Active versus passive restoration: forests in the southern Carpathian Mountains as a case study

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Abstract: Active and passive restoration are both increasingly considered as options for nature recovery, with potential to help address the current climate and biodiversity crises. So far, however, there is little practical information on how to gauge the benefits and limitations of each approach, in terms of their effects on large-scale ecosystem composition, structure, and functioning. To address this knowledge gap, this study used satellite remote sensing to investigate changes in land cover and primary productivity within the forests of the Făgăraș Mountains in southern Romania, where large-scale restoration and land abandonment have simultaneously taken place across the past two decades. To our knowledge, this study is the first to contrast the impacts of active and passive restoration within a single landscape on components of ecosystem structure and functioning at such temporal and spatial scales. Results show active restoration activities to be very effective at facilitating the recovery of cleared forests in small parts of the landscapes; but they also highlight substantial areas of natural forest expansion following agricultural abandonment, in line with regional trends. Altogether, our approach clearly illustrates how freely available satellite data can (1) provide vital spatially explicit insights about large-scale and long-term transformations in ecosystem composition, structure and functioning; and (2) help contrast the impacts of restoration approaches on vegetation distribution and dynamics, in ways that complement existing ground-based studies.

Keywords: Restoration; Rewilding; satellite remote sensing; land cover; environmental monitoring; Forests

Introduction

Human actions have "severely altered" three quarters of ecosystems and continue to drive the global climate and biodiversity crises (Díaz et al., 2019). Because of their capacity to support biodiversity and to remove and store carbon from the atmosphere, forest ecosystems are a key focus for efforts to combat these crises (Strassburg et al., 2020; Pörtner et al., 2021). However, agricultural expansion and forest degradation for resource extraction continue to drive forest loss, such that global forest cover is now 68% of pre-industrial levels (Díaz et al., 2019) and 70% of forest is within 1 km of a forest edge (Haddad et al., 2015). These changes, along with the associated losses of biodiversity, reduce the resilience of forest ecosystems to future perturbations and climate change (García et al., 2018) and also their ability to continue to provide the range of ecosystem services on which humanity relies (Cardinale et al., 2012, Gamfeldt et al., 2013).

Ecosystem restoration is a key facet of international initiatives to combat environmental declines: 2021 marked the start of the United Nations Decade on Restoration and nature restoration is one of the four legally binding pillars of the European Union (EU) Biodiversity Strategy for 2030 (European Commission, 2021). However, traditional active restoration projects tend to be costly and challenging to sustain over large temporal and spatial scales (Crouzeilles et al., 2020), and changing climates and species assemblages mean recreating past ecosystems is unlikely to be successful (Suding, 2011). This has increased interest in passive restoration approaches like "rewilding" and "open-ended restoration" that aim to restore ecosystem processes at scale and foster resilience to future change with minimal management intervention in the long term, rather than aiming for specific idealised historical states or compositions (Pettorelli et al., 2018a). Such projects focus on trajectories of change and creating diverse habitat mosaics and complex species communities that are likely to be more resilient to the effects of climate change (Hughes et al., 2012), making them appealing and potentially cost-effective strategies to address the biodiversity and climate crises. Nature recovery projects can be seen to occur along a spectrum of management levels between the two extremes of intensive ongoing management and complete non-intervention, with many falling between somewhere in between, for example requiring some initial intervention (such as reintroductions or planting) but without ongoing management or a final desired target state (Carver et al. 2021).

However, the question of how best to standardise the monitoring of changes in ecosystem functioning and service delivery, and by extension assess the ongoing success of passive and active restoration activities seeking to improve these, is challenging. Few studies have compared different restoration approaches in the same setting (Jones et al., 2018). More broadly, studies assessing the ecological and socio-economic benefits of restoration projects remain relatively rare, partly due to the fact that restoration is an ongoing process that requires long timescales (Wortley et al., 2013; Moreno-Mateos et al., 2020). As well as a need for more data, multiple studies have highlighted the need for a transparent, globally consistent framework to monitor the effectiveness and outcomes of conservation and restoration efforts, and the potential role for satellite remote sensing in such frameworks (e.g., Geldmann et al., 2021). In particular, the range of data products and resolutions, the global coverage, and the extensive back-catalogue of data offered by satellite remote sensing could allow for the cost-effective, practical and repeatable monitoring of ecosystem processes, functions and services across large spatio-temporal scales and remote areas (Pettorelli et al., 2018b). This potential is likely to increase as sensor technology, data processing and analytical approaches continue to advance. Despite this, few studies have used satellite remote sensing to investigate the effects of large-scale restoration, and to compare the outcomes of more active and more passive approaches within a given landscape, across decades.

