
Total	0.1272	30.0783	−10.8003	0.0204	−3.6256	12.2402

Source: own study.

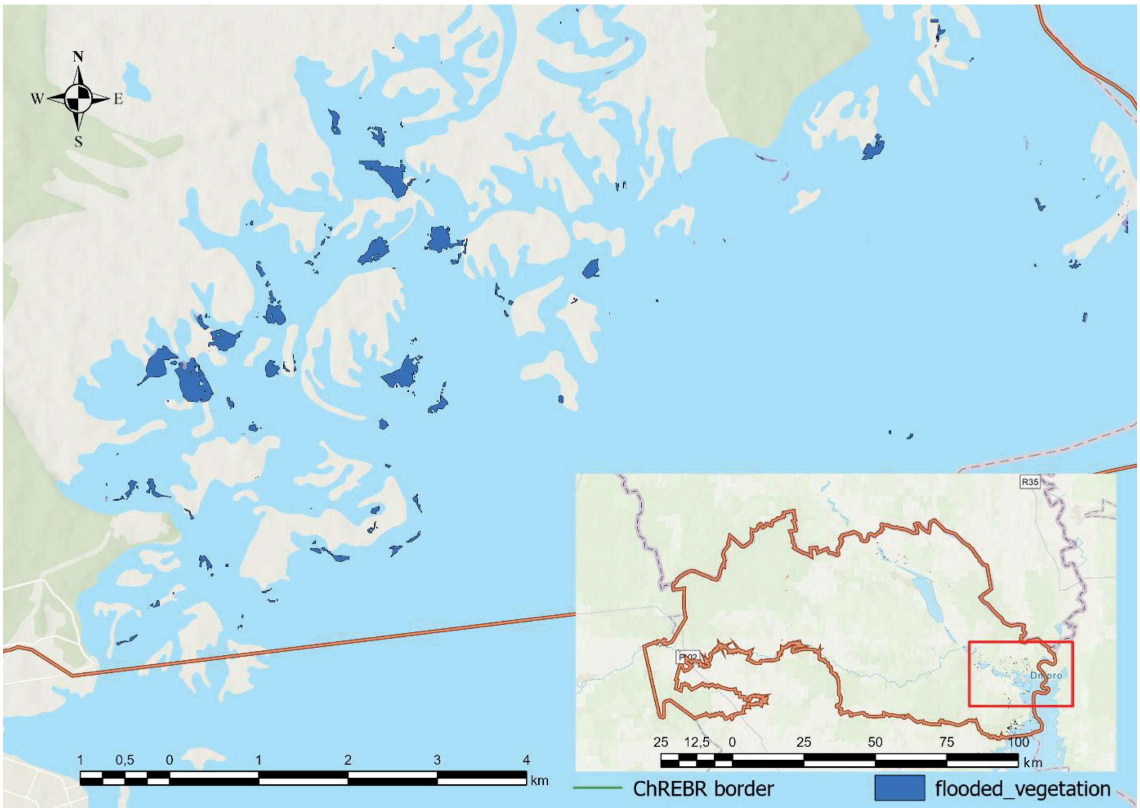

Fig. 3. Flooded areas of the Chornobyl Radiation and Ecological Biosphere Reserve (ChREBR) in 2022, transferred to the "water" category from the "tree" category; source: own study

connected with damage by fires (which is also indicated by the tendency to increase bare areas in 2021 (0.715 thous. ha) compared to 2020 (0.179 thous. ha)) and the gradual tightening of the previous year's burns by bushes and shrubs (Tab. 2). In our previous publications, it was noted that on fallows after fires, the grass began to recover intensively 2–3 weeks after the fire (Skydan *et al.*, 2021).

In general, remote sensing has shown to be a useful method for evaluating wildfire recovery. A brief overview of the burned region, both before and after (Skydan *et al.*, 2022a), can be obtained by using vegetation indices.

In addition, after the fires, new groupings and spatial structures are established, especially in the undergrowth of the forest, increasing the possibility of the migration of new plant species to this region (Fedoniuk and Skydan, 2023). However, in-depth field studies and more advanced techniques for remote sensing the earth are required to learn more about the new species that are moving into the region.

