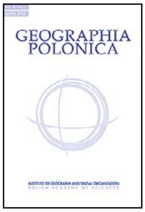


Geographia Polonica
2026, Volume 99, Issue 1, pp. 75-98
https://doi.org/10.7163/GPol.0318

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
www.igipz.pan.pl

www.geographiapolonica.pl

MAPPING RIPARIAN FOREST FRAGMENTATION ALONG THE IORI RIVER IN GEORGIA

Tamar Khardziani • Zurab Seperteladze

Department of Geography, Faculty of Exact and Natural Sciences
Ivane Javakhishvili Tbilisi State University
3 Ilia Tchavtchavadze Avenue, Academic Building II, 0179 Tbilisi: Georgia
e-mails: tamar.khardziani@tsu.ge (corresponding author) • zurab.seperteladze@tsu.ge

Abstract

This paper examines riparian forest fragmentation to assess how protection status influences the preservation of critical habitats of the Iori River's downstream riparian zone in Georgia. It also explores external threats impacting protected forests. Using remote sensing, landscape ecology, and spatial autocorrelation methods, 10-meter-resolution Sentinel-2 MSI data were analysed, and landscape- and class-level metrics were computed. The results showed that the fragmentation has decreased, mainly within protected areas, while non-protected zones remained highly fragmented. Besides, parts of the protected areas also showed an increased fragmentation. The research output, on the one hand, highlights the importance of protection but also emphasises the need for broader, integrated forest management and restoration efforts.

Keywords

landscape fragmentation • riparian forest • landscape metrics • landscape ecology • protected area • Iori River • Georgia

Introduction

Landscape degradation is a pressing environmental issue. According to the IPCC (2022), land degradation refers to a decline in land conditions caused by direct or indirect human activities. This leads to reduced biological productivity, ecological integrity, or the land's value to humans. This definition also applies to the degradation of forest land. Numerous anthropogenic factors contribute to the degradation of forest landscapes, disrupting their structural and functional integrity and impairing essential ecological processes. Forest degradation is often examined through the lens of the pattern-process relationship. A pattern refers to the spatial arrangement of landscape elements, such as ecosystems, land cover types, and other features, and is defined by composition and configuration. Process denotes the mechanisms and dynamics that generate and modify patterns over time. Such processes encompass human influences and ecological and biophysical factors that shape landscape patterns (Turner et al., 2001).

To understand the dynamics of woodland degradation and resilience and conduct effective landscape assessment, quantifying forest landscape fragmentation is essential. The concept of fragmentation is central to evaluating how ecological processes influence spatial patterns. As a result, various metrics have been developed to measure fragmentation, offering deeper insights into the structural and functional characteristics of landscapes. According to Forman (1995), landscape fragmentation is the process by which a continuous forest area is divided into smaller, more isolated patches. Fragmentation reduces the size and connectivity of natural habitats, disrupting ecological processes and impacting biodiversity by limiting species' ability to move between habitat patches.

Recent scientific studies have been highlighting the problem of landscape fragmentation in riparian forests. Fragmentation negatively impacts the forest's hydrological resources, including water flow and river runoff (Thomas et al., 2020). Riparian natural landscapes represent biodiversity hotspots, yet they are among the most degraded habitats in the world. Landscape transformation and increased fragmentation can occur even within protected areas (Pyryt & Pukowiec-Kurda, 2024). Effective planning and restoration strategies can mitigate these negative impacts on riparian habitats (Stieger & McKenzie, 2024) within and beyond the protected areas.

Restoration and conservation of riparian forests are key strategies in environmental policy to enhance biodiversity. Riparian forest landscapes are valuable because they support biodiversity, water quality, ecological functions, and the well-being of nearby communities. Naiman and Decamps (1997) describe riparian zones as a "diverse mosaic of landforms, communities, and environments within the larger landscape, serving as a framework for understanding the organisation, diversity, and dynamics of communities associated with fluvial ecosystems". They further emphasise that natural riparian zones are among the most diverse, dynamic, and complex biophysical habitats, susceptible to environmental change (Naiman & Decamps, 1997). A riparian landscape is unique in that it represents a terrestrial habitat that both influences and is influenced by aquatic environments. It possesses distinct spatial configurations and values derived from its characteristics (Malanson, 1993). Riparian forests provide a diverse range of essential ecosystem services, including water purification, enhanced soil health, flood regulation, shade provision, and contributions to large wood diversity, among others. Therefore, "the riparian zone plays an essential role in water and landscape planning, as well as in the restoration of aquatic systems" (Naiman & Decamps, 1997). Monitoring landscape fragmentation is essential for developing effective conservation strategies and implementing biodiversity policies (Opdam & Wascher, 2004).

Designation of protected areas to mitigate landscape fragmentation is crucial to successful biodiversity conservation. This study focuses on a riparian forest landscape along the lowland section of the Iori River. The study area is notable due to its riparian forests, which are of conservation importance and have led to the establishment of three protected areas. In addition, Georgia's environmental strategy highlights threats originating from adjacent landscapes outside protected areas that impact riparian forests. Thus, the goal of our research was to understand, on the one hand, the role of protected status in the preservation of riparian forests and, on the other hand, the impact of ongoing activities on the protected areas and their condition. To this end, we assessed forest fragmentation in the Iori floodplain zone by analysing satellite images, calculating landscape ecological metrics, and identifying spatial clusters. For the change assessment, we compared the conditions of 2016 and 2024. The paper also discusses the historical changes in the Iori riparian zone and the current legislative and policy frameworks.

Materials and methods

Study area

The study area encompasses the riparian landscape zone of the middle reaches of the Iori River, which is part of the Caspian Sea basin, specifically within the Mtkvari River basin in Georgia (Fig. 1). The Iori River originates on the southern slopes of the Caucasus, near the branching point of the Kakheti Ridge. It is a mountain-type river in its upper reaches. In the territory of Tianeti Municipality, it flows between the Kartli and Kakheti meridian ridges, crosses the Ertso Basin, and then continues through the southwestern part of the Iori Upland, encompassing the municipalities of Sagarejo, Gurjaani, Sighnaghi, and Dedoplistskaro. Beyond this point, the river exits Georgia, flows into Azerbaijan, and joins the Mingachevir Reservoir.

The area of interest (AOI) in the presented research encompasses a downstream section of the Iori River in the Kakheti region, characterised by lowland riparian forests. The Ujarma-Sartichala section marks the river's transition from mountains to plains, where it flows meridionally. From there, it shifts to a sub-longitudinal course, flowing northwest to southeast toward the Georgian-Azerbaijani border. In this direction, the landscape becomes increasingly arid. In the lower reaches, dry ravines that carry water only during rainfall join the river. The region's climate is continental, with low precipitation. The average annual temperature in this section of the Iori River Valley ranges from 13°C to 14°C, while annual precipitation is between 200 and 300 mm. The floodplain becomes inundated during floods and heavy rains, leading to frequent changes in the water bodies. The entire Iori River basin covers 4650 km^2. The river has a total length of 320 km, of which 233.7 km lies within Georgia. The river's average multi-year discharge is 15.1 m^3·s^{-1} (Tsitelashvili et al., 2020). The width of the river ranges from 8 to 45 m. The lower Iori Valley is characterised by surface water scarcity and is a fractured and porous artesian basin.

Geomorphologically, the central part of the study area consists of an alluvial-pluvial

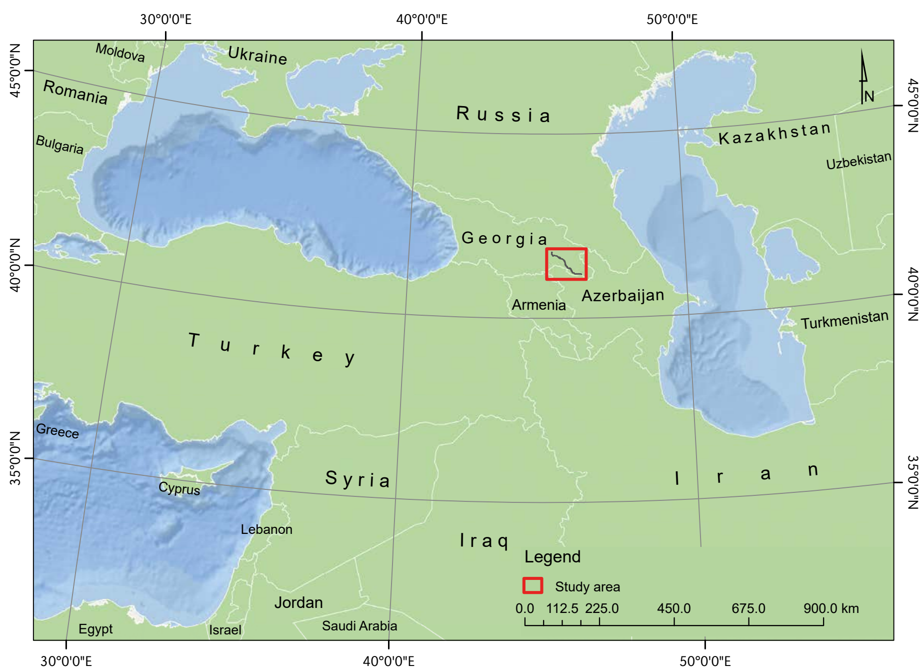


Figure 1. Study area location

plain, while the northwestern and southeastern parts are characterised by arid-denudation foothills. According to a 1:200,000-scale geological map, the Iori floodplain, including sand and gravel extraction areas, consists of Quaternary sediments: gravel, silt, and clay. The relief of the right and left slopes of the Iori Managed Reserve, as well as the river's upper reaches, is composed of Pliocene conglomerates, clays, and sands, along with Miocene and Pliocene conglomerates, sandstones, clays, andesite-dacites, and their associated pyroclastics. Upper Miocene clays, marls, sandstones, and conglomerates are on the right side of the Iori River, near the border with Azerbaijan. Upper Jurassic limestones, marls, clays, sandstones, and conglomerates are found upstream of the river. Also, Lower Jurassic sandstones and shales are present, as well as Upper Palaeozoic Triassic shales and quartzites.

