LANDSCAPE FRAGMENTATION AND DEFORESTATION IN SIERRA LEONE, WEST AFRICA, ANALYSED USING SATELLITE IMAGES

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ABSTRACT

Monitoring rainforests in West Africa is necessary for natural resource management. Remote sensing is valuable for mapping tropical ecosystems and evaluation of landscape heterogeneity. This study presents landscape analysis in Sierra Leone which affects wildlife habitats and biodiversity. Methods include modules “r.mapcalc”, “r.li.mps”, “r.li.edgedensity”, and “r.forestfrag” of GRASS GIS for satellite image processing by computation of mean patch size, edge density index and landscape fragmentation with six levels: exterior, patch, transitional, edge, perforated, and interior. The results demonstrate increased deforestation and landscape fragmentation in Sierra Leone over a 10-year period (2013 to 2023).

RÉSUMÉ: Fragmentation du paysage et déforestation en Sierra Leone, Afrique de l’Ouest, analysées à l’aide d’images satellite.

Le suivi des forêts tropicales en Afrique de l’Ouest est nécessaire à la gestion des ressources naturelles. La télédétection est précieuse pour cartographier les écosystèmes tropicaux et évaluer l’hétérogénéité des paysages. Cette étude présente une analyse du paysage en Sierra Leone qui affecte les habitats fauniques et la biodiversité. Les méthodes incluent les modules “r.mapcalc”, “r.li.mps”, “r.li.edgedensity” et “r.forestfrag” de GRASS GIS pour le traitement d’images satellite par calcul de la taille moyenne des parcelles, de l’indice de densité des bordures et de la fragmentation du paysage avec six niveaux: extérieur, point, transitionnel, bordure, perforé et intérieur. Les résultats démontrent une déforestation accrue et une fragmentation du paysage en Sierra Leone sur une période de 10 ans (2013 à 2023).

REZUMAT: Fragmentarea peisajului și defrișările din Sierra Leone, Africa de Vest, analizate folosind imagini din satelit.

Monitorizarea pădurilor tropicale din Africa de Vest este necesară pentru gestionarea resurselor naturale. Teledetecția este valoroasă pentru cartografierea ecosistemelor tropicale și evaluarea eterogenității peisajului. Acest studiu prezintă analiza peisajului din Sierra Leone, care afectează habitatele faunei sălbatice și biodiversitatea. Metodele includ modulele „r.mapcalc”, „r.li.mps”, „r.li.edgedensity” și „r.forestfrag” ale GRASS GIS pentru procesarea imaginilor satelitare prin calcularea dimensiunii medii a patch-ului, indicele de densitate a marginilor și fragmentarea peisajului cu șase niveluri: exterior, petic, tranzițional, margine, perforat și interior. Rezultatele demonstrează creșterea defrișărilor și fragmentării peisajului în Sierra Leone într-o perioadă de 10 ani (2013-2023).

INTRODUCTION

The crucial role of remote sensing data for landscape analysis and environmental assessment, both in a technical and scientific sense, has major implications for the way in which they can be analysed and used. In fact, information that can be retrieved from the satellite images is useful for ecological mapping in two different ways: detecting spatial heterogeneity of landscapes of land cover types (Lemenkova and Debeir 2023a; Fimbel, 1994;) and monitoring temporal changes that take place over a certain period of time (García-Álvarez et al., 2022; Tarawally et al., 2021). Combining both approaches enables to detect a spatial-temporal dynamics (Mustafa et al., 2021). While evaluating temporal changes in landscapes can be performed using comparative analysis of satellite images as a time series analysis for analysis of deforestation or landscape fragmentation (Lemenkova and Debeir, 2023b; Wilson et al., 2022; Haas et al., 2009), detecting spatial mosaic of landscape patterns is implemented by analysis of vegetation (Lemenkova and Debeir, 2023c; Nyerges and Green, 2000; Reid, 2016).