To help address this knowledge gap, this study aims to use satellite remote sensing to investigate and contrast changes in land cover and primary productivity across a landscape that is undergoing both active and passive approaches to nature recovery in the southern Romanian Carpathian Mountains, in Central Eastern Europe. This region is of key conservation interest, containing the largest remnants of old growth and semi-natural forest in Europe (Veen et al., 2010), many endemic plant species (Breman et al., 2020) and the most complete large carnivore and herbivore guilds in Europe (Griffiths et al., 2014). There, Fundația Conservation Carpathia (FCC), a private conservation organisation, hopes to create a new Romanian national park through a mix of targeted active restoration (tree planting), habitat protection and larger scale passive restoration of forests and alpine grasslands around the Făgăraș Mountain Range (Fundația Conservation Carpathia, 2021). This mix of activities in FCC sites and the importance and size of this landscape present an opportunity to investigate and contrast passive and active restoration outcomes at scale.

Based on existing information on FCC management activities in the area, in the areas actively restored by FCC we expect to see increased forest cover compared to the wider landscape (H1a); in areas protected but not actively restored we expect an intermediate level of forest expansion (H1b). We moreover expect decreased forest clearance in all FCC areas, compared to the wider landscape (H1c). In addition, we expect these activities would have increased primary productivity in FCC areas compared to the wider landscape (H2), due to an increase in woody vegetation from forest recovery and decrease in forest disturbance.

Material and Methods

Study area

The Făgăraș Mountains are part of the Southern Carpathians in South-Central Romania (Figure 1), spanning approximately 200,000 ha and reaching over 2,500 m in altitude. Largely uninhabited, they may contain the largest areas of old growth forest in Romania (Kathmann et al., 2017). Forests in lowland areas are dominated by broadleaf species, including beech *Fagus Sylvatica* L., pedunculate oak *Quercus robur* L., sycamore *Acer pseudoplatanus* L. and ash *Fraxinus excelsior* L., and by coniferous species on higher ground, such as Norway spruce *Picea abies* L. and silver fir *Abies alba* Mill. (Griffiths et al., 2014). Above the treeline, grassland and alpine meadows cover much of the mountain tops and snows typically fall between October and April.

Romania's forests have undergone substantial changes since the end of the 20th century. They were state-owned between 1947 and 1989 until the collapse of the socialist government. Following this, three phases of restitution between 1991 and 2005 have returned large areas of forest to private ownership. This is thought to have driven substantial increases in forest disturbance, degradation and clear-cutting to extract timber following each phase (Griffiths et al., 2012; Knorn et al., 2012) and annual rates of land-use change in Romania increased between 1990-2006 (Kucsicsa et al., 2019). More recently, the Făgăraș Mountains were designated as a Natura 2000 site in 2007 following Romania's accession to the EU. Within this site there is a combination of state, private and municipality ownership, as well as common land (Aastrup, 2020), and the habitats around these mountains continue to be used by local communities, primarily for livestock grazing and firewood extraction.

Within this context, Fundația Conservation Carpathia (FCC), a private conservation organisation founded in 2009, is purchasing, protecting and restoring areas with the end-goal of creating a new 'Carpathia' national park (Figure 1). As of February 2022, 26,693 ha of forest and pasture are protected by FCC, including areas of old-growth and clear-cut forest (Fundația Conservation Carpathia, 2022). FCC priority activities include restoring native forest, protecting native old growth forests, leasing hunting concessions across the wider landscape and engaging local communities. Restoration activities include replanting clear-cuts and monoculture plantations with a climate-resilient mix of native species; removing invasive species from riparian areas and alpine meadows; filling in logging tracks to reduce erosion; and re-introducing keystone species like bison and beaver (Fundația Conservation Carpathia, 2021).

Satellite imagery

To investigate land cover changes in FCC-owned land and the wider landscape over the past decade (H1), this work considered 30m resolution Collection 2 Level 2 Landsat imagery from 2011 and 2021. Specifically, a scene captured by Landsat 5's Thematic Mapper on 22/08/2011 and a scene captured by Landsat 8's Operational Land Imager on 17/08/2021. Both scenes covered WRS path/row 184/028 and are freely available from the United States Geological Survey Earth Explorer portal. The year 2011 was selected as the baseline because this was the earliest available Google Earth Imagery with sufficient coverage to collect training data and represents the earliest available very high-resolution imagery before significant active FCC restoration work began. Any flagged pixels, including those containing clouds, cloud shadows, water and snow/ice were removed from each Landsat image before analysis using the pixel quality assessment bands provided for each image (Roy et al., 2002; USGS, 2018).

To assess how FCC activities may have impacted primary productivity in the landscape (H2), we looked for spatio-temporal trends in the Normalised Difference Vegetation Index (NDVI) data, an indicator of vegetation greenness (Pettorelli, 2013). The NDVI is a vegetation index derived from the red (RED): near-infrared (NIR) reflectance ratio (NDVI = (NIR – RED)/(NIR + RED)), where NIR and RED are the amounts of near-infrared and red light reflected by the vegetation and captured by the sensor of the satellite. NDVI values range from -1 to +1. Green leaves have high visible absorption and high near-infrared reflectance, which results in values closer to +1; negative values correspond to an absence of vegetation (Pettorelli 2013). NDVI data were obtained from MODIS 250m resolution satellite imagery captured every 16-days between 2009 (the year FCC was founded) and 2021 (MOD13Q1 version 6.1). Flagged pixels containing snow, ice and clouds were removed before analysis using pixel-wise reliability layers (LAADS DAAC; 2022).