Other wildlife remote sensing studies of wildfire recovery have shown that revegetation can often be a lengthy process, taking many years if previous levels of both tree and shrub cover are to be restored. Thus, the development of forests on non-forest lands can take up to 60 years. Pine and birch seeds cannot germinate under a thick coating of sod. The likelihood of self-seeding increases only when the soil cover is disturbed. Birch, aspen, and shrub associations, which represent the first stage of the succession of the formation of forest vegetation, are the initial tree stands with many deciduous species that are developed in open regions. It will take at least 50 to 60 years for a dependable layer of pine to grow beneath the tent of these pioneer species, and some locations may not get any trees at all. The most successfully regenerated woody plants include the hanging birch (*Betula pendula* Roth), sticky alder (*Alnus glutinosa* (L.) Gaerth.), aspen (*Populus tremula* L.), buckthorn (*Frangula alnus* Mill.), species of blackberry (*Rubus caesius* L., *R. nessensis* W. Hall), and raspberry (*Rubus idaeus* L.). Scots pine (*Pinus sylvestris* L.) recovery is gradual and dependent on a variety of conditions (Fedoniuk *et al.*, 2021). This is a result of almost always increasing shrub vegetation areas at the expense of forest areas (Tab. 1).

It should be mentioned that the main structural elements of the shrub and grass layers of the pine and oak-pine forests are destroyed by 90–95% under the conditions of a strong ground fire. After 1–2 years, the abundance of the individual components (*Calluna vulgaris* (L.) Hull., *Vassinium myrtillus* L.) fell from 10–50% to 1–5%. The herbaceous layer of plants and the moss-lichen cover saw a change in species composition because of the fire. Most forest species play a minor part in the aftermath of the higher and lower intense fires in the affected areas. Simultaneously, an increase in projective coverage and persistence of synanthropic species (*Berteroa incana*, *Chamaerion angustifolium* L., *Chelidonium majus* L., *Erigeron canadensis* L., *Hieracium virosum* Pall., *Lactuca serriola* Torner, *Senecio vulgaris*, *Solidago canadensis* L., and *Taraxacum officinale* Webb) was discovered. The grass cover in the burners is a "mixture" of ruderal species, whose projective cover can occasionally reach 30–40%, and natural plants that were common here and are gradually regenerating after a low-level, medium-intensity fire after 1–3 years. Such shifts in vegetation cover are vividly shown by research done in the Drevlianskyi Nature Reserve (Ukr.: Drevlianskyi pryrodnyi zapovidnyk – DPZ) (Skydan *et al.*, 2022a).

WETLANDS CHANGES

According to DAZV (2022), climate change, reclamation, and drainage have caused changes in the wetlands in the exclusion zone. A characteristic feature of the hydrological regime of the watercourses of the ChREBR is the increased water content of the winter watershed, low spring waterlogging, and low and long summer–autumn watersheds. Small rivers, as well as smaller watercourses and reclamation canals, dry up during August–October (Fedoniuk *et al.*, 2019). In general, over the past seven years, there has been a tendency to increase the area of water bodies (Tab. 1). In part, the reason for this may be the clogging of the reclamation channels in the exclusion zone. This caused the appearance of several water bodies and the flooding of entire forest areas, which led to their deaths. The reason for this is that by 1986, 27 reclamation systems with a total area of >20 thous. ha (6.6 thous. ha are peatlands) were created on the current territory of the exclusion zone, mainly on the lands of agricultural enterprises. After the accident, their functional purpose (drying and humidifying) changed to control and prevent the inflow of radionuclides into the Pripet River (Shchyptsov *et al.*, 2019). A significant part of them (70–80%) is eutrophic and overgrown with reeds and cattails. More than half of the buildings have either been unusable for an extended period of time or necessitate renovation. Further use of reclamation systems for the purpose of radiation protection is not relevant. However, some of them can be used to regulate the flow and water regime of wetlands (maintenance of excess thaw and flood runoff), as well as to prevent and extinguish fires. Currently, their newness and neglect are the reasons for the formation of large areas of flooded territories everywhere in the CEZ.

As a result, the area of water ecosystems expanded by 1.9 thous. ha in 2018, which is explained by the fact that the yearly quantity of precipitation for the 2018 natural year was 762 mm, which is over two times more than for the previous natural year. Winter 2017–2018 on the Pripet River was marked by an increase in water content (caused by frost and rain inundation in December and snowmelt at the end of January) and an unstable ice cover. Even in the exceedingly dry year of 2020, the wetland areas of the Reserve decreased between 2019 and 2021, totalling between 7,204 and 7,483 ha. Flooding significantly affects changes in the structure of landscapes (Fig. 3). The transformation of 847 ha of forested land into flooded land in 2022 is a distinct illustration of the manifestation of this process.

