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Conservation policies and management in the Ukrainian Emerald Network have maintained reforestation rate despite the war

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The Russian-Ukrainian War, ongoing since 2014, impacts an area containing Emerald Network environmental-protection sites created through the implementation of the Bern Convention on the Conservation of European Wildlife and Natural Habitats. Here we explore the impact of this conflict on institutional links supporting environmental sustainability and conservation efforts. Using satellite data, we analyzed tree cover changes in the Luhansk region's Emerald Network protected areas from 1996 to 2020. The results reveal that the implementation of Bern Convention conservation policies led to a shift from deforestation (−4% each) to reforestation (+8% and +10%) on both sides of the Emerald Network divided by the demarcation line in 2014. It also shows that despite the war, territories under Ukraine control after 2014 continued reforestation (+9%), while sites under Russian control experienced dramatic forest loss (−25%). These findings emphasize the significant consequences of warfare-induced separation of local institutions on conservation areas and underscore the positive impact of the Emerald Network establishment, both before and after the conflict's onset.

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Sustainability, environmental protection, and biodiversity conservation are key objectives for European policymakers[1] as they pursue design-based actions for climate change mitigation[2], Green Deal[3], and sustainable development[4]. The signing of the Bern Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention) in 1979[5] was widely lauded as a key starting point for substantial progress in achieving ecological sustainability in Europe. Among other achievements, the Bern Convention enabled joint scientific efforts among member countries to help underlie sustainable development and biodiversity conservation policies focused on wildlife habitat preservation[6], bird conservation[7], and invasive alien species management[8] in European ecosystems. The Bern Convention also enabled state-level legislative action on the same sustainable development and biodiversity conservation goals[9]. In large part because of the Bern Convention, the European Union (EU) and neighboring countries created a transboundary conservation network called the Emerald Network, also called Nature 2000 for EU countries[9]. Beyond protecting endangered flora and fauna across a broad spatial area, the Emerald Network promoted sustainable human-nature interactions[9,10]. The Emerald Network required signatories to create special sites for biodiversity and endangered species conservation, implementation of EU environmental-protection legislation, and policies harmonized across the global network[10]. Nominating a site to be included in the Emerald Network involves four steps: (1) a national environmental commission identifies national areas of significant environmental value, (2) formal documentation is prepared and submitted, detailing the habitat characteristics of rare flora and fauna of the sites, (3) nominating the sites for including, and (4) integrating the new site into the international network through the conclusion of a biogeographical evaluation seminar[11]. By implementing policies to decrease soil degradation and erosion and improve climate regulation, water purification, and food production, for example, the Emerald Network has helped advance sustainable development and democratic decision-making concerning the environment. Positive impacts from the Emerald Network can be observed in two decades of reforestation trends in Europe[12] as well as long-term positive forecasts for future European forest extent[13] compared to global forest loss estimates of 2.3 million square kilometers during approximately the first decade of the 21st century[14]. Developing adaptive agri-environmental systems[15] and conservation practices[16] has helped to increase the ability of the Emerald Network signatories to maintain healthy agro-ecosystems while continuing to restore natural vegetation[17] and protect species population growth rates[18]. Many other examples of conservation success due to the Emerald Network exist, for example, the stabilization of the International Union for Conservation of Nature (IUCN) Red-List species population dynamics in different countries such as Armenia[19] and Ukraine[20].

Ukraine joined the Bern Convention in 1996 and started working towards the implementation of associated policies, environmental-protection legislations, and creation of Emerald Network sites in 2000 with the adoption of the national state program "National Program for the Formation of the National Ecological Network of Ukraine for 2000–2015"[21]. Today these sites serve as the southwesternmost boundary of the seven-country Emerald Network[22]. Ukraine's commitments to the Emerald Network were originally slated to be fully implemented by 2020, as outlined in the 2015 revised schedule for Emerald Network Implementation[23]. Ukraine has successfully included 377 sites in the Emerald Network, and currently, 160 of these sites are undergoing the verification process.[24,25]. The Russian Federations' launch of a military offensive in at least eight oblasts (regions) in Ukraine in early 2022, including the eastern oblasts of Donetsk and Luhansk which were already affected by occupation starting in 2014, substantially distributed the Emerald Network implementation process. Parts of Ukraine's Emerald Network sites were occupied via militarization by the Russian Federation. This conflict has not only provoked an economic and humanitarian crisis in Ukraine[26–28], bringing wide-spread destruction to industrial and civilian infrastructure and damaging socio-ecological systems[28–30], but also separated territories from conservation legislation, policies, and agreements[31]. Among the myriad of sustainable development and biodiversity conservation consequences stemming from this conflict are physical damage to protected areas and the absence of management and actions needed for adaptive management and evidence-based decision making[31,32]. New complex and dynamic risks to sustainable land use and conservation have emerged, in particular, new hotspots of high-level land cover/and use changes[28] and reduced socio-economic activities[33]. Ukraine has consistently demonstrated a commitment to restoration according to official statistics and remote sensing observations[34]. Such trends can be observed in territories that have been impacted by the war. For example, the "Kreidova Flora", an Emerald Network site located in the northern part of Donetsk oblast increased in pine tree cover area from 198.9 ha in 2009 to 316.9 ha in 2015[35].