To account for changes in water level across the study periods, a uniform mask of the three large water bodies within the Carpathia landscape was created in Google Earth Pro and applied to MODIS and Landsat imagery. These masks covered the water and any exposed shoreline in the most recent imagery to cover the potential ranges of water level. Human structures such as roads and buildings were also visually identified in Google Earth Pro and removed from MODIS and Landsat images before analysis.

FCC sites

Polygons of the Carpathia area and FCC sites were provided by FCC. FCC restoration sites are those areas under FCC ownership where active restoration work is underway. The main restoration activities that are likely to be detected from satellite images are the replanting of clear-cut areas with native tree species and the restructuring of conifer plantations to a more mixed species composition, by thinning the conifers and replacing with missing species. FCC purchase sites are also under FCC ownership or direct management, but tend to include areas of native habitat that are being conserved rather than actively restored. We therefore expect the rate of change of landcover to be low in these areas. There were 217 restoration polygons and 1071 purchase polygons within the Carpathia area. The total Carpathia polygon covers approximately 289,800 ha; within this, FCC restoration sites cover 2699 ha and FCC purchase sites cover approximately 16,002 ha.

Land cover classification and accuracy assessment

Five land cover classes were differentiated from exploratory unsupervised classifications and examination of Google Earth imagery. These were: grassland, bare ground, agricultural fields, coniferous forest and broadleaf forest. Grassland included lowland grasslands, alpine grasslands and habitats dominated by grass, such as sparsely shrubbed area. Bare ground included bare rock and bare soil. Some FCC polygons are very narrow and/or small in size; only FCC polygons (restoration or purchase ones) that fully included at least one Landsat pixel were considered for analysis, leading to the land cover analyses being carried out for 175 (of 217) FCC restoration polygons and 967 (of 1071) FCC purchase polygons.

Training and validation data for each of these classes were collected from Google Earth Pro. For the 2021 land cover map, reference images ranged from 2017 to 2021 across most of the study area with some limited captures from 2014 covering the mountain peaks in the south-eastern areas of the map. To minimise misclassification of sites in 2021, training and validation data were not taken from forest areas that showed low NDVI in 2021, which indicated deforestation may have occurred. For the 2011 map, reference imagery ranged from 2009 to 2012. Training and validation data for particularly transient classes such as bare ground were mostly taken from sites identified in summer 2011 imagery. When selecting training and validation data captured post-2011, sites that showed little change between the available images pre- and post- 2011 in Google Earth Pro were selected to avoid misclassification.

Sixty training and 60 validation polygons were used for each land cover class. Random Forest (Liaw & Wiener, 2002) models were used to predict land cover in the 2011 and 2021 Landsat imagery based on these training data. Overall accuracy, producer's accuracy, and user's accuracy metrics were calculated from validation data using a confusion matrix, which compares the predicted class of a validation pixel with the observed class of that pixel. Overall accuracy is the total proportion of correctly classified samples. Producer's accuracy gives the effectiveness of the model at recognising a class. User's accuracy gives the reliability of the classes predicted by the model (Wegmann et al., 2016).

Areas masked in one of the maps but not the other were removed from the analysis before comparing 2021 and 2011. Image processing and analyses were carried out in R Studio using R version 4.1.2 (R Core Team, 2021). Land cover classifications were produced using the RStoolbox package (Leutner et al., 2019) and RandomForest package (Liaw & Wiener, 2002). To investigate the direction of land cover change between 2011 and 2021, agriculture and bare ground pixels were given a value of 1, grassland pixels a value of 2, and forest pixels a value of 3 in each map. The 2011 pixel values were subtracted from the 2021 pixel values to give a map showing the direction of successional change in 2021 and number of stages moved. For example, a pixel that changed from bare ground in 2011 (1) to forest in 2021 (3) would have a value of +2, and a pixel that changed from forest in 2011 (3) to grassland in 2021 (2) would have a value of -1.

Primary productivity analyses

Changes in primary productivity were investigated using pixel-wise timeseries of maximum annual NDVI (max NDVI; Pettorelli, 2013) because this overcame the high prevalence of cloud cover and shorter growing season in the mountains. Mann-Kendall (MK) trend tests were used to assess the significance of temporal trends in max NDVI for each pixel and significant slopes were assumed for p-values < 0.05 (Schulte to Bühne et al., 2022). These tests were computed using the trend R package (Pohlert, 2020). As above, only FCC polygons that fully included at least one MODIS pixel were considered for analysis, leading to the NDVI analyses being carried out for 106 (of 217) FCC restoration polygons and 616 (of 1071) FCC purchase polygons.

Results

The supervised classifications produced maps with accuracies of 95.0% and 91.2% for 2011 and 2021 respectively (Table 1). These classifications distinguished broadleaf and coniferous forests very well, with the most confusion arising from grassland and agriculture pixels (Table S1).