Despite the positive impact of wetlands on the preservation of biodiversity (McCulloch and Robinson, 1993; Renzi, He and Silliman, 2019), the standing of flood waters for >20 days leads to the death of forest lands, especially young plantations up to 10 years old. The regions of the northern part of Ukraine are represented mainly by sub-forest conditions, in which Scots pine plays a key role. Scots pine does not need a lot of water, and such an amount is harmful to it (Grant, Tague and Allen, 2013). The danger also threatens those forest crops that do not stand in water but grow near the locations of flooding. The roots of trees can start to rot due to a high level of groundwater and soil overmoistening. A vivid example of the destruction of forest plantations is the coast of the Pripet River in the areas of the villages of Horodyshche and Kupuvate. Figure 2 presents the flooded areas of 2022, which moved to the category "water" from the category "forest" on the section of the Pripet River, where the erosion of the coastline is clearly marked, resulting in the formation of shoals, pockets, and islands, which negatively affect the stability of the channel.

At the same time, during the 7-year period, about 1,047 ha were transferred to the "forest" category from the "water" category (Tab. 1). In the floodplains of rivers, along the shores of lakes and reclamation channels, groups of marsh meadows and grassy marshes of *Phragmito-Magnocaricetea* develop, sometimes with the participation of willows. Groups of wet meadows in low and flat areas of river floodplains on meadow-swamp sandy soils of the association *Deschampsion cespitosae* are represented by the syntaxons *Deschampsietum cespitosae* and *Poa palustris – Alopecuretum pratensis*. These groupings are formed in the inter-band depressions of the central and tributary parts of the floodplain of the Pripet River. *Poetum pratensis* groups form on the upper parts of river floodplains and on the site of abandoned sown hayfields, on areas with sod, sod-meadow, and sandy meadow soils.

The decrease in ground water levels (in some places up to 2 m) during the last decades has led to the fact that part of the exclusion zone and adjacent territories are constantly in a state of high fire danger. For example, during the 2020 fires, bogs were significantly affected, and their recovery is longer compared to fallows. In particular, because of the fire in 2020, 1.96 thous. ha of bogs were damaged (Fedoniuk *et al.*, 2021). The restoration of bogs occurs only naturally, so returning them to their natural state and fully restoring the ecosystems will take a long time (Fig. 4).

ARABLE LAND CHANGES

If agricultural land remains undisturbed for a sufficient length of time, it is commonly expected that the land's vegetation will develop in accordance with the principles of secondary succession. Grasses typically "encroach" on agricultural land, with their successional phase lasting only a few months to a year (Perry, Oren and Hart, 2008). After their initial absorption by vegetation, the shrubs will migrate to the neglected area and cast a shadow over the emergent grasses, thereby outpacing them. The same is true for when trees arrive in the area and begin to outgrow the existing shrubs.

The dynamics of variations in the amount of ploughed land on the Chornobyl reserve's land during the analysed period are unsatisfactory (Tab. 3). If, over the preceding five years, their extent varied between 0.6 and 0.7 thous. ha, demonstrating the gradual stabilisation of plant communities on previously ploughed lands, then in 2022 it nearly quadrupled to 1.3 thous. ha (Tab. 1). Figure 3 depicts the cultivated areas in 2022. The Reserve and the Poliska community are disputing ownership of the lands close to the villages of Rudnia-Illinetska and Varovychi, and legal action is now being taken in this regard. The area between the villages of Marianivka and Nova Markivka is the territory of the 2020 fire, where the processes of artificial afforestation are ongoing. In addition, numerous minor ploughed areas are displayed on the territory of the Reserve, which indicate the places of artificial afforestation.