The Luhansk region, characterized by flat terrain and a temperate climate, encompasses three distinct types of terrain: forests, steppe, and sand dunes[36]. Presently, deciduous forests cover 8% of the land area, predominantly along the banks of the Aydar and Siverskyi Donets rivers. These forested areas consist mainly of floodplain forests and bairak forests (i.e., broad-leaved forests situated on the upper reaches and slopes of streams), classified under the 2nd and 1st protection categories. The regulations associated with these categories prohibit "main purpose forest use" logging in protected forests, and the 2nd category permits limited forest use, allowing only tree felling for forest development and enhancement, such as maintenance and sanitary logging. Additionally, the Luhansk region features artificial forests predominantly comprised of coniferous trees, which have been planted on the plains. Fifteen Emerald Network sites that cover over 326 thousand hectares (th. ha) of area in this region were created to protect at least 307 animal and 139 plant species[36] listed as endangered or under threat of extinction in the Ukrainian and European Red Books and Bern Convention Resolutions. These Emerald Network sites also cover seven extremely valuable natural forest habitat types protected at the pan-European level and listed in the Resolution 4 of the Bern Convention[37]. War in the Luhansk region is now associated with a range of ecological impacts related to militarization, abandonment of land, and specifics of industrialization that increased vulnerabilities of ecosystems[32]. The largest land cover, land use, and land management changes on both parts of the Luhansk region divided by the front line are related to militarization that damaged infrastructure and natural lands. For example, large wildfires on both parts of the Emerald Network, divided by a front line, were recorded in July 2020[38] and after the February 24th, 2022 large-scale invasion of Ukraine. Flooding of abandoned or damaged coal mines disturbed the water balance and decreased water quality due to consequent pollution of the region[39]. For instance, a disruption in the electricity supply at the "Zolote" coal mine resulted in its flooding, posing a substantial risk of pollution to the Siversky Donets river[39,40]. Since 2014, recurring mine flooding incidents have caused a notable increase in the concentration of pollutants such as lead, nickel, cadmium, and other persistent organic substances in the water bodies within the Luhansk region[41]. Extensive damage to Ukraine's energy infrastructure has led to interruptions or inefficient operation of water treatment facilities, resulting in a substantial decline in water quality standards due to the presence of polyaromatic hydrocarbons, volatile organic compounds, octylphenol, heavy metals, and mercury[42]. One of the most hazardous areas in eastern Ukraine is the "Yunkom" mine, situated in the Donetsk oblast near the administrative border of the Luhansk region. This mine was the site of a Soviet government nuclear explosion in 1979[43]. Since then, the mine has implemented special exploitation restrictions, including underground water pumping, to prevent radiation contamination of neighboring rivers and the Azov Sea. Since 2017, exploitation restrictions have been halted by the Russia-controlled local administrations; the current state of the nuclear waste storage facilities deep in the mine is unknown.

Modern warfare in Ukraine has dramatically increased risks to both the regional and global environment[44,45]. In the Luhansk region, both active and decommissioned industrial facilities house chemicals; damage from artillery shelling, fire, and electricity cuts release chemicals and cause substantial soil, water, and air pollution. For instance, in March and April of 2022, explosions on the grounds of the former "Barvnyk" factory in Rubizhne released unhealthy amounts of aromatic hydrocarbons and their derivatives into the atmosphere[44]. In April 2022, two powerful explosions at the "Zorya" chemical factory released a massive cloud of nitrogen oxide[46]. In March 2022, an explosion at the railway station in Rubizhne city resulted in the release of chemical products from the "Zarya" and "Azot" plants, leading to pollution of nearby areas, including water reservoirs[46]. Beyond explosions from missiles and carpet bombs at industrial chemical facilities, air pollution has been exacerbated by hard-to-extinguish fires at oil refining and storage facilities[47,48]. Otherwhere examples of environmental impacts from the war include the cessation of insect control activities, sanitary logging, and forest "fuel treatments" techniques, all of which are essential forest management practices implemented by Ukrainians but halted by Russia-controlled administrations. Forest management innovations such as the implementation of electronic wood accounting[49] and an electronic open register of forest tickets (i.e., an informational portal granting access to all issued logging approvals)[50] have helped reduce illegal logging and associated trade. These systems facilitate wood chipping[51] and electronic monitoring of its condition, purpose, transportation, and export[52], as well as the oversight of legal logging activities. The lack of monitoring has left the logging situation in the separated territories unregulated and unsupervised.