Based on the map of Europe's biogeographical regions, most of the study area lies within the Steppe region. At the same time, the upper reaches of the river are placed in the Alpine region (European Environment Agency, 2016). The riparian forests in the study area are dominated by plant species such as *Populus hybrida* M. Bieb., *Quercus longipes* Steven, *Salix australior* Andersson, *Ulmus suberosa* Moench, *Tamarix ramosissima* Ledeb., *Phragmites communis* Trin., and *Elaeagnus angustifolia* L. The Iori floodplains are characterised by flora (Tab. 1) and fauna (Tab. 2) species of high conservation value, which have led to the designation of riparian forest habitats as protected areas.

Table 1. Flora of the Iori River floodplain. Species included in the Georgian Red Book, Red List, and the IUCN Red List

Species Name	Red Data Book of the Georgia, 1982	Red List of Georgia, 2014	The IUCN Red List	IUCN Status
Sea Buckthorn	*Hippophae rhamnoides* L.	-	*Elaeagnus rhamnoides* (L.) A.Nelson	Least Concern (LC) (Chadburn & Wilson, 2018)
Greyish oak	*Quercus pedunculiflora* C. Koch. / *Quercus longipes* Steven	*Quercus pedunculiflora* C. Koch.	-	-
Wild Grape	*Vitis silvestris* Gmel.	-	*Vitis vinifera* L.	Least Concern (LC) (FFI/IUCN SSC, 2007)

Table 2. Fauna of the Iori River floodplain. Species included in the Georgian Red Book, Red List, and the IUCN Red List

Species Name	Red Data Book of the Georgia, 1982	Red List of Georgia, 2014	The IUCN Red List	IUCN Status
Otter	*Lutra lutra meridionalis* Ognev, 1931	*Lutra lutra* Linnaeus, 1758	*Lutra lutra* Linnaeus, 1758	Near Threatened (NT) (Loy et al., 2022)
Black Francolin	*Francolinus francolinus* Linnaeus, 1776	-	*Francolinus francolinus* (Linnaeus, 1766)	Least Concern (LC) (BirdLife International, 2018)
Great Bustard	*Otis tarda* Linnaeus, 1758	-	*Otis tarda* Linnaeus, 1758	Endangered (EN) (BirdLife International, 2023)
Little Bustard	*Otis tetrax* Linnaeus, 1758	*Tetrax tetrax* Linnaeus, 1758	*Tetrax tetrax* (Linnaeus, 1758)	Vulnerable (VU) (BirdLife International, 2021)

During the Soviet period, several reservoirs and aquaculture ponds were built along the Iori River, which today serves as an ecological barrier. Upstream of the river, beyond the study area, are the Sioni and Iori reservoirs, which serve irrigation purposes. In an area of interest, the Lower Samgori Dam and the Dali Mountain Reservoir, which have been created for irrigation, are downstream of the river. The first of them is still functioning. In the river's lower reaches, former fish farming ponds have also remained, filled with silt.

Satellite imagery, geospatial data, and software tools

Research was conducted using multispectral satellite imagery, geodata sources, and the software described below:

The primary data source, 10-meter resolution Sentinel-2 multispectral imagery (MSI), a foundational dataset for forest fragmentation analysis, was obtained from the Copernicus Data Space Ecosystem – an open platform managed by the European Space Agency, an official data infrastructure for the Copernicus Programme (European Space Agency, 2024a).

Geospatial data for delineating protected areas within the AOI was downloaded from the Protected Planet platform, a global resource that provides up-to-date, comprehensive data on protected areas by country. It is a joint project of the United Nations Environment Programme (UNEP) and the International Union for Conservation of Nature (IUCN), which serves as the online interface for the World Database on Protected Areas (WDPA). Data on the Emerald Network sites were also obtained from the Areas of Special Conservation Interest (ASCI) database (Council of Europe, 2019). To create the study area map, we used country polygons from the World Bank Data Catalogue (World Bank, 2025).

The primary software used for image classification and the generation of woodland raster maps from Sentinel-2 multispectral imagery was ESA SNAP 10.0.0 (Sentinel Application Platform) (Tab. 3). ESA SNAP is a free, open-source software developed by the European Space Agency (ESA) for processing and analysing Earth Observation (EO) data (European Space Agency, 2024b).

For further processing of classified images/categorical maps, including calculating landscape fragmentation, generating grid maps, and executing other geospatial procedures, we utilised QGIS 3.34.11. (QGIS Development Team, 2023). In particular, for calculating and mapping landscape metrics, e.g., woodland area and Effective mesh size (MESH), we used the LecoS (Landscape Ecology Statistics) plugin, version 3.0.1 (Jung, 2022), which incorporates metrics derived from FRAGSTATS (McGarigal et al., 2023). LecoS was designed to facilitate landscape ecology analysis by automating the calculation of various spatial metrics and is available as an open-source tool. FRAGSTATS is a software program used for landscape pattern analysis, calculating landscape metrics that quantify the composition, configuration, and spatial arrangement of landscape elements. Cohen's Kappa coefficient (k) was calculated in the Semi-Automatic Classification Plugin (SCP) (Cohen, 1960; Congedo, 2021). Spatial autocorrelation maps were created in QGIS using the Visualist plugin (Rossy, 2019), and the Getis-Ord Gi statistic (Getis & Ord, 1992) was used to analyse Hot-spots and Cold-spots.

At the landscape level, we used the FRAGSTATS program (McGarigal et al., 2023) to analyze the riparian zone of the Iori River,

Table 3. Iori riparian forests were digitised from 1:50,000 topographic maps (1978) and classified as woodland using Sentinel-2 MSI data (2016, 2024). Kappa coefficient (κ) values included

AOI	Woodland (km^2)		
	1978	2016 (k= 0.90)	2024 (k = 0.91)
Korughi MR	5.7	12.9	11.1
Iori MR	10.1	13.8	15.4
Chachuna MR	5.4	8.4	7.1
Total Protected	21.2	35.1	33.6
Nonprotected	5.6	11.5	16.8

through which we calculated: Mean Patch Area (MPA), Standard Deviation of Patch Area (SD), Mean of Euclidean Nearest Neighbor Distance (ENN), Contagion Index (CONTAG) and Effective Mesh Size (MESH) (Tab. 4). The 8-cell neighbourhood rule was selected as a parameter for the landscape metrics analysis.

The Mean Patch Area (MPA) at the landscape level is the average patch size, calculated by dividing the total patch area within the landscape by the number of patches. Higher MPA values suggest lower fragmentation, while lower values indicate higher fragmentation (McGarigal et al., 2023).

The Standard Deviation of Patch Area (SD) metric measures the variability in patch sizes. At the landscape level, it represents the standard deviation of the areas of all patches within the landscape, regardless of class. A high SD value indicates greater variability in patch sizes, whereas a low value indicates more uniform patch sizes (McGarigal et al., 2023).

Euclidean nearest-neighbour distance (ENN) measures the isolation of patches. ENN is defined as the shortest straight-line distance between a focal patch and its nearest neighbouring patch. At the landscape level, ENN summarises the distance that a patch is from its nearest neighbour, considering all patches in the landscape rather than focusing on a single class. Higher ENN values indicate a more fragmented and isolated landscape, while lower values indicate a more connected or clustered landscape (McGarigal et al., 2023).

The Contagion Index (CONTAG) measures the extent to which landscape elements are aggregated. CONTAG is based on the proportions of each class and the adjacency

Table 4. Fragmentation Metrics

AOI	Year	Landscape-level metrics					Class-level metrics / Forest class	
		Mean Patch Area (AREA_MN, ha)	Standard Deviation of Patch Area (AREA_SD, ha)	Mean of Euclidean Nearest Neighbour Distance (ENN_MN, meters)	Contagion Index (CONTAG)	Effective Mesh Size (MESH)	Mean of Euclidean Nearest Neighbour Distance (ENN_MN, meters)	Effective Mesh Size (MESH)
Entire RZ	2016	0.52	12.19	30.52	38.26	285.01	29.86	124.74
	2024	0.21	8.38	26.50	25.00	338.89	25.41	198.38
Total Protected	2016	0.41	9.10	31.59	49.93	204.44	25.34	199.35
	2024	0.16	6.19	27.28	33.40	232.59	24.48	230.64
Nonprotected	2016	0.51	9.87	35.14	40.76	192.28	39.81	15.47
	2024	0.22	6.69	27.97	27.26	206.71	27.21	3.81
Korughi MR	2016	0.83	15.92	38.28	65.39	306.54	30.97	297.64
	2024	0.19	5.99	27.54	38.93	191.13	23.15	187.39
Iori MR	2016	0.44	8.28	34.23	53.24	155.12	25.05	151.73
	2024	0.19	8.09	28.87	46.01	350.23	24.02	349.67
Chachuna MR	2016	0.25	3.70	27.82	34.38	55.77	24.36	52.45
	2024	0.13	2.38	25.80	19.52	44.35	25.80	42.47

of cells between classes. High values indicate that classes are aggregated and the landscape is more homogeneous, while low values indicate that the classes are more fragmented and interspersed (McGarigal et al., 2023).

Deriving classified images for the analysis of landscape fragmentation

A categorical map pattern, or, in other words, a classified image, is a visual or conceptual mapping that organises data into distinct categories, exemplified by a land-use/land-cover map, also known as a "patch mosaic." In the presented research, the categorical map consisted of raster-format grid cells with a 10-meter resolution, initially classified into five land cover classes – woodland, agricultural land, water bodies, open spaces, and urban areas – then reclassified into woodland and non-woodland areas.

The categorical maps for the study area were derived using Sentinel-2 multispectral imagery (MSI) L1C (10-meter resolution), extracted from the Copernicus Data Space Ecosystem (European Space Agency, 2024a). The selection criteria included a cloud cover threshold of 10% to download the oldest and most recent available products. The final selection included four products from 2016 (sensing date: 2016-09-14) and 2024 (sensing date: 2024-08-23).