BUILT-UP AREAS CHANGES

From 0.047% of the Reserve's area in 2016 to 0.023% in 2022, the proportion of built-up areas in the Reserve's territory has been nearly steady. As a result, a gradual transition from formerly

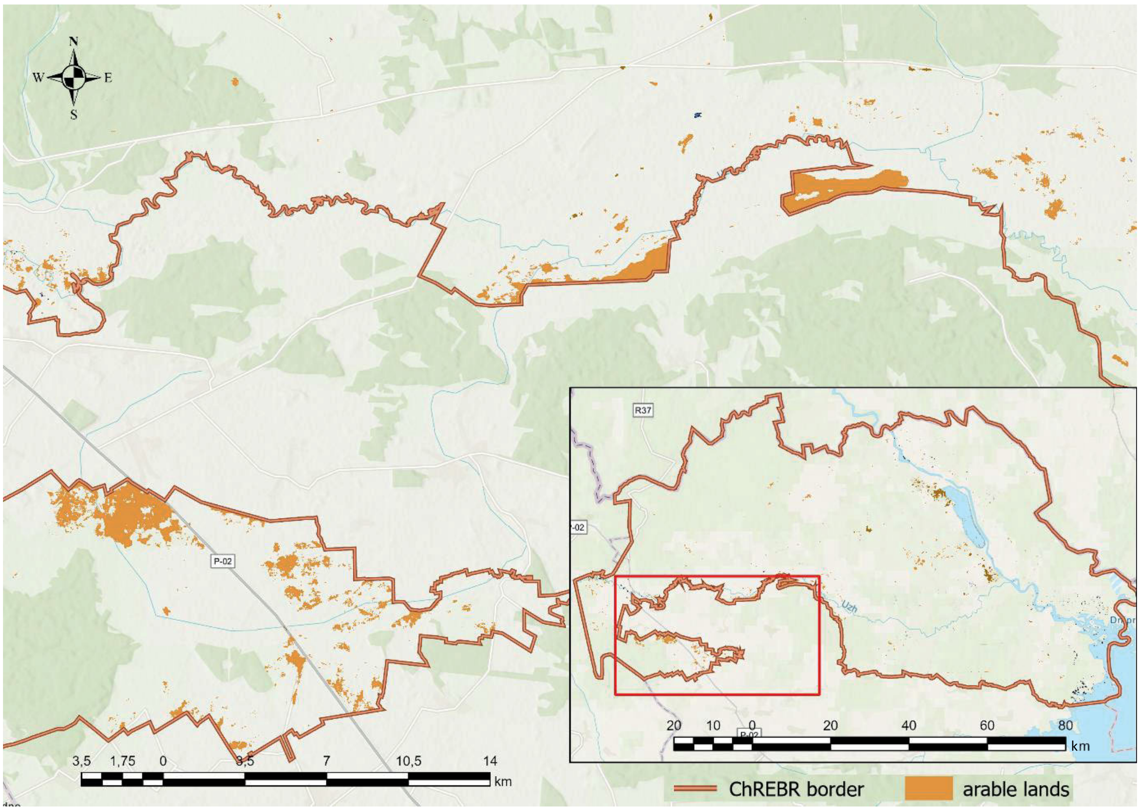

Fig. 4. Arable lands in the Chornobyl Radiation and Ecological Biosphere Reserve's (ChREBR) landscape structure according to 2022; source: own study

Table 3. Transition area matrix of the land cover of Zhytomyr Oblast from 2016 to 2022 (in %)

Land cover in 2016	Land cover in 2022							
	water	forest	grass	flooded vegetation	crops	shrub and scrub	built	bare
Water	6192.85	1478.94	0.04	322.83	0.11	23.77	9.15	127.37
Forest	94.98	2171.96	0.01	413.96	0.12	26.42	0.72	30.60
Grass	0.35	–	47.87	6.27	0.04	9.05	0.01	0.14
Flooded vegetation	225.85	292.62	43.94	173162.61	52.29	6935.72	6.04	756.78
Crops	0.34	0.65	0.99	478.22	115.66	536.71	0.83	306.40
Shrub and scrub	13.90	76.47	29.45	9156.49	158.21	17021.86	25.27	1866.61
Built	2.43	0.19	0.22	270.33	30.44	62.72	35.95	17.52
Bare	4.60	1.58	0.01	862.69	48.99	1256.48	0.45	1486.21

Source: own study.

urban areas to different kinds of landscapes is seen. Thus, there are several dozen former villages on the Reserve's land, some of which were destroyed during decontamination or because of fires. Some areas (Opachychi, Teremtsi, Paryshiv, and Kupovate) are still inhabited. Villages can be found in a variety of biological and physical settings. Settlements on steep sand deposits with a thickness of >2 m under fresh pine conditions make up one type.