The use of remote sensing data is especially valuable for tracking environmental changes in Sierra Leone (Fig. 1). A small-sized coastal country of West Africa, it has a unique reserve of tropical rainforests and at the same time, notable level of deforestation (Nyerges, 1994). High pressure from human activities and development of infrastructure (Akiwumi and Butler, 2008) aggravated by civil unrest (Kaplan et al., 2022) resulted in recent land cover changes and deforestation in Sierra Leone with a general trend of declining areas of natural vegetation and expanding urban areas (Brandt et al., 2018). Environmental problems of Sierra Leone are diverse and in general, triggered by recent trends of climate change in West Africa which include increase in temperatures, decrease of precipitation and droughts (Bangura et al., 2013). The consequences of climate effects on the landscapes of Sierra Leona include flooding of wetlands and alluvial lowlands, deforestation, decrease of mangroves, and retreat of natural types of vegetation replaced by croplands.

Wetlands of the Sierra Leone area are a precious hotspot of biodiversity and habitats for species adapted to temporarily flooded ecosystems such as rare birds and endemic species (Field, 1968). Nevertheless, wetland areas in Sierra Leone are recently reported to be a subject of substantial (51%) decrease (Lahai et al., 2022). Moreover, Duncan et al. (2018) recently reported the processes of sea level rise that affect the distribution of mangrove forests in Sierra Leone. This raises questions of conservation of these precious ecosystems in coastal and riparian areas of Sierra Leone. Besides natural value, mangrove ecosystems of Sierra Leone are invaluable agro-ecological entries since rice yields are higher in temporarily flooded areas, swamps, coastal and riparian wetlands due to suitability of soil properties (Baggie et al. 2018).

Cultivating rice in wetlands of Sierra Leone has a rich history. Wetlands create favourable climate conditions, distribution of lowlands and repetitively flooded areas that create perfect conditions for rice plantations. As a result, rice is the major staple food in households of Sierra Leone. At the same time, climate and environmental issues resulted in reported problems with rice cultivations such as rice disease and crop losses (Fomba and Singh, 1990; Fomba, 1984). This may have consequences for food availability and sustainable development, thereby illustrating the link between the environmental and social issues.

Climate factors are aggravated by the increased anthropogenic pressure that includes urbanization, restructuring of landscapes, agricultural activities, increase of artificial areas and cropland fields and development of industrial facilities in Sierra Leone (Tarawally et al., 2019). Thus, West African landscapes are particularly vulnerable for social pressure and experience consequences of overuse of natural resources.