The selected MSI products were processed using ESA SNAP, which involved resampling, subsetting, mosaicking, reprojection, and raster classification. The 10-meter resolution was maintained during the resampling process, and 13 bands (B1-B12) were included in the subsetted image. Natural Colors (B4-B3-B2) were used as the RGB image channels for classification. We selected a supervised classification approach for image analysis, specifically the Random Forest Classifier. The Random Forest Classifier is a supervised machine learning algorithm that employs ensemble learning methods by combining the predictions of multiple decision trees to enhance overall accuracy. According to Breiman (2001), "Significant improvements in classification accuracy have resulted from growing an ensemble of trees and letting them vote for the most popular class". The Random Forest Classifier, integrated into the SNAP software, is used to classify satellite images into various land cover classes using labelled training data. Further data processing and analysis were performed using QGIS.

Calculation of landscape fragmentation metrics and local autocorrelation analysis

Landscape metrics are quantitative measures used to analyse spatial patterns within a landscape, focusing on composition, configuration, and structure at different scales. In the FRAGSTATS environment, "landscape metrics are algorithms that quantify specific spatial characteristics of patches, classes of patches, or entire landscape mosaics" (McGarigal et al., 2023). The Effective Mesh Size (MESH) was calculated as a class-level landscape metric using the LecoS tool in QGIS to quantify landscape fragmentation. A landscape vector overlay in LecoS was used to generate a grid map depicting landscape fragmentation statistics – Effective Mesh Size (MESH) for the woodland class. Effective mesh size quantifies landscape fragmentation as the area of a patch within which two randomly chosen points are likely to be connected without barriers (Jaeger, 2000). As a rule, MESH is calculated by summing the squared areas of all patches in the landscape and dividing them by the total landscape area (McGarigal et al., 2023). Lower values signify higher fragmentation, while higher values indicate greater landscape connectivity and lower fragmentation. This metric was calculated for the entire riparian landscape and its parts, including protected (total) and non-protected areas, using a 10-hectare rectangle grid (Fig. 2). The same metric (MESH) for individual protected areas (Korughi, Iori, and Chachuna Managed Reserves) was calculated using a 1-hectare hexagonal grid (Figs. 3, 4, 5, and 6). To determine the size of the grid cells, we relied on Mean Patch Area (MPA) values,

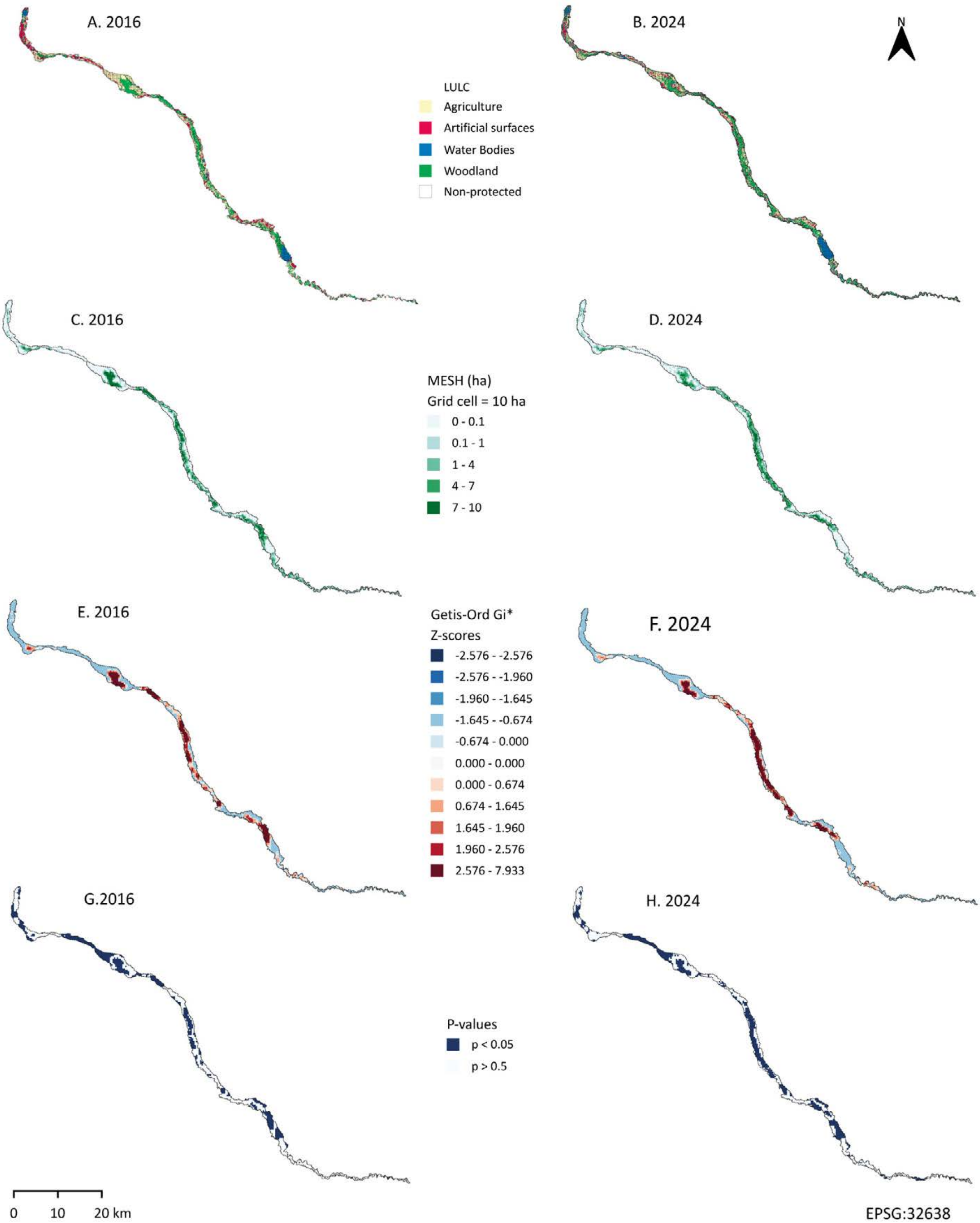


Figure 2. Forest fragmentation across the entire riparian zone in 2016 and 2024: LULC, forest cover and non-protected areas (A. and B.), Effective Mesh Size (C. and D.), Z-scores (E. and F.), Statistical Significance G. and H.)

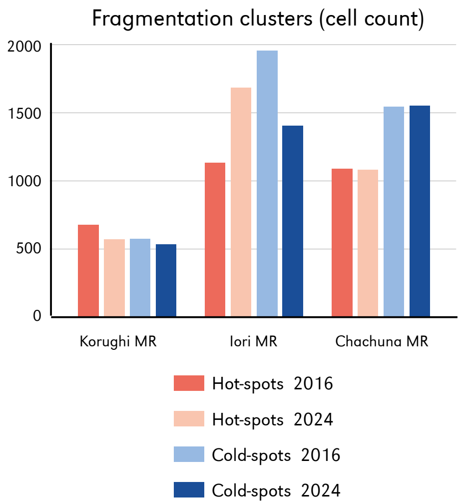


Figure 3. Riparian forest fragmentation clusters in protected areas. Grid cell size is 1 ha

which were less than 1 ha in each area of interest (AOI) (Tab. 4). The riparian zone was delineated by manually digitising boundaries from topographic maps and Google imagery in QGIS. In addition, as mentioned above, the following landscape-level metrics were also computed in FRAGSTATS: MPA, MPA SD, ENN, CONTAG, and MESH (Tab. 4).

Finally, local spatial autocorrelation statistics were analysed using the grid vector layer with Effective Mesh Size values. Precisely, Getis-Ord Gi Z-scores and P-values were calculated, and hot spots and cold spots were mapped and assessed by counting the number of clusters and cells to depict the 2016 and 2024 status quo and compare the changes. The Nearest Neighbour was selected as the spatial weights matrix for the analysis, with eight neighbours indicated. The Getis-Ord Gi* Z-score is a standardised spatial statistic used to identify clusters of high values (hot spots) and low values (cold spots) in geographic data. A high positive Z-score indicates a statistically significant hot spot, where high values surround high values; a low negative Z-score indicates a statistically significant cold spot with low values surrounded by low values; and values near zero indicate no significant spatial clustering.

Results and discussion

Past changes in forest cover

The oldest cartographic and geographical sources we have examined regarding the Iori riparian forests date back to the middle eighteenth century. One such source is a map drawn by Vakhushti Bagrationi in the first half of the eighteenth century, which depicts forests on both sides of the Iori River as a continuous strip. The forest began approximately at the present-day Kvemo Samgori Dam to the southeast (Bagrationi, 1745/1997). It extended to the confluence with the Alazani River, in what is now the territory of Azerbaijan, at the site of the Mingachevir Reservoir. Before the construction of the reservoir, the Iori River flowed directly into the Alazani River.

Vakhushti Bagrationi describes the Iori River in his 1745 book Description of the Kingdom of Georgia. According to his account, the river was bordered by a small floodplain covered with reeds, notable for its abundance of wild animals and birds, including numerous pheasants. Due to the presence of water and irrigation, both riverbanks were very fertile, with fields where all kinds of grain were cultivated. The area along the Iori River, approximately corresponding to the present-day Korughi Managed Reserve, was used for winter hunting. It was a pleasant and beautiful area with natural springs. Vakhushti Bagrationi described the slopes bordering the Iori floodplain in this section as treeless, dry, and covered with thorny shrubs and bushes, such as Christ's thorn (*Paliurus spina-christi* Mill.) and sumac (*Rhus coriaria* L.). Part of the landscape along the Iori River was used as winter pasture (Brosset, 1842).

According to the German naturalist Johann Anton Güldenstädt, large quantities of rice were cultivated on the Iori Plain at the end of the eighteenth century, as the area was irrigated by canals drawn from the Iori River. He visited the place near the village of Khashmi and described the vegetation along the riverbanks. Among the plants he recorded were common elm (*Ulmus glabra* Huds.), hazelnut (*Corylus avellana* L.), alder (*Alnus* *glutinosa* (L.) Gaertn.), poplar (*Populus tremula* L.), sea buckthorn (*Hippophae rhamnoides* L.), Asiatic elm (*Ulmus pumila* L.), and white willow (*Salix alba* L.). He observed that the Iori riverbed was filled with sandstone and limestone transported from the mountains (Güldenstädt, 1787).