As expected under (H1a), areas where active restoration has occurred saw increases in both broadleaf and coniferous forest compared to the wider Carpathia landscape (non-FCC areas), where broadleaf forest decreased but coniferous forest increased (Table 2; Figure 1). As expected under (H1b), forest cover increased in FCC purchases, but this mirrored trends in forest cover seen in the wider landscape (Table 2). Similarly, in line with (H1c), FCC purchase and restoration areas saw less forest cover loss compared to the wider landscape: 8.81% of pixels in the wider landscape showed a negative change in succession between 2011 and 2021 compared to 4.29% in FCC purchases and 6.05% of pixels in FCC restoration areas (Figure 2). In general FCC restoration areas had a much higher proportion of areas showing a positive change since 2011, with 43.0% of pixels showing an increase in successional stage towards forest between 2011 and 2021, compared to 9.64% in purchases and 9.33% in the wider landscape (Figure 2).

As partially expected under (H2), a higher proportion of pixels in FCC restoration areas showed significantly positive trends in max NDVI compared to FCC purchases and non-FCC areas between 2009 and 2021 (Table 3). However, the proportion of FCC restoration and purchase pixels showing significantly negative trends in max NDVI trends was broadly comparable to the proportion for non-FCC areas. Interestingly, the map of significant max NDVI trends between 2009 and 2021 indicates large areas of greening spread widely across various parts of the study area, particularly in the north (Figure 3).

Discussion

Our results show that (i) active restoration activities by FCC have been very effective at facilitating the recovery of cleared forests in small areas of the southern Carpathian Mountains landscape, (ii) forest cover has expanded substantially in many parts of the landscape following agricultural abandonment, (iii) changes in primary productivity dynamics in the area over the past decades are consistent with local changes in land cover and global trends in NDVI linked to climate change and increased carbon dioxide concentrations. The scale of passive forest expansion and natural regeneration we report in this study provides an interesting contrast to the impressive but smaller scale impacts of active restoration in FCC sites, suggesting that mixed-management approaches could be a cost-effective way to restore ecosystems and ecosystem services within landscapes of this size. Patterns of forest cover change between 2011 and 2021 indeed suggest that passive restoration in non-FCC areas resulted in similar forest cover changes to those seen in FCC purchases, whilst active restoration was more effective at restoring broadleaf forest and associated levels of primary productivity.

The increased coniferous forest and decreased broadleaf forest we detected in lowland Carpathia is surprising because broadleaf forests typically dominate below 1400m (Mihai et al., 2007). The replacement of broadleaf forest with coniferous timber plantations could explain some of this trend in non-FCC areas, but not within FCC purchases. Carpathian coniferous forests tend to have been more impacted by past disturbances (Griffiths et al., 2014), so this pattern may indicate coniferous recovery over secondary broadleaf forest. Alternatively, increases in broadleaf forest cover may take longer to detect, due to generally slower growth rates compared to coniferous species. As we compared two time points, our land cover analyses would not detect succession reversals or the replacement of mature forest by young forest unless forest class changed. Furthermore, we were unable to distinguish shrub cover from broadleaf or coniferous forest cover which would provide a finer resolution of successional change. Biodiversity recovery has previously been reported to be greater under passive regeneration than active forest restoration (Crouzeilles et al., 2017), with re-planted forests potentially lacking the functional complexity found in naturally regenerated forests (Staples et al., 2019). Here, active restoration rapidly increased tree cover to cleared land in relatively small areas, but passive regeneration restored much larger areas of tree cover. Investigating the quality of forest in FCC areas and the permanence of these changes, with a finer scale distinction between wooded vegetation types, compared to non-FCC areas and historical land cover change, could provide more insight on how passive restoration within FCC purchases compares to that in the wider landscape.

The positive trends in maximum NDVI we reported across the majority of the Carpathia project landscape between 2000 and 2021 are consistent with similar global trends in NDVI linked to climate change and increased carbon dioxide concentrations (Piao et al., 2020). Over the mountain tops, these positive trends may indicate the expansion of trees and shrubby vegetation over alpine grasslands from warmer winters (Dinca et al., 2017); decreased livestock grazing (Mihai et al., 2007); or an increasing upper forest limit that had been 'artificially lowered' in the Făgăraș mountains by deforestation (Kucsicsa & Bălteanu, 2020). Significant positive trends in max NDVI on the northern forest edges likely result from vegetation succession after agricultural abandonment. This is corroborated by the overlap of those areas with successional changes in land cover pixels away from bare ground/agricultural pixels between 2011 and 2021; it also matches trends of forest expansion and agricultural abandonment seen across the Carpathian Mountains following the collapse of socialism and changes in agricultural subsidies and technology (Munteanu et al., 2014). Agricultural areas in southern and eastern Romania are particularly likely to be abandoned (Perpiña Castillo et al., 2018) and the land restitution associated with clear-cutting Romanian forests has also been associated with the abandonment of restituted agricultural land. Combined with demographic shifts of populations towards living and working in cities, this has been suggested as a cause of forest expansion over abandoned agricultural land in Argeș county, which overlaps the southern portion of the Carpathia area (Kuemmerle et al., 2009).