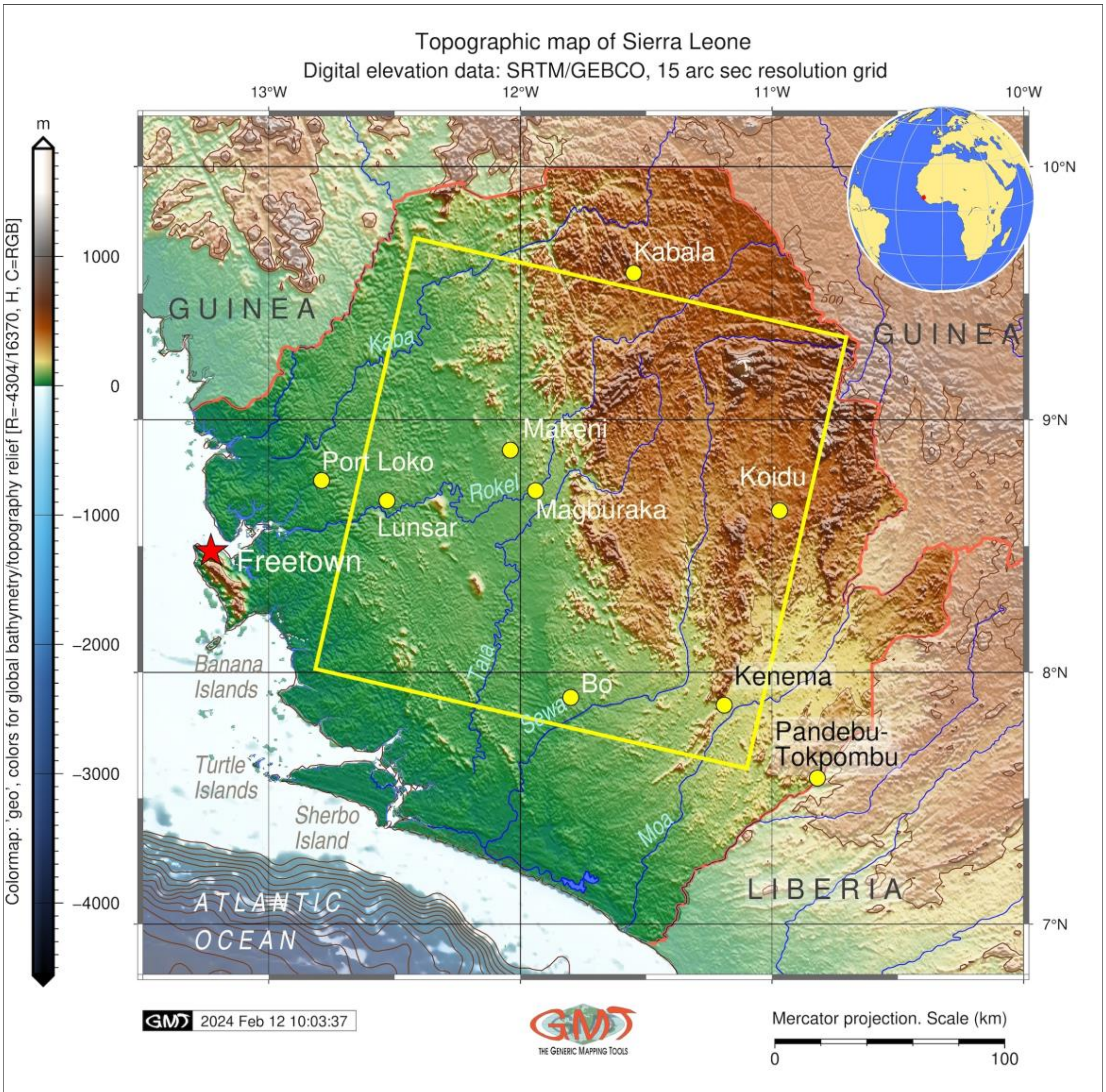

Figure 1: Topographic map of Sierra Leone showing the extent of study area (rotated yellow square). Data source: GEBCO. Software: GMT scripting toolset.

Recently, rainforests of the Sierra Leone area have been reported to be decreasing. For instance, the highest rates of rapid forest degradation associated with urbanization are detected since 2005 (Jin et al., 2020). Besides natural process of the increase in population that necessarily requires more land areas to be used for food production and agricultural activities (Herrmann et al., 2020), there are restructuring process that involves developing of infrastructure, business as well as increase of land areas intended for use in industrial purposes. In this regard, Gornitz (1985) raises questions of cumulative effects from anthropogenic and climate factors on vegetation changes in West Africa. At the same time, reorganisation of land and environmental changes may cause social consequences. Thus, Yengoh and Armah (2016) reported continuing process of restructuring of land use system in Sierra Leone which in turn has led to the restructured access to the suitable for agriculture areas.

Besides wetlands, other land cover types in Sierra Leone include complex mosaic of tropical rainforests, rainfed and aquatic croplands, flooded and irrigated vegetation along the coasts, broadleaved deciduous forests and woodlands, cultivated areas, grasslands and shrubland, evergreen and deciduous trees with different level of fragmentation (open/closed forests). The complex distribution of the landscape types and landscape patterns in Sierra Leone are shown in figure 2.