According to the topographic "five-verst" maps published in 1890, the forest in the Iori riverine landscapes extended almost continuously across what is now the Chachuna Managed Reserve. The present-day Dali Mountain Reservoir area was once forested and extended northwestward into the floodplain adjacent to Qajiri Mountain. The same map shows no forests in the Korughi and Iori reserves.

Thus, at the beginning of the eighteenth century, the Iori riparian forest covered a larger area than today. However, by the end of the nineteenth century, it had decreased and become fragmented.

According to 1:50,000 topographic maps from 1978, the forest covered a much smaller area than it does today (Tab. 3). Since then, the forest area within today's protected areas has increased significantly.

The riparian forests in the study area have expanded since the end of the twentieth century, approximately after the collapse of the Soviet Union. At the end of the 1970s, the Iori Hunting Farm was located within the territory of the present-day Korughi Managed Reserve, where, according to the 1978 topographic map, 32.9% of the modern protected area was forested, increasing to 64.4% by 2024. On a late-1970s map, the riparian forest surrounding the village of Iormuganlo was depicted as a small grove. Riparian forests were distributed as fragmented groves throughout the modern Iori Managed Reserve, covering 47.3% of the current protected area, which increased to 72.4% by 2024. According to the same topographic map, forest occupied 10.8% of the current protected area in the Chachuna Managed Reserve, up from 14.1% in 2024. In addition, the unprotected lower reaches of the river were also covered with riparian forest, including the current Dali Mountain Reservoir area, where the forested area measured 2.3 km^2 in the late 1970s.

According to the 1:50,000 topographic map from 1978, the total forest area was 26.8 km^2, increasing to 50.3 km^2 by 2024. The forest areas in the Iori and Korughi protected areas increased at nearly the same rate, while the forest area in the Chachuna Managed Reserve showed only a slight increase.

The large structures built on the river, which act as ecological barriers and contribute to fragmentation, date back to the Soviet era and result from the planned economy. These barriers include the Dali Mountain Reservoir, the Lower Samgori Dam, and the former fish farms and aquaculture ponds of Ninotsminda, located near the Samgori Dam and Khashmi. The aforementioned facilities occupy a large area in the floodplain and are no longer functional, except for the Kvemo Samgori Dam.

Despite the overall trend of increasing floodplain forest area over a longer time (1978-2024), forests in the Korughi and Chachuna protected areas have decreased recently (2016-2024) (Fig. 2A and B).

Analysing riparian zone fragmentation at the landscape-level

Across the entire riparian zone (RZ), landscape fragmentation increased between 2016 and 2024, as indicated by the MPA, SD and CONTAG metrics (Tab. 4). In particular, the patches became smaller, more uniform, increasingly disaggregated, and intermixed. The variability (SD) of patch areas also decreased. The opposite trend was indicated by the increased MESH value, which may be attributed to the emergence of larger connected patches in certain classes and sections of the RZ, thereby offsetting the values in other classes. In addition, patch isolation decreased (Mean ENN declined), indicating that patches became more proximate. All five metrics indicate that the fragmentation is uneven across the entire riparian zone. In some classes or areas, patches became larger or more connected, whereas in others, larger patches were disaggregated, though they sometimes remained close to each other.

Across the entire protected area, fragmentation increased from 2016 to 2024, as evidenced by a significant reduction in MPA, together with decreases in patch area variability (SD) and aggregation (CONTAG). In contrast, Mean ENN decreased, while MESH increased. This indicates a change in the landscape that led to the fragmentation of large and medium-sized patches. At the same time, in some parts of the protected area, fragments were consolidated and connected.

Mean Patch Area decreased across all three protected areas; however, the sharpest decline was observed in the Korughi Reserve. The variability (SD) of patch area decreased noticeably in the Korughi Reserve and declined slightly in Chachuna, while remaining nearly unchanged in the Iori Reserve, indicating that large patches were fragmented and their sizes became more uniform in Korughi and Chachuna. CONTAG decreased in all three protected areas, indicating a more fragmented and intermixed landscape. Mean ENN decreased across all three areas, indicating that although large patches were fragmented, they remained close to one another. As shown by the data, the MESH values for the entire riparian zone and the protected area were significantly influenced by the Iori Reserve, where values increased sharply from 2016 to 2024. The opposite trend is observed in the Korughi Reserve, where the MESH value decreased significantly. A slight decrease in MESH was also observed in the Chachuna Reserve.

Thus, landscape fragmentation also increased in the protected areas, as evidenced by the Korughi Managed Reserve and the Chachuna Reserve metrics. Fragmentation is also observed in the Iori Reserve, as indicated by some metrics (MPA and CONTAG); however, the sharp increase in MESH, the unchanged SD of patch size, and the decrease in mean ENN suggest a reduction in fragmentation.

Across the entire non-protected area, the landscape has become more fragmented. Mean Patch Area decreased dramatically, the Standard Deviation of Patch Area also declined, and CONTAG decreased sharply, indicating that patches became more uniform, the landscape became less connected, and different land-use classes became more intermixed. Similar to the entire riparian zone and the whole protected area, Mean Euclidean Nearest Neighbour Distance decreased, and MESH increased in the non-protected part, indicating that despite overall fragmentation, patches in some locations became closer to each other and the probability that two randomly selected points fall within a single patch increased. Additionally, landscape fragmentation was reduced in some isolated locations, possibly due to natural regeneration.

Analysing the class-level metrics for the forest class

Landscape-level analysis of the 2016 and 2024 data showed that the increase in MESH values is associated with the consolidation and connectivity of patches within certain classes and sections of the riparian zone. To clarify this, we calculated MESH at the class level for the same years and analysed the forest class data, which we discuss below in line with the changes in the landscape-level metric CONTAG (Tab. 4).

At the forest class level, MESH for the total area increased despite a decrease in CONTAG, which can be explained by some forest patches becoming larger while remaining more dispersed within a diversified matrix.

The MESH values of the forest class differed sharply between protected and non-protected areas as early as 2016, reflecting the fact that forests were primarily preserved within protected areas. By 2024, forest class MESH had further decreased in the unprotected area, while it had increased significantly in the entire protected area. At the same time, CONTAG decreased in both non-protected and protected areas. This change can be explained by the presence of larger forest fragments in the protected area, although their aggregation is reduced. In addition, the protected area matrix has become more diverse in some places.

Among protected areas, the increase in forest class fragmentation from 2016 to 2024 is most noticeable in the Korughi Reserve, where significant losses were observed in both the MESH and CONTAG indices. Most likely, there is internal fragmentation here. A different pattern is observed in the Iori Reserve, where MESH increased significantly. CONTAG is slightly reduced even here, which can be explained by some patches becoming larger through natural regeneration. Additionally, in certain areas, the classes have become more intermixed.

The above indicates that the increase in overall MESH data is significantly associated with a reduction in forest class fragmentation in the Iori reserve. In the case of the Chachuna reserve, firstly, it was already the most fragmented in 2016, and by 2024, both indicators – MESH and CONTAG – had decreased even further. It is also worth noting that, in the case of Chachuna, the lower MESH values compared to the other two protected areas can be explained by the presence of a different forest species.

Thus, local differences were observed not only between protected and unprotected areas, but also among individual protected areas. Forest regeneration characterises the Iori Reserve, while in Korughi, connectivity is declining and fragmentation has increased sharply. Chachuna is the most fragmented according to most indicators, and only here was an increase in the forest class Mean ENN observed, indicating that forest patches are farther apart.

Getis-Ord Gi analysis of riparian forest fragmentation

The Getis-Ord Gi analysis of the Effective Mesh Size (MESH) values in the Iori River riparian forest landscape revealed an increase in hot spots and a decrease in cold spots across the entire area of interest (AOI). This pattern indicates that areas with higher landscape connectivity have become more spatially clustered, and areas of lower connectivity (i.e., higher fragmentation) have diminished in extent, suggesting an overall reduction in landscape fragmentation. The analysis indicates that protected areas were crucial in mitigating landscape fragmentation. The proportion of hot spots is substantially higher within protected areas than in non-protected zones, as reflected in the concentration of high MESH values within their boundaries.

By 2016, the non-protected portion of the study area was already highly fragmented. Accordingly, several large cold spots were identified in the data from this period. Cold spots were primarily concentrated in non-protected areas. Statistically significant ($p < 0.01$) negative Z-scores were predominantly observed in a zone extending from the northwest of Korughi to the Kvemo Samgori Dam and surrounding areas of Sartichala, Mughanlo, and Ujarma. Cold spots were also identified near the village of Paldo, in areas bordering the Iori Managed Reserve and adjacent to the Dali Mountain Reservoir. The cold spots within the protected areas were located in the Chachuna Reserve, downstream from the dam. As of 2016, riparian forest areas without protected status were severely fragmented.

By 2024, the same cold spots identified in 2016 remained present. As mentioned above, the northwestern part of the Dali Mountain Reservoir underwent significant changes during the study period. While a forested area was still present in 2016, it had been flooded by 2024. Accordingly, this location exhibited a cluster of statistically significant ($p < 0.01$) negative Z-scores. Although the number of hot spots in the non-protected area increased overall, and the number of cold spots decreased, this did not significantly reduce fragmentation. Based on the 2024 data, in the non-protected areas, both clusters identified in 2016, the Sartichala and Dali Mountain Reservoir hot spots, have disappeared. The most significant change was observed at the Dali Mountain Reservoir, where a previously identified hot spot ($p < 0.01$) transitioned into a cold spot of equal statistical significance ($p < 0.01$).

Notably, the riparian forest grove adjacent to the vineyards of Khashmi village was classified as a statistically non-significant area ($p > 0.05$) in both 2016 and 2024. Surrounded by cold spots, it remained outside any statistically significant cluster in both years. The Khashmi forest separates the terroir, known for its vineyards, from the sand and gravel extraction sites along the Iori River, thus having great environmental significance at the local level.

Thus, the local spatial autocorrelation analysis revealed that fragmentation is generally low within protected areas, with hot spots of high MESH values concentrated there. In contrast, fragmentation remains high in non-protected areas.