Traditional conservation approaches and limited funding often result in initiatives focusing on a specific site within a landscape rather than conservation across that landscape. Here we demonstrate the potential opportunities of integrating large-scale passive restoration into landscape-scale strategies. Although the passive restoration of forested habitats witnessed in the region should be capitalised upon, a passive-active distinction may be something of a false dichotomy (Chazdon et al., 2021) and in practice, there remains a need for a mixed-management approach. In Carpathia, more active restoration may indeed be needed to restore heavily degraded or high-altitude areas, where natural regeneration proves difficult (Holl & Aide, 2011), or to protect high value non-forest habitats threatened by forest expansion, like alpine meadows (Malek et al., 2018). Pollen analyses in Northern Romania have suggested that natural regeneration may be an inefficient restoration strategy for native conifers because they are at their lowest abundance in history (Grindean et al., 2019), and broadleaf forests appeared to fare worse under passive restoration in this study. A mix of restoration approaches is also likely to be needed in Carpathia because of spatial variation in the type and intensity of threats and also in the potential for effective passive restoration. Mitigating the effects of climate change, which is altering ecological communities as species move to cooler latitudes and elevations (Pecl et al., 2017) and increasing the vulnerability of European forests to disturbance (Forzieri et al., 2021), may also necessitate a more active restoration approach. Beech trees, a common lowland species in the Carpathia landscape, are especially susceptible to water and heat stress from droughts that are increasing in frequency and severity (Lindner et al., 2014; Martinez del Castillo et al., 2022). In this context, monitoring FCC restoration efforts could enable conservation planning and the selection of restoration strategies to ensure that restoration trajectories remain favourable under different climate scenarios.

The EU Biodiversity Strategy for 2030 sets out plans to plant three billion trees by 2030 (European Commission, 2021). This follows other global tree planting initiatives (Dave et al., 2018), and warnings that tree planting schemes must be ecologically appropriate (Holl & Brancalion, 2020). The passive forest expansion identified in this study beyond FCC areas could form part of a cost-effective nature-based solution to increase carbon storage and other ecosystem services in this landscape (Olofsson et al., 2011, Hua et al., 2022), on top of Carpathia's existing climate value (Critchley et al., 2021), whilst enhancing FCC's vision for protecting biodiversity and improving connectivity).

Whilst this study has improved our understanding of the outcomes of FCC actions and different restoration regimes at a landscape scale, this is an area for further monitoring and investigation, especially as the outcomes of FCC restoration programmes and impacts of climate change will take decades to be realised. Monitoring the outcomes of FCC actions is also important for justifying FCC expansion towards and designation of a new national park, which remains controversial in some communities despite general support (Aastrup, 2020). There may be more indicators of ecosystem functioning relevant to wider EU's restoration goals that could be monitored using satellites (Pettorelli et al., 2018b), with remote sensing indicators being used to track and assess restoration progress across a range of projects in both terrestrial and aquatic habitats (Pettorelli, 2019). Going forward, we hope more practitioners will consider satellite remote sensing as an approach that can provide useful standardized baselines and indicators of restoration progress.

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TABLES

Table 1. Producer's and User's accuracies for each class of the 2011 and 2021 land cover classifications generated for the whole of the Carpathia study area, and the overall accuracy for each classification year.

	2011		**2021**	
	Producer's accuracy (%)	User's accuracy (%)	Producer's accuracy (%)	User's accuracy (%)
Agriculture	92.0%	91.5%	89.6%	87.8%
Bare ground	90.9%	85.9%	85.3%	85.0%
Broadleaf forest	99.4%	97.1%	94.3%	91.2%
Coniferous forest	99.7%	99.2%	91.5%	95.5%
Grassland	89.8%	94.1%	90.9%	91.9%
Overall accuracy	95.0%		91.2%	

Table 2. Percentage area coverage of each land cover class in 2011 and 2021 within the Carpathia landscape outside of FCC areas, within FCC purchase areas, and within FCC restoration areas. Areas are also included for scale.

Area	Land cover class	2011 area (Km^2)	**2011 area cover (%)**	2021 area (Km^2)	**2021 area cover (%)**	**Change direction**
Carpathia area excluding FCC areas	Agriculture	252.43	**9.88%**	325.52	**12.7%**	↑
	Bare ground	32.73	**1.28%**	50.45	**1.97%**	↑
	Broadleaf forest	1007.51	**39.4%**	948.20	**37.1%**	↓
	Coniferous forest	607.85	**23.8%**	752.22	**29.4%**	↑
	Grassland	654.97	**25.6%**	479.11	**18.7%**	↓
FCC purchases	Agriculture	2.50	**1.62%**	3.97	**2.58%**	↑
	Bare ground	2.40	**1.56%**	1.46	**0.946%**	↓
	Broadleaf forest	60.48	**39.3%**	56.22	**36.5%**	↓
	Coniferous forest	61.84	**40.1%**	73.71	**47.8%**	↑
	Grassland	26.83	**17.4%**	18.69	**12.1%**	↓
FCC restoration sites	Agriculture	0.38	**2.67%**	0.59	**4.18%**	↑
	Bare ground	3.00	**21.1%**	0.07	**0.482%**	↓
	Broadleaf forest	2.26	**15.9%**	4.13	**29.1%**	↑
	Coniferous forest	3.11	**21.9%**	4.40	**31.0%**	↑
	Grassland	5.45	**38.4%**	5.00	**35.2%**	↓