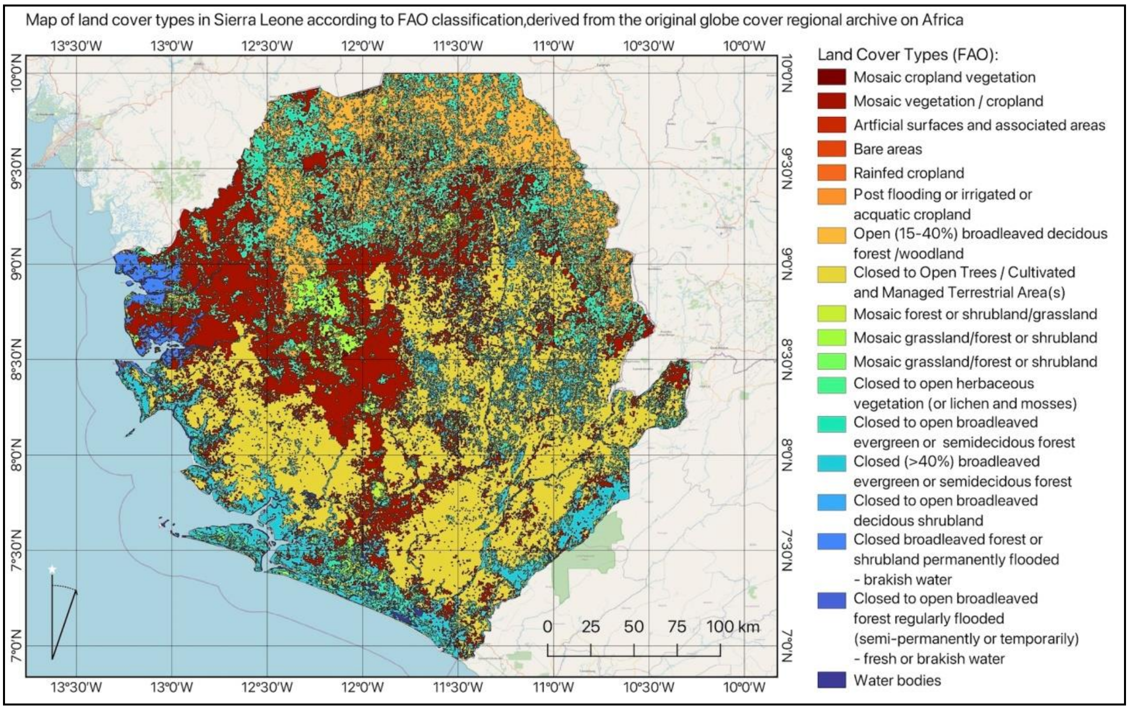

Figure 2: Land cover types and habitats in Sierra Leone. Data source: vector layers obtained from Food and Agriculture Organization (FAO) data repository.

A viewpoint commonly shared among the GIS community is that the advanced methods and operational tools for spatial data management significantly expand the dissemination of the proper techniques to the practice of cartographic data processing and empirical analysis in environmental studies. As argued at length in previous studies (Lemenkova, 2022b), the process of mapping becomes more efficient when using scripts because programming codes automate repetitive workflow, iterative steps and functions (Lemenkova and Debeir, 2022b). Consequently, specialized techniques of GRASS GIS that use modules enable to facilitate and advance landscape analysis. With a few exceptions, current mapping approaches in Sierra Leone lack such applications and mostly include the use of traditional GIS software that operates with user interface (Bah and Tsiko, 2011). In this study, we proposed using scripting approach of GRASS GIS to processing remote sensing data with aim to detect changes in forest areas of coastal Sierra Leone and analyse landscape fragmentation. Technical basis for the cartographic implementation of this research is the use of several modules of GRASS GIS involved in spatial analysis of satellite images.

MATERIAL AND METHODS

The data include two satellite images, Landsat 8-9 OLI/TIRS taken on 24.12.2013 and 27.02.2023 and covering Sierra Leone. The data originally produced by the USGS were obtained from the EarthExplorer website (Fig. 3). The Landsat images were selected as a data source since remote sensing provides a valuable source of information which can be retrieved using image processing methods as reported in numerous environmental studies (Lemenkova P. and Debeir O. 2022a; Lemenkova, 2020a; Heiskanen et al., 2019; Hillson et al., 2019).