Riparian forest fragmentation in protected areas

Spatial analysis of the 2016 Effective Mesh Size data (10 m grid cell) revealed that within the entire riparian zone, the areas with statistically significant ($p < 0.01$) high positive Z-scores (3.5-8.8) were concentrated within the Korughi and Iori Reserves. The largest cluster was located within the Korughi Reserve, while in the Iori Reserve, hot spots were represented by several distinct clusters. As of 2016, statistically significant ($p < 0.05$) positive Z-scores in non-protected areas were identified in only two locations: northwest of the Dali Mountain Reservoir and near the village of Sartichala. The Chachuna Reserve, in contrast, was characterised by the absence of hot spots. Only a single grid cell (10 ha) with a statistically significant positive value at the 0.05 level was identified in the lower part of the reserve. In the upper part of the Chachuna, a large hot spot was detected, extending beyond the current protected area.

According to 2024 data, compared to 2016, fragmentation has generally decreased within protected areas and increased in non-protected areas, although the situation varies across individual locations. More specifically, the 2024 Effective Mesh Size spatial autocorrelation analysis showed the same hot spots as in 2016, with more cells exhibiting statistically significant ($p < 0.05$) positive Z-scores (10 m grid cell). However, the area of hot spots decreased in the Korughi Reserve, whereas in the Iori Reserve it increased, and the cluster became larger than in 2016. In the Chachuna Reserve, only two cells in the lower part of the reservoir exhibited statistically significant positive values. Meanwhile, the previously identified hot spot in the upper part of the reservoir has decreased in extent.

Given that the previous analysis reflects a generalised pattern based on 10 ha grid cells, we conducted a more detailed assessment using 1 ha grid-cell MESH data to produce a more detailed map and capture spatial variations between protected areas (Figs. 4, 5 and 6).

In the Korughi Reserve, the number of cells with high MESH values decreased from 2016 to 2024 (1 ha grid cell). As a result, the number of statistically significant ($p < 0.05$) positive Z-scores declined, and the two previously identified hot spots fragmented into multiple smaller clusters (Figs. 3 and 4). This change in hot spots indicates an increase in fragmentation. However, within the Korughi Reserve, the number of cold spots has also decreased slightly.

The degree of fragmentation increased in the sections of the Korughi Reserve located northwest of the village of Paldo and opposite to the village of Iormuganlo. In contrast, fragmentation decreased in the eastern part adjacent to the Iori Reserve.

The Iori Reserve itself recorded a noticeable reduction in fragmentation in 2024 compared to 2016 (1 ha Grid cell). Here, the total area of hot spots has increased significantly, while the area of cold spots has decreased. Many of the cells exhibited high MESH values. Overall, fragmentation in the Iori Reserve has decreased.

The number of hot spots in the Chachuna Reserve has decreased slightly (1-ha grid cell), while the number of cold spots has increased (Figs. 3 and 6). The increase in fragmentation, i.e. the decrease in the number of cells with statistically significant ($p < 0.05$) positive

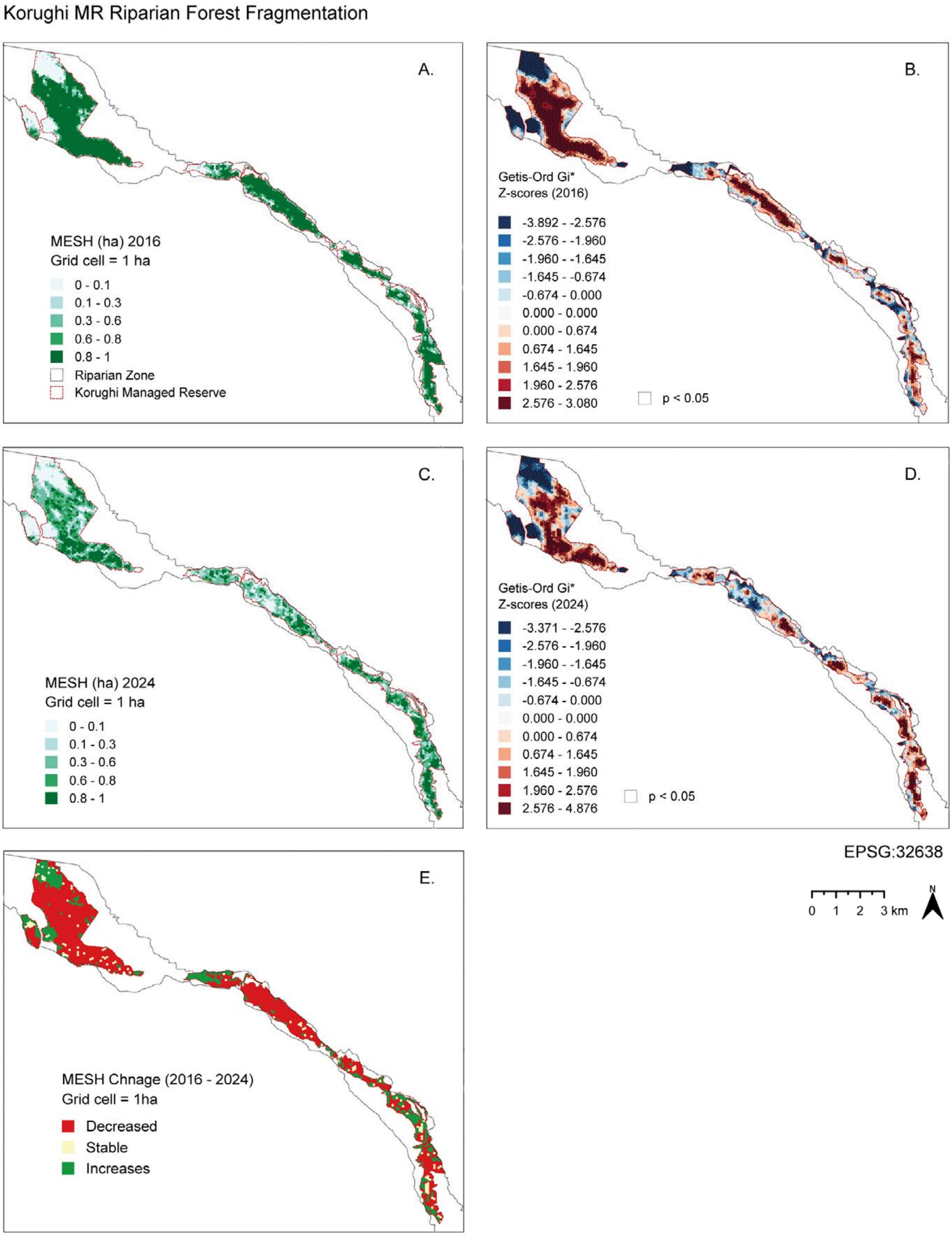


Figure 4. Riparian forest fragmentation degree in Korughi Managed Reserve in 2016 and 2024: Fragmentation index – Effective Mesh Size (MESH), Spatial clusters (Getis-Ord Gi*) and Statistical significance (p-values) maps

Z-scores, became noticeable in the section above the Dali Mountain Reservoir.

Thus, the Iori Managed Reserve is the least fragmented protected area, and the Effective Mesh Size increased significantly from 2016 to 2024. An increase in fragmentation is observed in the Chachuna and Korughi Managed Reserves. Of these, Chachuna was already fragmented in 2016, and the situation has not improved, while Korughi was the least fragmented in the same year and has seen the sharpest increase in fragmentation.

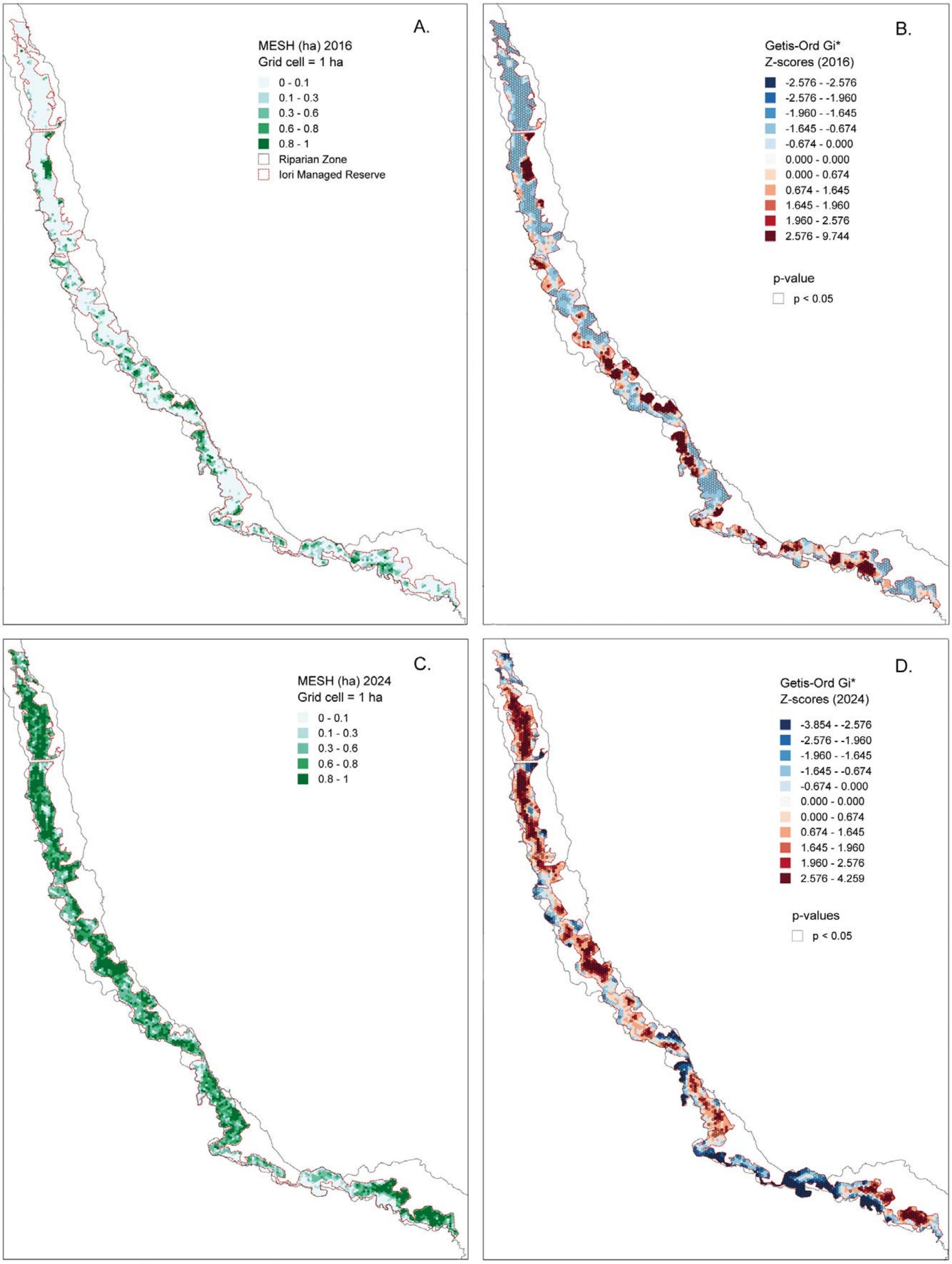
Legal and policy frameworks for riparian forest conservation