Modern warfare has also had profound impacts on the well-being of communities, particularly those directly relying on natural resources for their livelihoods (e.g., agriculture). Unsurprisingly, international laws emphasize the need for restoration of and compensation for war-damaged ecosystem services[53]. The destruction wrought by war goes beyond direct damage to ecosystems through shelling; it extends to the indirect effects of military infrastructure development, weapons testing, and the disposal of military equipment and ammunition once peace is secured[54]. The use of artillery and landmines not only inflicts direct harm on people but also triggers a cascade of secondary impacts from soil acidification[55], disruptions in soil formation due to soil material displacement[56], and contamination with metal and plastic fragments. Moving military equipment such as heavy tanks can lead to altered soil hydraulic properties, erosion, liquefaction, and mud formation[57,58]. Restoring damaged soils is a costly and time-consuming process[59]. Furthermore, leaking diesel fuel and other chemicals into the soil and underground water can take decades to remediate. The presence of unexploded shells and land-mine fragments in the soil heightens the risks and complexities of cleanup efforts, as their magnetic properties can hinder metal detectors, making the process extremely dangerous for remediation. Landmines threaten local populations and wildlife species, as explosives may go undetected[60]. These adverse effects underscore the critical importance of addressing the impact of warfare on biodiversity and wildlife populations, which is of paramount concern for the preservation of nature itself. The study conducted by Daskin et al. in 2018[61] sheds light on the profound impact of conflicts on Africa's natural reserves from 1946 to 2010. This research highlights the pivotal role of conflict frequency as an essential variable directly affecting wildlife populations within these reserves, showing a strong correlation with significant wildlife population declines. On a global scale, military conflicts emerge as potent catalysts for species extinction, posing a grave threat to biodiversity. Furthermore, the ongoing trends in conjunction with other drivers of climate change, such as greenhouse gas emissions and deforestation, paint a dire picture for the future. If these patterns persist, it is projected that by 2060–2080, we may witness the extinction of as much as 10–15% of animal species[62]. However, the situation becomes even more alarming when we consider the potential consequences of a nuclear conflict, where this staggering figure could skyrocket to a devastating 20–50%[62]. The war in Ukraine can have catastrophic consequences for European ecological security and biodiversity. According to the Land-Mine Monitor reports in July 2022 over 280,000 km^2 were exposed to the conflict, 21,000 km^2 of which were exposed in 2018[63]. The environmental devastation, coupled with its adverse effects on Ukraine's ability to fulfill its climate change commitments and SDGs[64], as well as the reliability of the Russian Federation as a partner for climate change initiatives[65], will have far-reaching and detrimental consequences on the long-term prospects of sustainable development and climate resilience in the region.

In summary, the war has inflicted a range of harms on the socio-ecological system which are very likely to have lasting socio-ecological impacts. Assessing the environmental consequences of these events is nearly impossible due to the lack of physical access to these areas. To these ends, we aimed to explore the impact of the militarized occupation of natural protected areas and the subsequent interruption of conservation efforts on ecosystem sustainability. Such research can be conducted only using long-term observations before the military conflict and after the hot phase of the conflict and the establishment of a stable demarcation line. Due to the active warfare in 2022 and 2023, it is premature to quantify ecosystem conservation consequences. Thus, we focused on the progress of the Emerald Network establishment in the Luhansk region (Fig. 1) in terms of land-cover changes in the environmental protection zones from 1996 to 2020.

Quantification and evaluation of policies and processes underlying the establishment of Emerald Network in the Luhansk region was conducted by analyzing forest cover changes trends in the territories on both sides of the conflict demarcation line established after the "Minsk 2" and "Misnk-3" agreements in 2014 and 2015. Utilizing the principles of deforestation pressure-based management regime comparison[66], we evaluated the effectiveness of the Bern Convention's conservation policies and examined the impact of the territory's separation on the environment by comparing forest area changes in territories under Ukrainian and Russian control. Gathering ground-referenced data in active conflict zones is impossible because of the high risks to security. Consequently, we employed remote sensing-based approaches, commonly used for assessing areas affected by warfare, to analyze changes in land cover and land use before, during, and after the conflict. A similar approach was employed in a study by Aung[67], which investigated the environmental impact of armed conflict in Rakhine. We chose 1996 to 2020 as a research time period for the analysis because during these years Ukraine joined The Bern Convention, and the planned final year for