Table 3. The number and percentage of MODIS pixels showing significant Mann-Kendall trends in maximum annual NDVI between 2009 and 2021 across the Carpathia landscape excluding FCC areas, within FCC purchases (excluding restoration areas) and within FCC restoration areas.

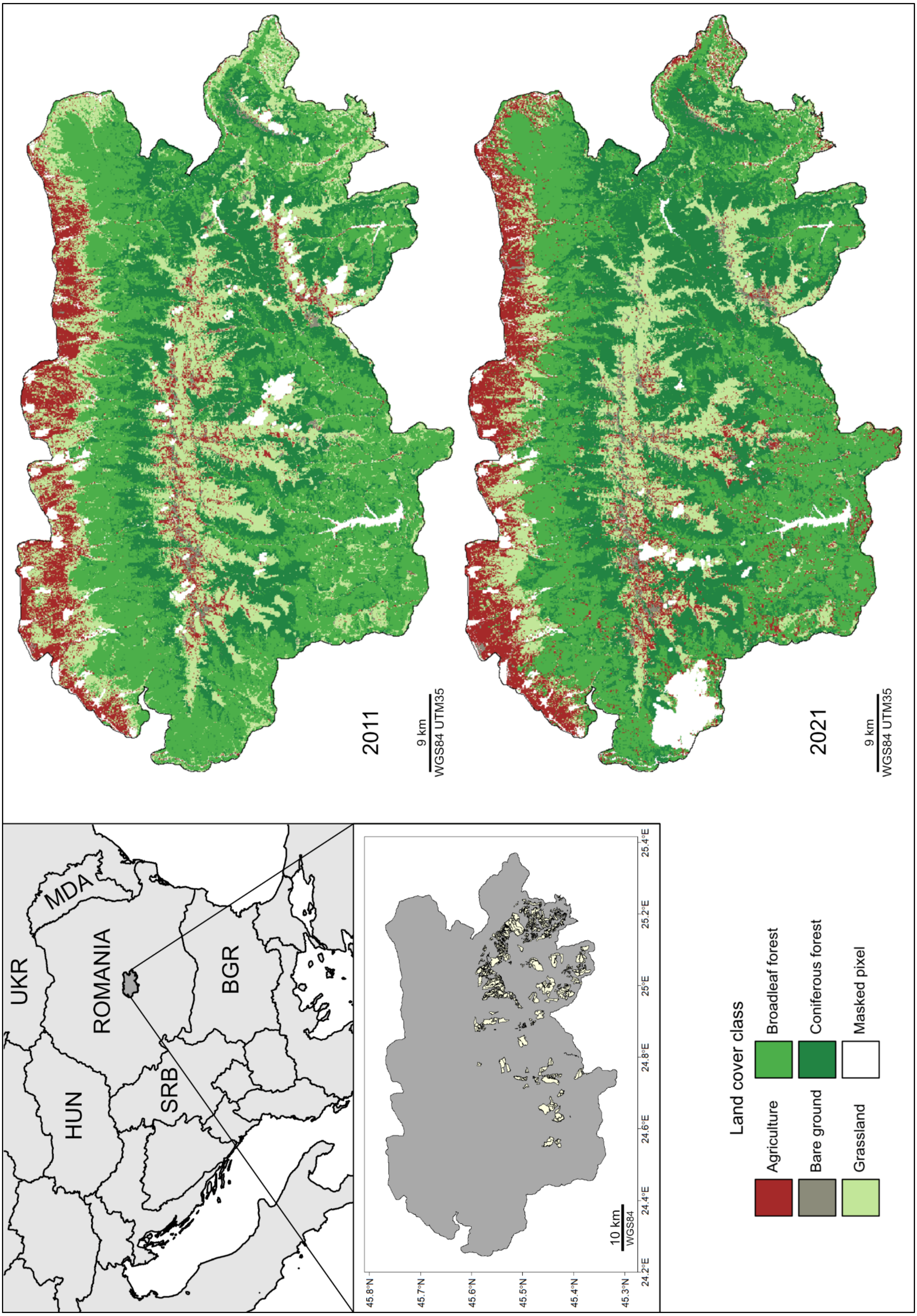
Area	**Significant positive trend**	**Significant negative trend**
Carpathia area excluding FCC	5894 11.89%	264 0.53%
FCC purchase sites	364 12.32%	24 0.81%
FCC restoration sites	133 49.44%	1 0.37%

FIGURES

Figure 1. Panel 1: Carpathia project area, displaying FCC-owned sites (purchases and restoration areas, light polygons) within the Carpathia project landscape, Romania, and the wider regional setting with bordering countries labelled (BGR = Bulgaria, HUN = Hungary, MDA = Moldova, SRB = Serbia, UKR = Ukraine). Panel 2: Land cover classifications for the Carpathia Project area for 2011 and 2021. Areas shown in white could not be classified due to cloud cover.