As demonstrated above, the riparian forests of the Iori River downstream area are primarily concentrated within protected areas, where overall forest cover has increased, and fragmentation has decreased over the past 50 years. Unlike the non-protected areas, protected areas showed higher Effective Mesh Size values in 2016 and 2024, accompanied by statistically significant ($p < 0.01$) positive Z-scores, indicating strong spatial connectivity clustering. The timely regulatory framework for protecting the Iori habitats, which aimed to create protected areas, has conditioned the maintenance of riparian forests. In the context of the research presented, international conventions such as the Convention on Biological Diversity (1992), which Georgia joined in 1994, and the Bern Convention on the Conservation of European Wildlife and Natural Habitats (1979) are important. Establishing the Korughi, Iori, and Chachuna Managed Reserves in 1996 played a key role in protecting riparian forests. These protected areas fall under the Terrestrial and Inland Waters Protected Areas category, classified as IUCN Management Category IV (World Database on Protected Areas, 2024). All three areas share similar status, protection regime, zoning structure, and permitted activities. According to the Technical Regulations (Government of Georgia, 2014), the primary goal of establishing them was to preserve, protect, maintain, and restore riparian forest ecosystems. Two territorial-functional zones have been designated: 1. Managed Protection Zone and 2. Traditional Use Zone. The second zone, with a more lenient regime, permits the creation and development of tourist and recreational infrastructure. The neighbouring population can also use specific resources, such as grazing, livestock transit, sustainable logging, hunting, fishing, and more (Legislative Herald of Georgia, 2014). Generally speaking, the inclusion of key habitats in the international system of protected areas, along with international support for Georgia's environmental protection sector following the collapse of the Soviet Union (Khardziani, 2026), played crucial roles in preserving the Iori riparian forests.

The research results show that creating a protected area system has proven effective in preserving the Iori riparian forests. However, challenges to the forests persist, particularly in the non-protected areas of the Iori floodplain. Also, the continued decline of forest area, albeit small, and the increasing fragmentation observed in the Korughi and Chachuna reserves over the past eight years. The Forest Code of Georgia (2020) is an important national-level document that regulates the condition of riparian forests outside protected areas. In addition, the Law of Georgia on Subsoil (1996) is an important document due to recent developments in the AOI, including the intensive extraction of construction materials, such as sand and gravel, in non-protected zones.

According to the Forest Code of Georgia, our research object falls under the protected forest category. In addition, if a riparian forest is designated as a protected area, it is considered a first-category protected forest subject to a special protection regime. If a riparian forest is not designated as a protected area, it is classified as a second-category protected forest, a potential or reserve protected area, serving as a basis for the possible expansion of the protected areas network (Forest Code of Georgia, 2020). The same law regulates forest restoration and planting, which may be carried out by a forest management body

Iori MR Riparian Forest Fragmentation



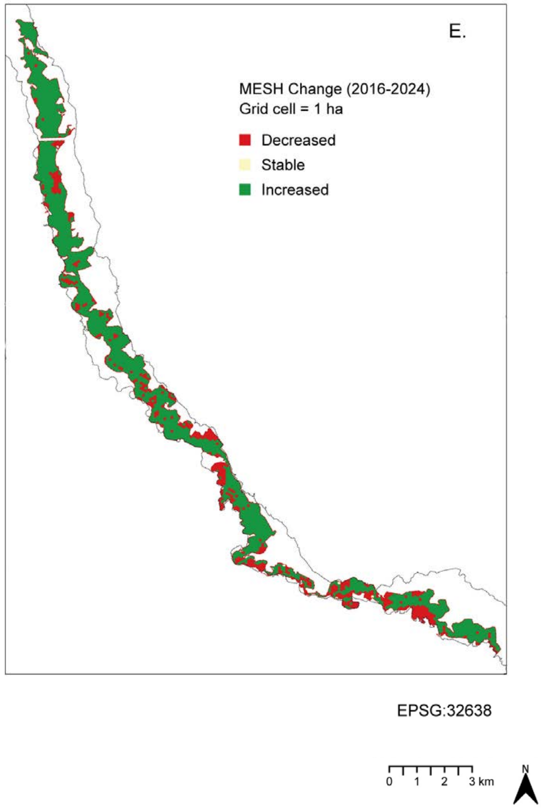
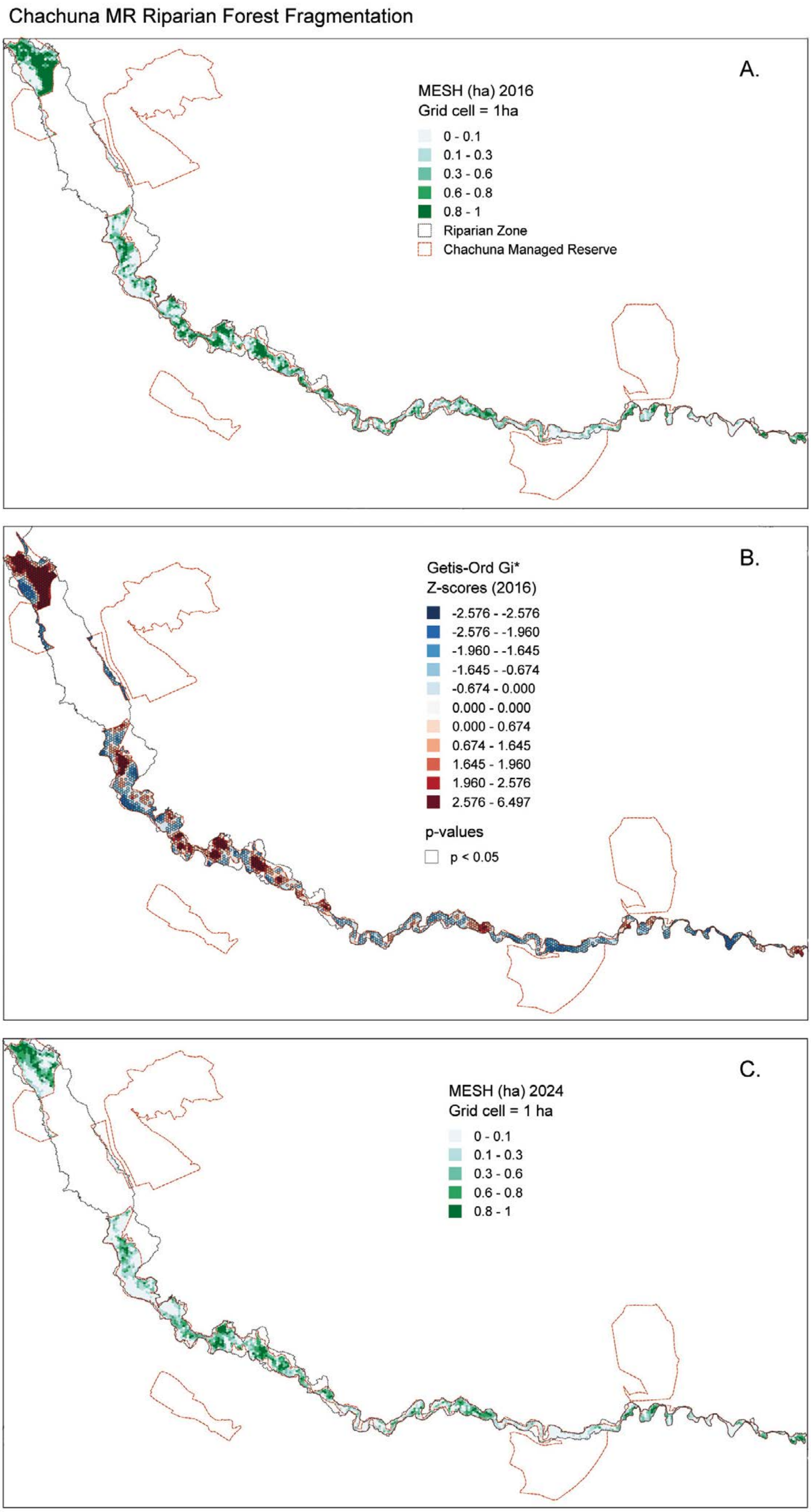


Figure 5. Riparian forest fragmentation degree in the Iori Managed Reserve in 2016 and 2024


Chachuna MR Riparian Forest Fragmentation
A.
MESH (ha) 2016
Grid cell = 1ha
0 - 0.1
0.1 - 0.3
0.3 - 0.6
0.6 - 0.8
0.8 - 1
Riparian Zone
Chachuna Managed Reserve
B.
Getis-Ord Gi*
Z-scores (2016)
-2.576 - -2.576
-2.576 - -1.960
-1.960 - -1.645
-1.645 - -0.674
-0.674 - 0.000
0.000 - 0.000
0.000 - 0.674
0.674 - 1.645
1.645 - 1.960
1.960 - 2.576
2.576 - 6.497
p-values
p < 0.05
C.
MESH (ha) 2024
Grid cell = 1 ha
0 - 0.1
0.1 - 0.3
0.3 - 0.6
0.6 - 0.8
0.8 - 1