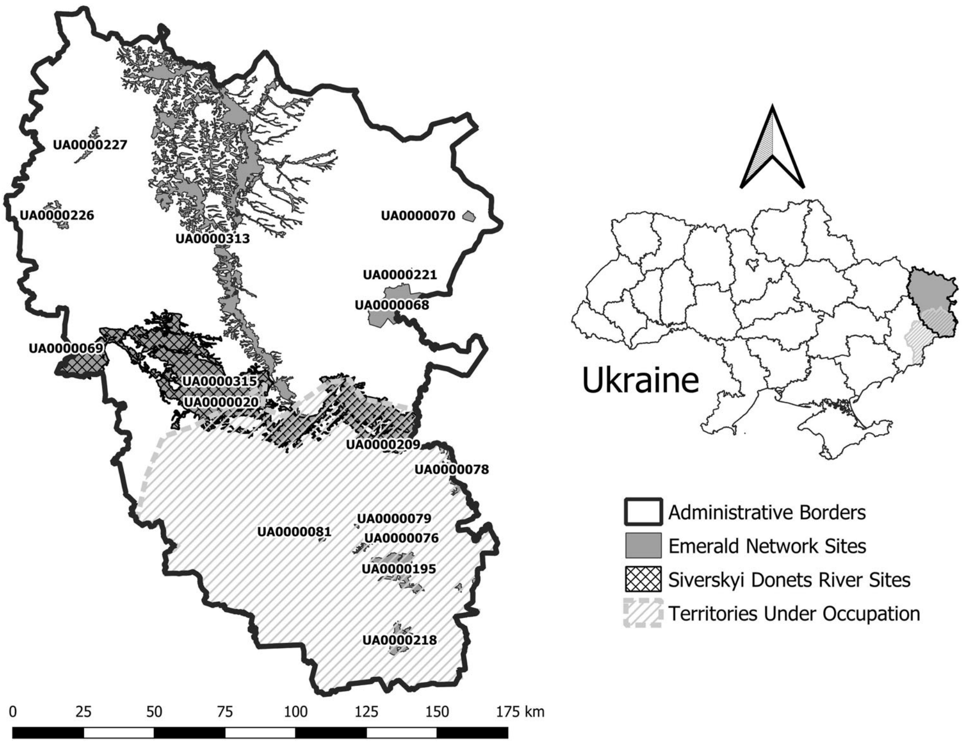


Fig. 1 Emerald Network sites in Luhansk region separated by demarcation line. Each unique ID of the Emerald Network site is listed in the European Union documentation[77] and linked to the centroid of the polygons represented on the map. The gray hashed area represents territory under Russian control after 2014 with an established demarcation line in 2015. The hashed area represents Emerald Network sites established on the blanks of Siverskyi Donets river.

Emerald Network establishment[23] (excluding time after the catastrophic wildfire[38]). This time period is further divided into three parts. The first (from 1996 to 2000) shows the trend before the creation of the Emerald Network. The second (from 2000 to 2013) shows the progress of the Emerald Network establishment before the conflict. The third (from 2013 to 2020) shows the progress of conservation after the beginning of the conflict. After the end of the Russian–Ukrainian war, the establishment of a stable demarcation line, and ecosystem's restoration process beginning, the methodology presented in this article can be extended to other regions of Ukraine for the post-war ecosystem conservation damage assessment.

Results

We carried out a land-cover change assessment with the use of generated maps of the Luhansk region for 1996, 2000, 2013, and 2020 (Fig. 2). The accuracy values of tree cover maps in terms of F1 score (which is the harmonic mean of the user's accuracy and producer's accuracy[68]) were 0.9, 0.9, 0.84, and 0.88, correspondingly (Supplementary Table 1).

Between 1996 and 2000, the annual deforestation rate on the territories under Ukrainian control was -0.86 ± 0.22 th. ha per year or overall -3.42 ± 0.86 th. ha (Fig. 3). A similar rate was observed in territories taken under Russian control after 2014 at an annual rate of -0.28 ± 0.1 th. ha per year or overall -1.1 ± 0.4 th. ha. Since 2000 Ukrainian government considered the creation of Emerald Network sites as a priority for the short- and long-term environmental-protection strategies[69,70]. After work began on establishing Emerald Network sites and implementing EU sustainable development policies, changes in trends on both parts of the Emerald Network are evident. Between 2000 and 2013, annual reforestation rates in territories under Ukraine control were $+0.67 \pm 0.09$ th. ha per year with $+8.7 \pm 1.2$ th. ha total forest area growth. At the same time, territories that were to be under Russian control had an annual rate of $+0.19 \pm 0.06$ th. ha per year and total $+2.48 \pm 0.79$ th. ha growth. The military conflict in 2014, and the subsequent segmentation of territory on the occupied and non-occupied by demarcation line, changed trend's patterns during 2013–2020. During this time period, we found that territories that remained under Ukraine's control kept in place reforestation and conservation processes with $+1.19 \pm 0.18$ th. ha per year annual rate and total area in an increase of $+8.3 \pm 1.25$ th. ha. However, territories that were taken by the Russian control experienced rapid deforestation of -1.23 ± 0.15 th. ha per year annual rate and -8.6 ± 1 th. ha total forest area loss. Results (Supplementary Tables 2 and 3) indicate that territories remained under Ukraine's control even under the conditions of military conflict with increased vulnerability and consequent ecological problems[31,32,36] in the region continued progression of conservation while territories under Russian control lost 20 years of sustainable development progress with 25% of forest loss (compared the 2013 estimates).

The majority of forest area in the Luhansk region is concentrated in the floodplains of the Siverskyi Donets River site (Fig. 4) and was divided into two parts by a demarcation line. Both parts have the same ecological communities of flora and fauna[36] and are equally vulnerable to ecological problems due to post-military action damage. Before the conflict in 2014, this area was entirely under Ukrainian government control and not segmented; this is reflected by the uniform and consistent land-cover change trends before the war. However, after the partial separation of the region, we observed severe deforestation. Between 2013 and 2020, Ukraine-controlled territories gained 18% of forest area, while Russia controlled lost 31%.