Figure 2. Relative frequency of successional changes within FCC restoration sites (left hand), FCC purchase sites (middle) and non-FCC areas (right hand). FCC restoration activities here focus on tree planting and restructuring of plantation forests. To investigate the direction of land cover change between 2011 and 2021 agriculture and bare ground pixels were given a value of 1, grassland pixels a value of 2, and forest pixels a value of 3 in each map. The 2011 pixel values were subtracted from the 2021 pixel values to give a map showing the direction of successional change in 2021 and number of stages moved; for example, a pixel that changed from bare ground in 2011 (1) to forest in 2021 (3) would have a value of +2, and a pixel that changed from forest in 2011 (3) to grassland in 2021 (2) would have a value of -1. Positive values thus indicate an increase towards forest, zero indicates no change, and negative values indicate a change towards agriculture/bare ground, from 2011 to 2021. The number indicates the magnitude of movement in either direction.

Figure 3. MODIS pixels within the Carpathia landscape that showed significantly positive (yellow), non-significant (green), or significantly negative (dark blue) change in maximum annual NDVI.



2011
9 km
WGS84 UTM35
2021
9 km
WGS84 UTM35
UKR
MDA
ROMANIA
HUN
SRB
BGR
10 km
WGS84
45.8°N
45.7°N
45.6°N
45.5°N
45.4°N
45.3°N
24.2°E
24.4°E
24.6°E
24.8°E
25°E
25.2°E
25.4°E
Land cover class
Agriculture
Broadleaf forest
Bare ground
Coniferous forest
Grassland
Masked pixel

Figure 1

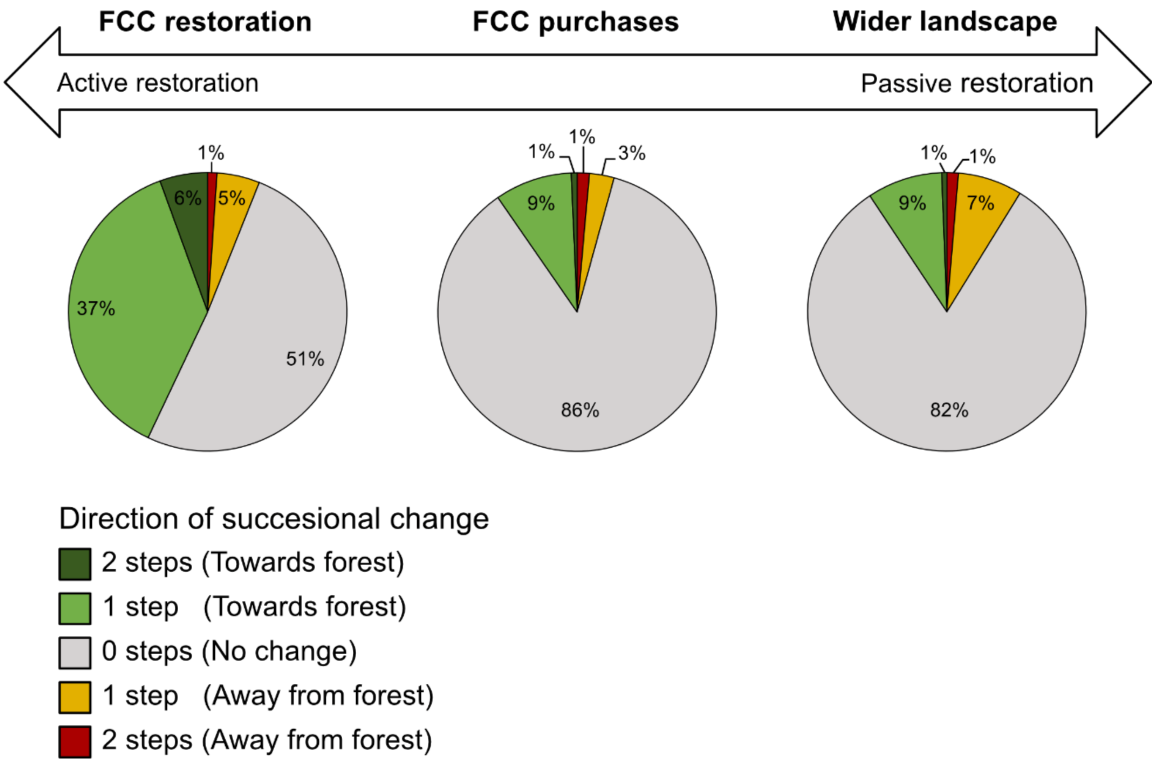

FCC restoration
FCC purchases
Wider landscape
Active restoration
Passive restoration
1%
6%
5%
37%
51%
1%
1%
3%
9%
86%
1%
1%
9%
7%
82%
Direction of succesional change
2 steps (Towards forest)
1 step (Towards forest)
0 steps (No change)
1 step (Away from forest)
2 steps (Away from forest)