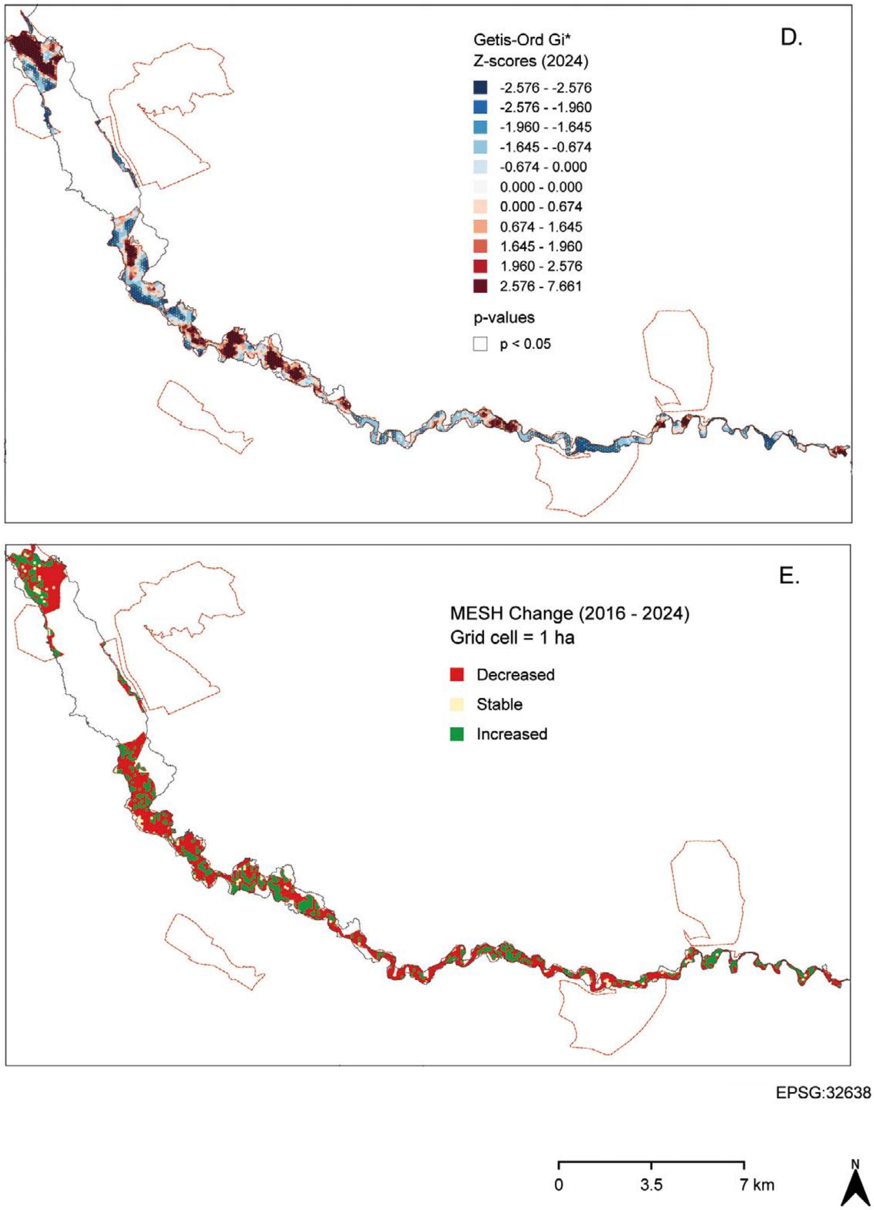


Figure 6. Riparian forest fragmentation degree in Chachuna Managed Reserve in 2016 and 2024

or by natural persons and legal entities with the appropriate authority (Forest Code of Georgia, 2020). These two laws create a legal basis for forest restoration in the Iori unprotected zone.

The Law of Georgia on Subsoil regulates the use of forested areas for subsoil, along with the Forest Code. According to this law and the terms of subsoil use licensing, the extraction of inert construction materials from riverbeds is prohibited if the river lacks an additional tributary supplying sufficient solid sediment. Extracting material on floodplain terraces within 50 m of the riverbed is prohibited. The extraction of inert construction materials is not prohibited in other sections of the river (Low of Georgia on Subsoil, 1996). According to the same law, subsoil users must protect forests and protected areas from harmful impacts and "restore land damaged by subsoil use to a safe and usable condition" (Law of Georgia on Subsoil, 1996).

The study area clearly shows groves outside protected areas disappearing due to extraction activities. Examples include the forests surrounding Sartichala and Khashmi, which are small and identified as statistically insignificant in fragmentation metric analyses. The objectives of the sectoral priority Biodiversity and Protected Areas in the National Environmental Action Program (2022-2026) include protecting habitats outside protected areas and establishing ecological corridors connecting them (Government of Georgia, 2022). The sectoral priority Forest Management objectives in the same action program include forest maintenance and restoration of degraded areas. However, at this stage, no restored forests are present in the study area, and tree growth has been recorded only through natural succession. It is recommended that forest restoration measures be included in the completion stage of sand and gravel extraction in river floodplains. In this case, a continuous strip of riparian forest will be established in the future, potentially serving as an ecological corridor.

Georgia's current environmental strategy document also reflects the threats identified in the area of interest (Government of Georgia, 2022). The threats identified in the document may contribute to the increased fragmentation of the Korughi and Chachuna Reserves. Among the threats mentioned are the failure to account for the river's environmental discharge and the unsustainable use of reservoirs, water resources, and pastures (Government of Georgia, 2022). The most recent hydrological study of the Iori River also highlights the impact of changing hydrological regimes on the riparian forests. The same work emphasises the role of floods and periodic flooding in forming Iori riverine forests (Tsitelashvili et al., 2020). Accordingly, the same authors have proposed artificial flooding to improve the condition of the forest habitat in the Chachuna Managed Reserve. In the future, the impact of reduced river flow on riparian forest fragmentation should be investigated in more detail, in an interdisciplinary context. For example, the increasing fragmentation of the Korughi Reserve remains a significant challenge. Further investigation is needed to determine the extent to which this is related to the disruption of the hydrographic network caused by sand and gravel extraction.

The landscapes surrounding the Iori floodplain have historically been used as pastures. As mentioned above, in the early eighteenth century, Vakhushti Bagrationi noted that this area "was grassy in winter and served as pasture for herds of sheep and goats driven from various directions, as well as for horse herds" (Brosset, 1842). The Iori floodplain is partially bordered by pastures, and sheep trails also pass through its territory. The routes connecting winter and summer pastures are overgrazed (Gargallo et al., 2023). Specific measures have already been implemented to address this issue. In particular, the Chachuna Reserve and its surrounding steppe landscapes of Kotsakhura and Samukhi were included in the Standing Committee of the Bern Convention's updated list of officially adopted Emerald Network sites in December 2023 (Council of Europe, 2023). Thus, expanding the protected area network is a measure to prevent threats to the Iori riparian forests.

The condition of the forests in the Iori floodplain is similar to that in Azerbaijan, which, like our study area, is located in the steppe biogeographical region. According to Abbasov et al. (2023), historical evidence indicates that the so-called "Tugai forest" (riparian) once covered a large area in the Mtkvari and Araks valleys in Azerbaijan. The area of such forests has decreased, influenced by various factors, including water flow regulation. Among other factors, dams and reservoirs (Mingechevir and Bahramtapa) have been named as causes of habitat fragmentation. These create obstacles on major rivers and effectively fragment floodplain habitat. Overgrazing of winter pastures is also considered a contributing factor to fragmentation in Azerbaijan. Riparian forests are relatively well preserved in protected areas like the Qarayazi State Reserve (Abbasov et al., 2023) on the Mtkvari River, also known as the Kura River. Thus, the riparian forest landscapes of the same ecoregion in Azerbaijan share a history and comparable barriers, threats, and solutions similar to those in our study area.

In conclusion, the environmental policy implemented since the 1990s, particularly international support for the environmental protection sector and the granting of protected status, has preserved the Iori riparian forests and improved their condition. In the unprotected part, no sustainable riparian forest management is evident, and the remaining forest groves are disappearing. Also, no visible reforestation and restoration project has been implemented yet. In recent years, fragmentation has also increased in specific locations of protected areas, highlighting the need to strengthen the monitoring system, including the research component.

Conclusions and recommendations

In summary, the research aimed at assessing the fragmentation of the Iori River riparian forests, an ecosystem of high conservation value, and evaluating the role of protected area status in their preservation and enhancement. We were also interested in the processes occurring within the non-protected riparian zone and their potential impact on the adjacent protected forests.

It was found that in the first half of the eighteenth century, the Iori forests formed a continuous stretch across a large study area, reaching the river mouth and being rich in biodiversity. By the end of the nineteenth century, the forest was no longer continuous, and parts of what are now protected areas were treeless. Forest cover decreased and became fragmented in the twentieth century. Shortly before the collapse of the Soviet Union, it occupied a much smaller area than it does today or in the eighteenth and nineteenth centuries. Forest areas have increased significantly, mainly within protected areas, since the 1990s, following the creation of three managed reserves. Despite the increase in total forest area over the past 50 years, data from the past approximately 8 years show that forest cover has decreased in some areas, including protected zones.

The results indicate that fragmentation in the study area decreased from 2016 to 2024, mainly due to data on protected areas, which are hotspots of high Effective Mesh Size values. The unprotected zone remains highly fragmented, with MESH cold spots dominating (Fig. 2). Despite overall improvements in forest condition in protected areas over the last 50 years and a reduction in total fragmentation over the last 8 years, differences persist between locations. In particular, in the Korughi and Chachuna reserves, the distribution area of statistically significant ($p < 0.05$) positive Z-scores decreased slightly from 2016 to 2024, indicating increased fragmentation. During the same period, the condition of the Iori Managed Reserve improved, as indicated by a reduction in fragmentation. The preservation and improvement of the riparian forest in the study area are closely linked to the establishment and development of protected areas. This, in turn, was made possible by including existing habitats in the international network of protected areas, the emergence of international support for environmental sector development following the collapse of the Soviet Union, and subsequent developments.