Our analysis indicates that Ukraine achieved a total reforestation area of 11.17 ± 1.45 th. ha before the beginning of the conflict and 17 ± 1.74 th. ha from 2000 to 2020 on the Ukraine-controlled territories. At the same time, deforestation rates of

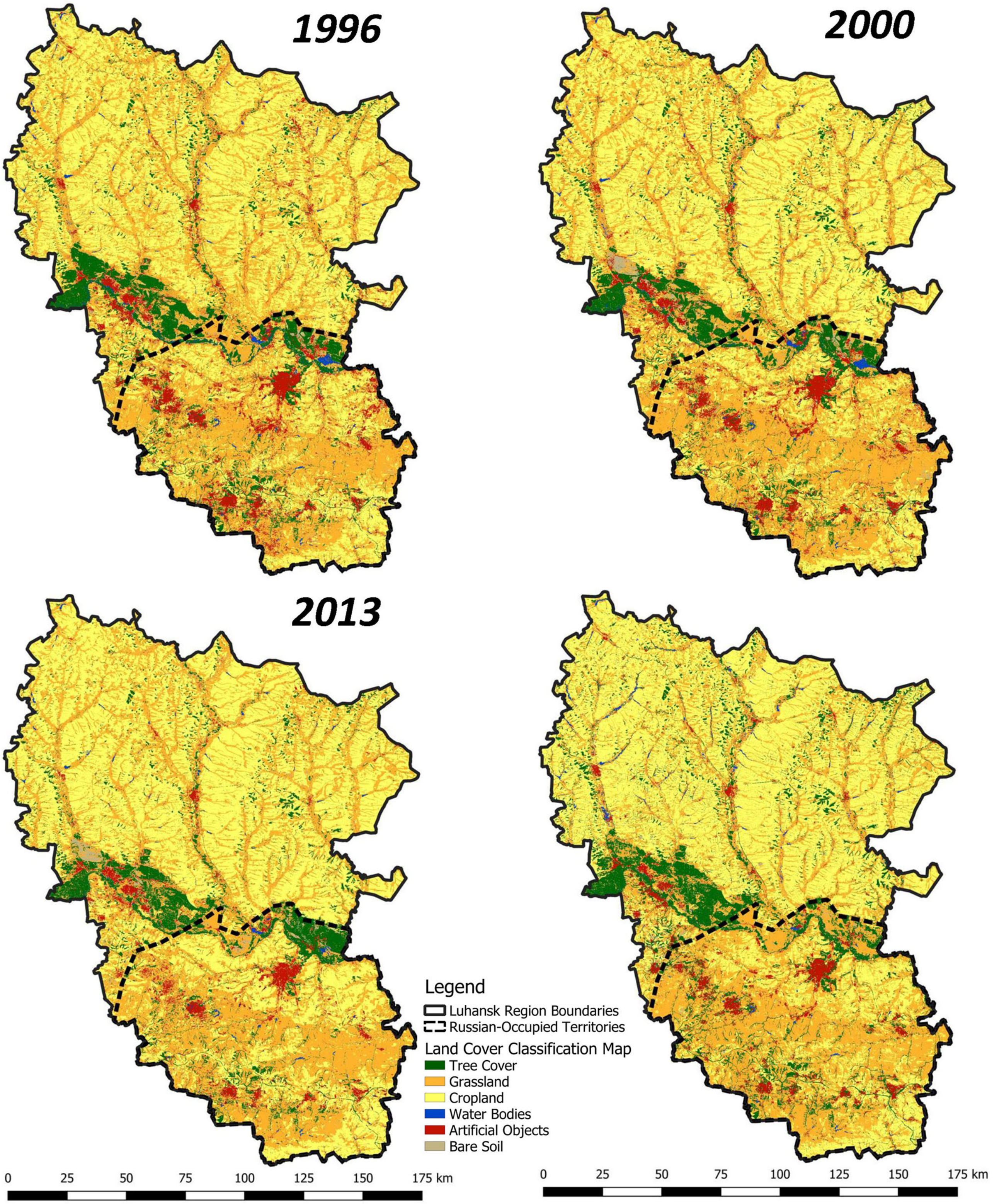
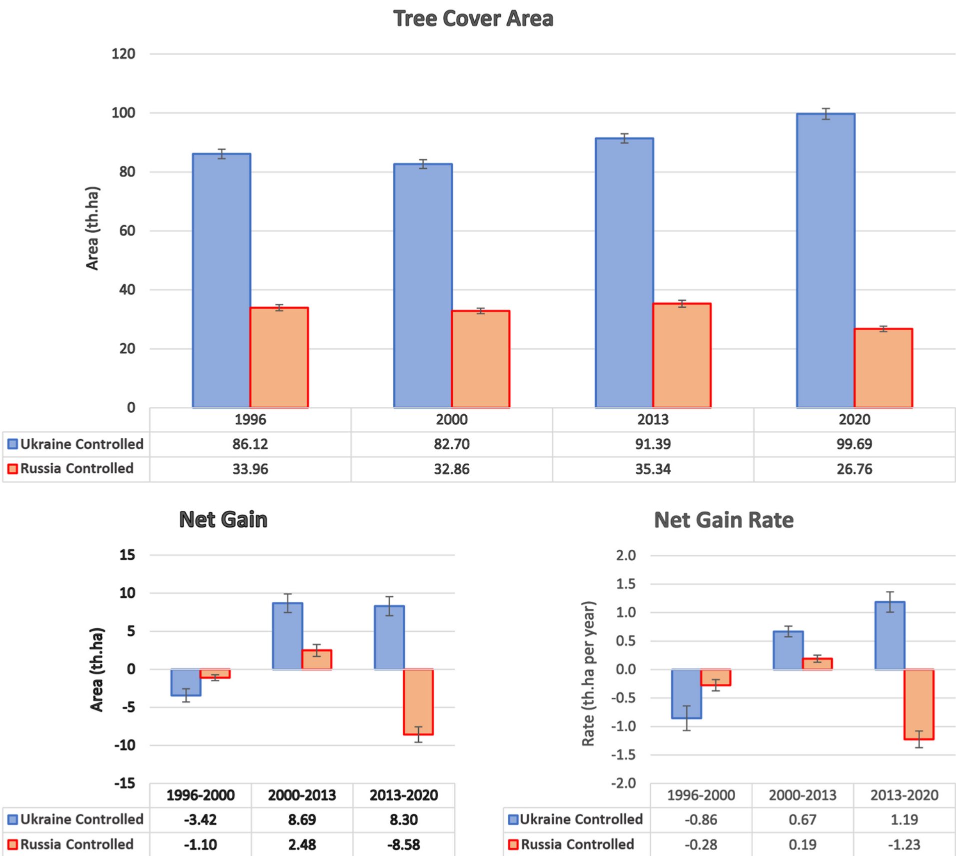