Villages can be found in a variety of biological and environmental conditions. Settlements on steep sand deposits with a thickness of >2 m under fresh pine conditions make up one type. All the communities on the left bank of the Pripet River, aside from Paryshiv, as well as Horodyshche, Kupovate, Ivanivka, Otashiv, Benivka, a portion of Opachychi, and Novi Shepelychi are included in this list. Most of the settlements are found in regions with moderate soil and water conditions, which are mostly determined by edaphic complexes with fresh and wet conditions. Today, their extensive transformation is visible (gardens are forming in semi-natural successions, and wooden structures are nearly destroyed). Many animals are drawn to the foraging opportunities (fruit trees and a variety of cultivated plants) and shelter offered by constructions or building remnants. Now, a variety of animal species, including ungulates and rodents with mouse-like bodies, live in these settlements. An earlier analysis of the tree cover in the CEZ's urban environment also revealed a noticeable increase in trees and the fact that most of the trees in these formerly urbanised regions are in good health (Laćan, McBride and Witt De, 2015). Some of the settlements from our study that are represented today are not depicted in the images as typical urban areas.

DISCUSSION

After the Chornobyl nuclear power plant accident, radioactive waste and an abrupt decrease in anthropogenic activity provided the conditions that allowed ecosystems of animals and plants to recover and return to their natural states inside the Reserve's borders. Former anthropogenic landscapes can be restored and continue to exist thanks to the broad territory and landscape diversity. The natural mechanisms of both aquatic and terrestrial ecosystems are activated, and their natural dynamics are restored when human regulation is minimal. The activity of species and environment converters and the impact of extreme abiotic factors (fires, windstorms, floods, etc.) both contribute to the variability of the environment in natural biocenoses. Species of environmental converters (edifiers, key species, or ecosystem engineers) are characterised by the fact that they cause the greatest transformations in the ecotope because of their vital activities (Perry, Oren and Hart, 2008; Matsala *et al.*, 2021).

All elements of the landscape are included without exception in the rewilding processes. The same patterns were seen in the works of other authors, and according to Gemitzi (2020), 20% of the exclusion zone areas had a change in the type of land cover. According to him, the lack of human activity and the disregard for the soil in this area caused areas of dense and sparse forest to spread, displacing meadows. However, due to our research, we were able to examine all other types of land cover as well (Fig. 4), in addition to the dynamics of changes in the forest cover in the exclusion zone. A study by Gemitzi (2020) also highlighted this overgrowth of pastures since, in contrast to the previous study, the size of forest areas has changed over the past 7 years. However significant areas of forests were also lost because of flooding, particularly in the Pripet and Uzh rivers in 2018 and significant forest fires in 2020. Bushes and shrubs will grow more widely because of forest fire creation and the successional processes of such fires. These facts are discussed in other works that deal with post-pyrogenic restoration of the exclusion zone land (Babushka *et al.*, 2021; Matsala *et al.*, 2021).

The percentage of conditionally urbanised areas within the Reserve has exhibited a consistent trend over the course of the last seven years, as depicted in Figure 5. A considerable proportion of previous human settlements are currently undergoing or have already undergone the process of transitioning into natural landscapes. So, the processes of transformation of buildings (semi-natural successions are formed in the gardens; wooden