Despite overall progress, significant challenges remain as ongoing processes in the surrounding areas threaten the protected zones. Namely, old structures built on the river that impede its free flow, as well as grazing and ongoing sand and gravel extraction operations, alter hydrography and affect river flow. The first two of these problems are historically embedded, while the last is a recent threat to biodiversity. Impacts from winter grazing are expected to cease shortly, as the surrounding area of the Chachuna Managed Reserve has been included in the expansion of protected areas and is now part of the Emerald Network. Strengthening the monitoring and research component of protected area management is important. Further investigation is needed to determine the impact of reduced water flow on increased fragmentation.

Finally, this study's findings suggest that although the necessary legal and political framework for forest restoration has already been established, no restoration measures have been implemented in the study area. Several activities are needed to reduce fragmentation of the Iori riparian forests. In particular, forest restoration after the completion of sand and gravel extraction works and the preservation of small groves remaining outside protected areas; Demolition of Soviet-era structures that have lost their function and creation of a free-flowing hydrographic network; Managing and modifying the Dali Mountain Reservoir in a way that provides water to the riparian forest of the Chachuna Managed Reserve; and restoring the continuity of the Iori riparian forest by afforesting the non-protected area to reestablish its corridor function.

Acknowledgements

This research was funded by the Shota Rustaveli National Science Foundation of Georgia (SRNSFG) [grant number YS-22-415]. The authors are grateful to the anonymous reviewers and the journal editors for their constructive comments on earlier versions of the manuscript, which significantly improved the quality and clarity of the paper.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

References

Abbasov, R. K., Allahverdiyev, R., Zaynalov, R., Habilov, A., & Aliyeva, R. (Eds.). (2023). Azerbaijan National Ecosystem Assessment. Baku, Azerbaijan: Government of Azerbaijan, RECC Azerbaijan.

Bagrationi, V. (1997). Atlas of Georgia. Tbilisi: Academy of Science Georgia.

BirdLife International. (2018). *Francolinus francolinus*. The IUCN Red List of Threatened Species 2018. e.T22678719A131903818. https://doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22678719A131903818.en

BirdLife International. (2021). Tetrax tetrax. The IUCN Red List of Threatened Species 2021. e.T22691896A166234017. https://doi.org/10.2305/IUCN.UK.2021-3.RLTS.T22691896A166234017.en

BirdLife International. (2023). Otis tarda. The IUCN Red List of Threatened Species 2023. e.T22691900A226280431. https://doi.org/10.2305/IUCN.UK.2023-1.RLTS.T22691900A226280431.en

Breiman, L. (2001). Random forests. *Machine Learning*, *45*(1), 5-32. https://doi.org/10.1023/A:1010933404324

Brosset, M. (1842). Description of the Kingdom of Georgia. Saint Petersburg: Typography of the Academy.

Chadburn, H. & Wilson, B. (2018). Elaeagnus rhamnoides. The IUCN Red List of Threatened Species 2018. e.T55686342A119996497. https://doi.org/10.2305/IUCN.UK.2018-1.RLTS.T55686342A119996497.en

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement, 20*(1), 37-46. https://doi.org/10.1177/001316446002000104

Congedo, L. (2021). Semi-Automatic Classification Plugin (SCP) – Documentation. https://fromgistors.blogspot.com/p/semi-automatic-classification-plugin.html

Convention on Biological Diversity. (1992). Convention on Biological Diversity. United Nations. https://www.cbd.int

Council of Europe. (1979). Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention). https://www.coe.int/en/web/bern-convention

Council of Europe. (2019). Emerald Network site: Chachuna. https://emerald.eea.europa.eu

Council of Europe. (2023). Updated list of officially adopted Emerald Network sites by the Standing Committee of the Bern Convention, December 2023. https://rm.coe.int/draft-list-of-adopted-emerald-network-sites/1680ad54a1

European Environment Agency. (2016). Biogeographical regions in Europe. https://www.eea.europa.eu/en/analysis/maps-and-charts/biogeographical-regions-in-europe-2?activeTab=a7caf3b5-7254-4a24-8919-693d4115158b

European Environment Agency. (2019). EUNIS habitat classification. https://eunis.eea.europa.eu/habitats.jsp

European Space Agency (2024b). Sentinel Application Platform. https://step.esa.int/main/toolboxes/snap/

European Space Agency. (2024a). Copernicus Data Space Ecosystem. https://dataspace.copernicus.eu.

FFI/IUCN SSC. (2007). Central Asian regional tree Red Listing workshop, Bishkek, Kyrgyzstan (11-13 July 2006). Vitis vinifera. The IUCN Red List of Threatened Species 2007. e.T63537A12687723. https://doi.org/10.2305/IUCN.UK.2007.RLTS.T63537A12687723.en

Forest Code of Georgia. (2020). Legislative Herald of Georgia, No. 5949. https://matsne.gov.ge/en/document/view/4874066?publication=3

Forman, R. T. T. (1995). *Land Mosaics: The Ecology of Landscapes and Regions*. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781107050327

Gargallo, E., Haller, T., Chatty, D., Weissman, S., Meessen, H., Giger, M., ... & Chkhobadze, N. (2023). The new green grabbing frontier and participation: conserving drylands with or without people. In *Drylands Facing Change* (pp. 132-152). Routledge. https://doi.org/10.4324/9781003174486-10

Getis, A., & Ord, J. K. (1992). The analysis of spatial association by use of distance statistics. *Geographical Analysis, 24*(3), 189-206. https://doi.org/10.1111/j.1538-4632.1992.tb00261.x

Government of Georgia. (2014). *Red List of Georgia*. Ordinance of the Government of Georgia. https://matsne.gov.ge/ka/document/view/2256983?publication=0

Government of Georgia. (2022). Fourth National Environmental Action Programme of Georgia 2022-2026 (Decree No. 1629). Legislative Herald of Georgia. Retrieved from https://matsne.gov.ge/en/document/view/5563250?publication=0

Güldenstädt, J. A. (1787). Reisen durch Rußland und im Caucasischen Gebirge (Travels through Russia and the Caucasian Mountains). Volume 1. St. Petersburg: Imperial Academy of Sciences.

IPCC. (2022). Climate Change and Land. In *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* (pp. 345-436). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157988.006

Jaeger, J. A. (2000). Landscape division, splitting index, and effective mesh size: New measures of landscape fragmentation. *Landscape Ecology*, *15*, 115-130. https://doi.org/10.1023/A:1008129329289

Jung, M. (2022). LecoS – Landscape Ecology Statistics. http://conservationecology.wordpress.com/lecos-land-cover-statistics/

Khardziani, T. (2026). Compromised riparian landscapes: A landscape ecological assessment of the riparian forests in the Lower Kartli Lowland, Georgia. In L. Soares, M. Saraiva, & R. de Miguel González (Eds.), *Compromised geography: Key challenges in geography* (pp. 361-378). Cham: Springer. https://doi.org/10.1007/978-3-032-05201-8_18

Law of Georgia on Subsoil. (1996). Legislative Herald of Georgia, No. 242. https://matsne.gov.ge/en/document/view/33040?publication=17.

Legislative Herald of Georgia. (2014). Government of Georgia. Resolution No. 84. January 16, 2014. https://www.matsne.gov.ge

Loy, A., Kranz, A., Oleynikov, A., Roos, A., Savage, M., & Duplaix, N. (2022). *Lutra lutra* (amended version of 2021 assessment). The IUCN Red List of Threatened Species 2022. e.T12419A218069689. https://doi.org/10.2305/IUCN.UK.2022-2.RLTS.T12419A218069689.en

Malanson, G. P. (1993). *Riparian Landscapes*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511565434

McGarigal, K., Cushman, S. A., & Ene, E. (2023). FRAGSTATS v4: Spatial pattern analysis program for categorical maps [Computer software]. University of Massachusetts, Amherst. http://www.umass.edu/landeco/research/fragstats/fragstats.html

Naiman, R. J., & Decamps, H. (1997). The ecology of interfaces: riparian zones. *Annual review of Ecology and Systematics*, *28*(1), 621-658. https://doi.org/10.1146/annurev.ecolsys.28.1.621

Opdam, P., & Wascher, D. (2004). Climate change meets habitat fragmentation: linking landscape and biogeographical scale levels in research and conservation. *Biological Conservation*, *117*(3), 285-297. https://doi.org/10.1016/j.biocon.2003.12.008

Pyryt, P., & Pułkowiec-Kurda, K. (2024). The landscape fragmentation: Analysis of land cover transformation in high mountain environments on the example of the Tatra region (southern Poland). *Quaestiones Geographicae*, *43*(1), 111-126. https://doi.org/10.14746/quageo-2024-0007

QGIS Development Team. (2024). QGIS 3. 34. Prizren. https://qgis.org

Red Data Book. (1982). State Committee for Nature Protection of the Georgian SSR, Academy of Sciences SSR, & Tbilisi State University. Red Data Book of the Georgian SSR. Tbilisi: Sabchota Sakartvelo.

Rossy, Q. (2019). Visualist: A spatial analysis plugin for crime analysts. Ecole des sciences criminelles, Lausanne. https://plugins.qgis.org/plugins/visualist/

Stieger, M., & McKenzie, P. (2024). Riparian landscape change: A spatial approach for quantifying change and development of a river network restoration model. *Environmental Management, 74*, 853-869. https://doi.org/10.1007/s00267-024-02025-w

Thomas, A., Masante, D., Jackson, B., Cosby, B., Emmett, B., & Jones, L. (2020). Fragmentation and thresholds in hydrological flow-based ecosystem services. *Ecological Applications*, *30*(2), e02046. https://doi.org/10.1002/eap.2046

Tsitelashvili, N., Guliashvili, G. & Bitsadze, M. (2020). Hydrological Report on the River Iori. https://sabuko.org/wp-content/uploads/2021/01/HYDROLOGICAL-REPORT-ON-THE-RIVER-IORI_ENG.pdf

Turner, M. G. (1989). Landscape ecology: the effect of pattern on process. *Annual Review of Ecology and Systematics*, 171-197. https://www.jstor.org/stable/2097089

World Bank. (2025). World Bank Official Boundaries Data Catalogue. https://datacatalog.worldbank.org/search/dataset/0038272/World-Bank-Official-Boundarie

World Database on Protected Areas. (2024). Protected Planet. https://www.protectedplanet.net

Article first received • 3 March 2025
Article accepted • 14 January 2026