Fig. 2 Land-cover classification maps for Luhansk region from 1996 to 2020. Land-cover classification at 30 m spatial resolution was conducted based on the compositing of Landsat-5 data for 1996, Landsat-5 and 7 for 2000, Landsat-8 for 2013, and Sentinel-2 for 2020. The dashed line represents the demarcation line established after 2015.

territories under Russian control with similar bio-physical characteristics[36] and the same war-related vulnerability factors indicate that the separation of ecosystems from environmental-protection institutions and policies through the occupation of territory led to dramatic degradation of the environment and loss of ecosystem sustainability.

The shift from deforestation trends during 1996–2000 to reforestation between 2000 and 2020 (in Ukraine-controlled



	1996	2000	2013	2020
Ukraine Controlled	86.12	82.70	91.39	99.69
Russia Controlled	33.96	32.86	35.34	26.76

	1996-2000	2000-2013	2013-2020
Ukraine Controlled	-3.42	8.69	8.30
Russia Controlled	-1.10	2.48	-8.58

	1996-2000	2000-2013	2013-2020
Ukraine Controlled	-0.86	0.67	1.19
Russia Controlled	-0.28	0.19	-1.23

Fig. 3 Tree cover area changes for Emerald Network sites in the Luhansk region. The top plot shows the total areas for territories under Ukraine (blue) and Russia's control (red). The bottom plots demonstrate net gain changes and net gain rates for respective time periods. Error bars represent standard error.

territories) can be attributed to amendments and ongoing enhancements in national legislation related to forest management. Ukraine's primary legal framework governing the forestry sector is the "Forestry Codex of Ukraine," which was adopted in 1994[71]. Although Ukraine joined the Bern Convention in 1996, the country initiated legislative amendments to align with international environmental standards and EU policies only in 2000. From 2000 to 2013, there was a consistent evolution of national legislation addressing the legal and financial aspects of forest use in Ukraine. During this period, the "Ukrainian Forests" state program[72] was introduced, outlining Ukraine's forestry development strategy and the establishment of the Emerald Network as part of the "National Program for the Formation of the National Ecological Network of Ukraine for 2000–2015"[21]. The new forestry strategy in Ukraine encompasses various objectives, including reforestation, enhancing forest productivity, quality, environmental conservation capabilities, biodiversity preservation, sustainability, climate resilience, the implementation of sound forest management practices, forest protection, and the enhancement of state oversight[72]. These principles were reflected in the further changes of forestry legislation[71]:

- Implementation of forest tickets for logging control (article 69 with changes in 2009 and 2012);
- Conservation of endangered tree species listed in the Red Book (article 70 from 2012), seeding trees and trees used for Red Book species nesting (article 70, from 2017);
- Compulsory reforestation of forest areas damaged by logging, fires, storms, or drought within one year of the incidents (article 80 after 2012);
- Mandate for forest owners and users to implement fire prevention and other measures for the protection and preservation of forests (article 86 from 2012);
- Regulation of forest protection, restoration, utilization, and the role of aerial operations (article 86 and article 94 from 2012);
- Halt of forest-hazardous operations by enterprises (article 109 from 2012);
- Establishing allowable limits for timber harvesting (article 74 from 2012);
- Rules and limitations for altering land use in forested areas (articles 57 and 59 from 2014);
- Definition of natural forests (article 1 from 2017);
- Supervision of the environmental impact caused by enterprises (article 29 from 2017);
- Discontinuation of a forest user's operations due to environmental impact (article 29^2 from 2017);
- Ban on all forms of logging in natural forests. (article 70, 79, 84 from 2017);
- Identification, protection, and integration of natural forests into the ecological network have become integral aspects of forest management (article 46 from 2017).