Figure 2

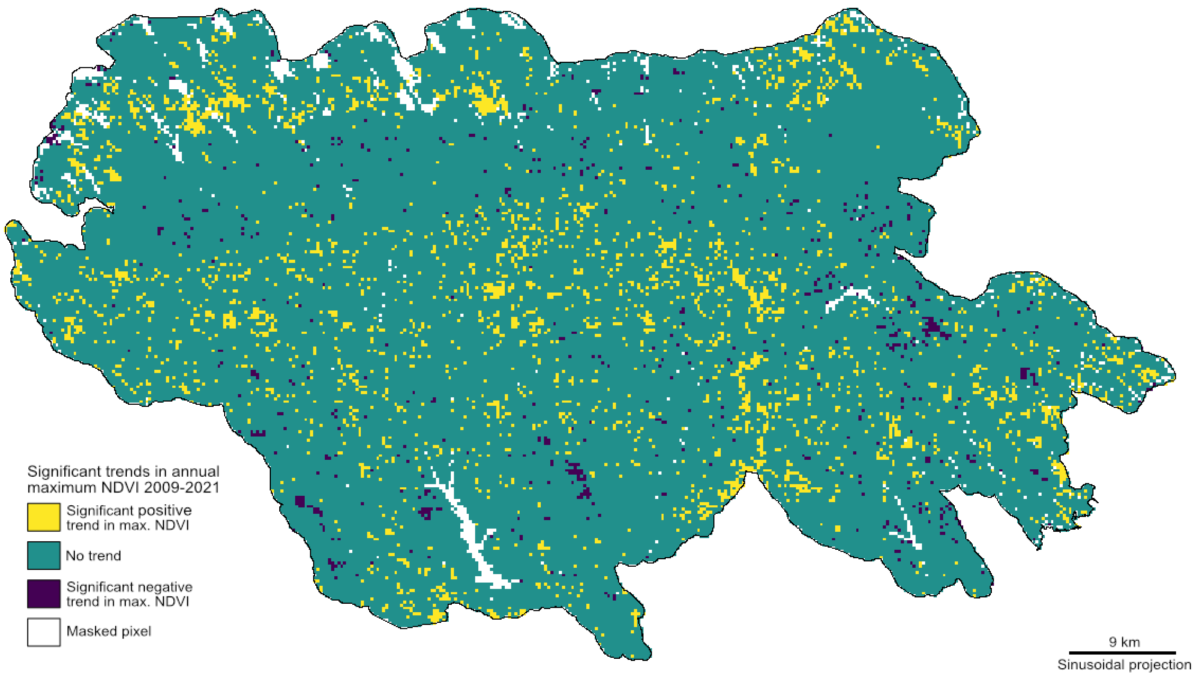

Significant trends in annual maximum NDVI 2009-2021
Significant positive trend in max. NDVI
No trend
Significant negative trend in max. NDVI
Masked pixel
9 km
Sinusoidal projection

Figure 3

SUPPLEMENTARY MATERIALS

Table S1: Confusion matrices of land cover classifications for 2011 and 2021.

2011	Agricultural (Reference)	Bare ground (Reference)	Broadleaf (Reference)	Coniferous (Reference)	Grassland (Reference)
Agricultural (Prediction)	942	12	0	0	76
Bare ground (Prediction)	29	189	0	0	2
Broadleaf (Prediction)	0	1	1019	3	26
Coniferous (Prediction)	0	2	5	1027	1
Grassland (Prediction)	53	4	1	0	925

2021	Agricultural (Reference)	Bare ground (Reference)	Broadleaf (Reference)	Coniferous (Reference)	Grassland (Reference)
Agricultural (Prediction)	917	16	26	0	85
Bare ground (Prediction)	26	198	0	3	6
Broadleaf (Prediction)	7	0	952	85	0
Coniferous (Prediction)	0	16	28	941	0
Grassland (Prediction)	74	2	4	0	904

Table S2. Percentage cover of successional changes in Carpathia between 2011- and 2021-pixel values from Figure 3. Across the wider landscape excluding FCC areas, within FCC purchases (excluding FCC restoration) and within FCC restoration sites. 0 indicates no change, +/-1 indicates one step, +/-2 indicates two steps. Areas included for scale.

Area	Direction of succession change	Area (Km^2)	% Cover
Carpathia area excluding FCC areas	2	15.02	0.588%
	1	223.23	8.74%
	0	2092.18	81.9%
	-1	191.11	7.48%
	-2	33.95	1.33%
FCC purchases	2	1.03	0.668%
	1	13.83	8.97%
	0	132.58	86.1%
	-1	4.43	2.87%
	-2	2.19	1.42%
FCC restoration sites	2	0.79	5.56%
	1	5.31	37.4%
	0	7.24	51.0%
	-1	0.71	4.97%
	-2	0.15	1.08%