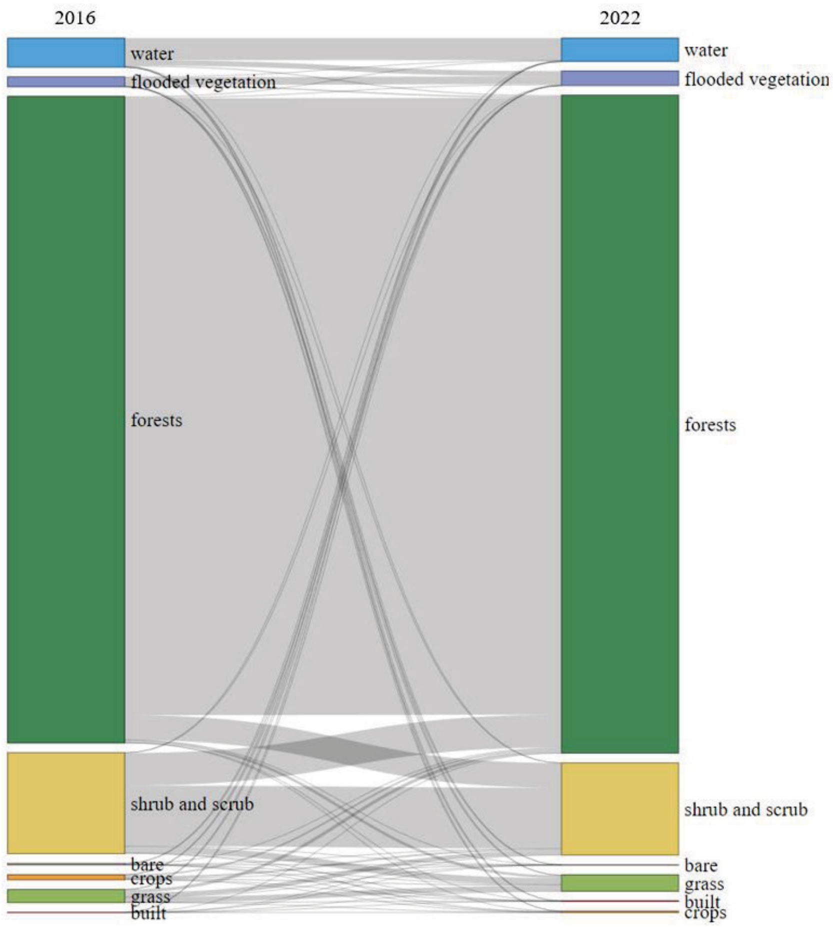

Fig. 5. The general scheme of transformation of land cover classes in the Chornobyl Radiation and Ecological Biosphere Reserve for the period from 2016 to 2022; source: own study

buildings are almost destroyed) are almost complete. Several settlements are no longer shown in space images as urbanised areas but rather as overgrown with shrubs and woody vegetation. The same trend is observed for the former ploughed areas; the only exceptions are the areas that are the subject of legal disputes since the formation of the settlement and some areas that are recorded as ploughed during the analysis of space images, but access to ground observations is limited due to the mining of the territory due to the Russian military aggression.

In general, the changes in the structure of landscapes in the last seven years prove that the intensity of transformation processes is gradually decreasing compared to previous decades. The reasons that cause changes in the structure of the land cover are determined primarily by the course of natural processes in the ecosystems with animals and plants, as well as by the periodic occurrence of fires, the clogging of reclamation channels, etc.

CONCLUSIONS

The conditions on the territory of the Chornobyl Radiation and Ecological Biosphere Reserve (ChREBR), which were formed after the accident at the Chornobyl nuclear power plant due to radioactive contamination and a sharp decrease in anthropogenic activity, led to the restoration of natural processes in the ecosystems of the animal and plant worlds. Rewilding processes cover all landscape components without exception.

The forest areas have changed over the past seven years, thus further overgrowth of pastures has occurred; however, significant areas of forests have been lost due to flooding, especially in the course of the Pripet and Uzh rivers (2018) and large forest fires (2020). The share of urbanised areas within the Reserve has remained stable over the past seven years. The processes of transformation of buildings (semi-natural successions are formed in the gardens; wooden buildings are almost completely destroyed) are almost complete. A number of settlements are no longer shown on space images as urbanised areas but rather as overgrown with shrubs and woody vegetation. The same trend applies to ploughed areas; the dynamics of their area are mostly connected with reforestation works or with violations of the regime of the protected area by the surrounding communities.

In general, the intensity of transformation processes is steadily diminishing compared to prior decades, as evidenced by the changes in the structure of landscapes over the past seven years. This indicates that most ecosystems have gone through phases of active transformation, and some of them have already moved into a state of homeostasis. The results of our research indicate that the main changes in the landscape structure of the ChREBR are caused by weather abnormalities (periodic forest fires, floods, etc.). Anthropogenic influence is practically excluded, and to this day only the influence of the consequences of human activity remains, such as the contamination of reclamation canals, which cause semi-natural successions. The methodology used in this study allows for real-time monitoring of the territory and current landscape changes, which provides tools for the continuous management of the territory of the largest reserve of Ukraine and, at the same time, the territory most contaminated by radionuclides in the world.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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