Between 2000 and 2020, the "Forestry Codex of Ukraine" underwent a total of 110 amendments, with 55 of them being enacted before 2014. The reforestation of regions within the Emerald Network was notably influenced by the implementation of these new amendments and forest policies, along with adherence to forest legislation. In the Ukraine-controlled areas, most of the restored forest was the result of deliberate planting as part of

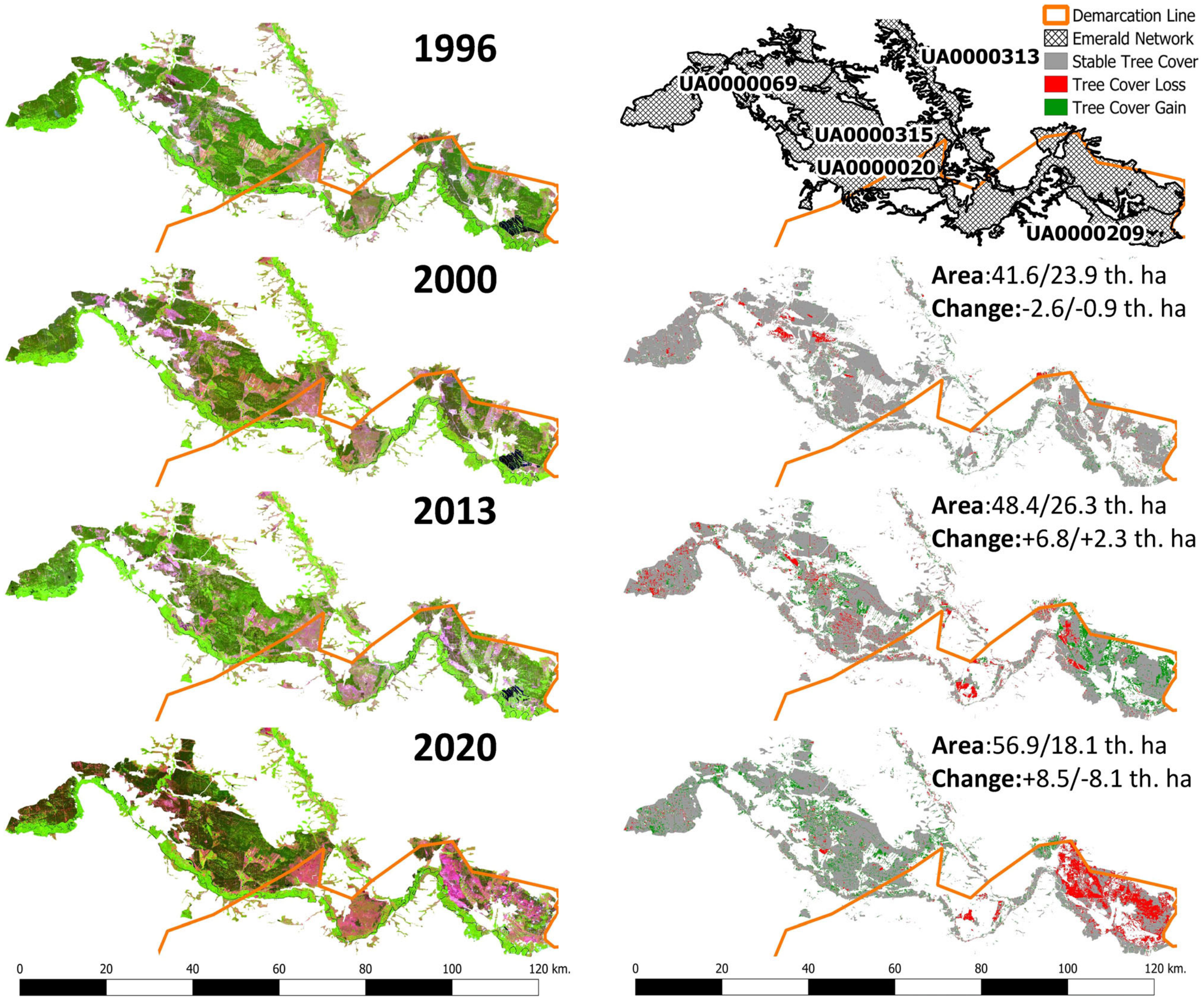


Fig. 4 Emerald Network sites established on the blanks of Siverskyi Donets river in Luhansk region. The map represents Emerald Network sites with IDs UA0000069, UA0000315, UA0000209, UA0000078, and the southern portion of UA0000313[77]. The left images show Landsat images for 1996 to 2013 and Sentinel-2 images for 2020 in false color with short wave infrared 1 (~1.6 µm), near-infrared (~0.8 µm), and blue (~0.4 µm) band combinations. The right images show the stable, gained, and lost tree cover for respective years and time periods. Areas and changes represent tree cover changes and net gains for territories under Ukraine and Russia's control, respectively.

site restoration and development plans. Conversely, in areas under Russian control, there was a lack of forest management activities, and there was discouragement in the implementation of chapters 14, 15, and 16 of the "Forestry Codex of Ukraine,"[71] which are crucial for forest protection and restoration. This contravenes Ukrainian forestry legislation, which mandates that forest users or responsible administrations must restore lost forest areas with the same tree types within one year of deforestation events. This discrepancy helps to explain the considerable deforestation in areas of the Emerald Network under Russian control.

Methods

Land-cover classification. Land-cover mapping was conducted in the Google Earth Engine platform using Landsat and Sentinel-1/2 satellite images and a supervised classification approach[73]. For this purpose, we generated collections of cloud-free month composites based on four data collections (Supplementary Table 4) for the study area and ground reference samples that covered main land-cover classes: tree cover, grassland, cropland, water bodies, artificial objects (impervious surfaces), and bare land. Taking into account the geospatial variations in the imagery used for compositing and the constraints posed by GEE, we created separate training data collections comprising 5000 points for each year. It was not possible to acquire ground-based reference data for the study region because of warfare activities and/or the absence of historical data. Therefore, the reference data were derived through photointerpretation by visual analysis of satellite data from Sentinel-2 and Landsat missions as well as historical very high spatial resolution imagery available through the Google Earth platform. For labeling, we used all available images for each target year which allowed us to accurately identify each land-cover class. Due to the differences in the numbers of available images and properties of data collection, to reach optimal accuracy and considering limitations of GEE in terms of resources and the model's complexity to classify each pixel of the map represented as a vector of multi-spectral features in the time-series of composites of satellite images we used a random forest algorithm[74] with 10 decision trees for 1996 and 2000, 100 for 2013, and 200 for 2020. The resulting maps were delivered in the Albers Equal Area projection at 30 m spatial resolution. For validation purposes, we independently generated and labeled 1,200 random points over the territory of the interest that was never used for model training.

Area estimation. Area estimation of land-cover changes directly from maps (pixel counting) is a biased estimator due to the problems related to the pixel's resolution limitations, mixed-pixels effect, pixel shifts caused by the image misregistration problems, and classification errors. Thus, we used a stratified random sampling approach[68], where samples were represented by a 30 × 30 m pixel. The number of samples N_i for strata i of stratification set S that targets overall accuracy can be estimated with the use of precision p_i obtained by validation with the use of generated random points and weight of strata (proportion of strata area and total area) w_i by formula[68,75]:

$$N_i = w_i \left(\frac{\sum_{j \in S} w_j \sqrt{p_j(1-p_j)}}{0.01} \right)^2 \quad (1)$$

Our stratification was designed based on changes in the four maps and represented three types of temporal behaviors for the forest: stable forest, forest with changes (at least one per 4 years), and stable non-forest. We used the strata buffering technique to mitigate the emission error effect on the land-cover change area[76]. Area estimations required 876 samples for territory of interest, however considering the high level of segmentation of forest in the region we decided to generate individual sample sets for each Emerald Network site to reduce uncertainties. In total, we generated 2327 points for territories under Russian control and 2665 for territories under Ukraine control (Supplementary Table 5). Based on this stratification we estimated areas A of each change type k of C (tree cover gain, loss, stable, or stable not forest) for each time period by formula[68,75]:

$$A_k = A_t * \sum_{i \in S} \frac{n_{i,k} * w_i}{\sum_{j \in C} n_{i,j}} \quad (2)$$

where $n_{i,k}$ and $n_{i,j}$ represent the number of samples of each i strata class that correspond to k or j on the map and reference. The error E_k was estimated based on the total area of the study area (A_t)[68,75]:

$$E_k = A_t * \sqrt{\sum_{i \in S} w_i^2 * \left(\frac{n_{i,k} * w_i}{\sum_{j \in C} n_{i,j}} \right) * \left(1 - \frac{n_{i,k} * w_i}{\sum_{j \in C} n_{i,j}} \right)} \quad (3)$$

Data availability

Data related to the paper can be downloaded from the following: Land-cover Maps for Luhansk region (1996, 2000, 2013, 2020) with style: https://doi.org/10.5281/zenodo.10009646. Stratification map: https://doi.org/10.5281/zenodo.10010158. Generated sample points that reflect stratification type and land-cover change: https://doi.org/10.5281/zenodo.10010466. Excel sheets with area estimation: https://doi.org/10.5281/zenodo.10010519.

Code availability

Google Earth Engine Scripts for satellite image compositing and land-cover classification are available at https://github.com/LeonidShumilo/Occupation-of-Environment-Classification

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