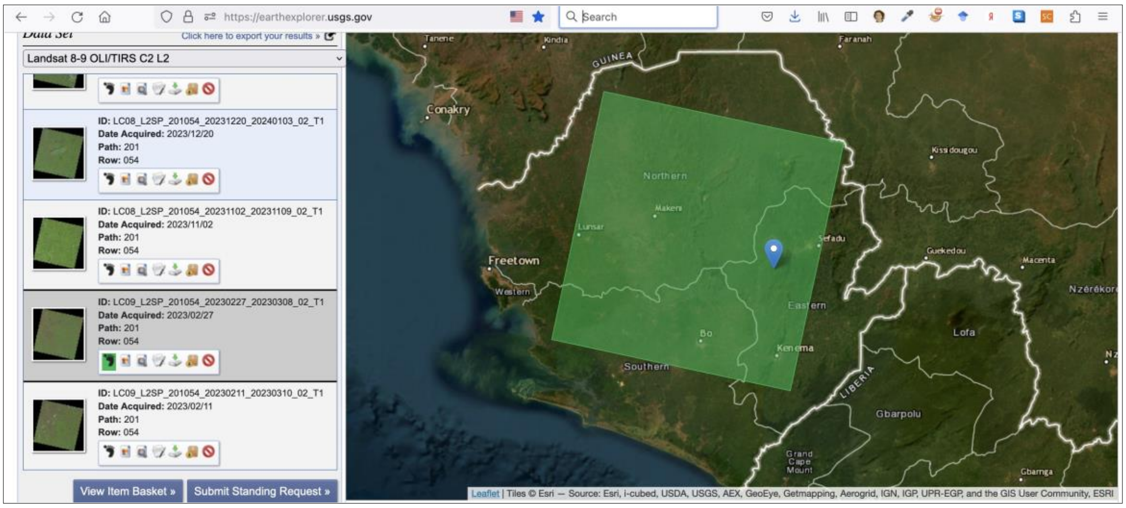

Figure 3: Data collection: satellite images Landsat 8-9 OLI/TIRS covering Sierra Leone obtained from the USGS EarthExplorer repository.

The original unprocessed satellite images are demonstrated in figure 4 where the scenes are represented in RGB in natural colours. The landscape analysis was performed using Geographic Resources Analysis Support System (GRASS) Geographic Information System (GIS) software (Neteler and Mitasova, 2008; Neteler et al., 2008). The effectiveness and powerful functionality of the open source GRASS GIS has been explained with demonstrated maps created using scripts (Lemenkova, 2022a, 2020b). Therefore, it has been selected as a main cartographic software for processing raster images. The topographic map in figure 1 was created using Generic Mapping Tools (GMT) software (Wessel et al., 2019) with applied existing methodology of scripts (Lemenkova, 2021a,b).

The forest fragmentation process was performed from the GRASS GIS console using codes organized in scripts as consecutive process that employs several GRASS GIS modules.

The first stage involves the classification of the two images and then reclassifying clusters into land cover types (Figs. 5 and 6). First, the computational region was set to match the scene using the following command: “g.region raster=L_2013_01 -p”. Then, the group of bands was created for each of the images to include all the multispectral scenes as follows: “i.group group=L_2013 subgroup=res_30m input=L_2013_01,<...>,L_2013_07”. Afterwards, clustering was done using “i.cluster” module which generates signature file and reports results using k-means: “i.cluster group = L_2013 subgroup=res_30m signaturefile=cluster_L_2013 classes=10 reportfile=rep_clust_L_2013.txt”. Finally, the classification is performed using “i.maxlik” module for both images as follows: “i.maxlik group=L_2013 subgroup=res_30m signaturefile=cluster_L_2013 output=L_2013_Cl reject=L_2013_Cl_reject”.

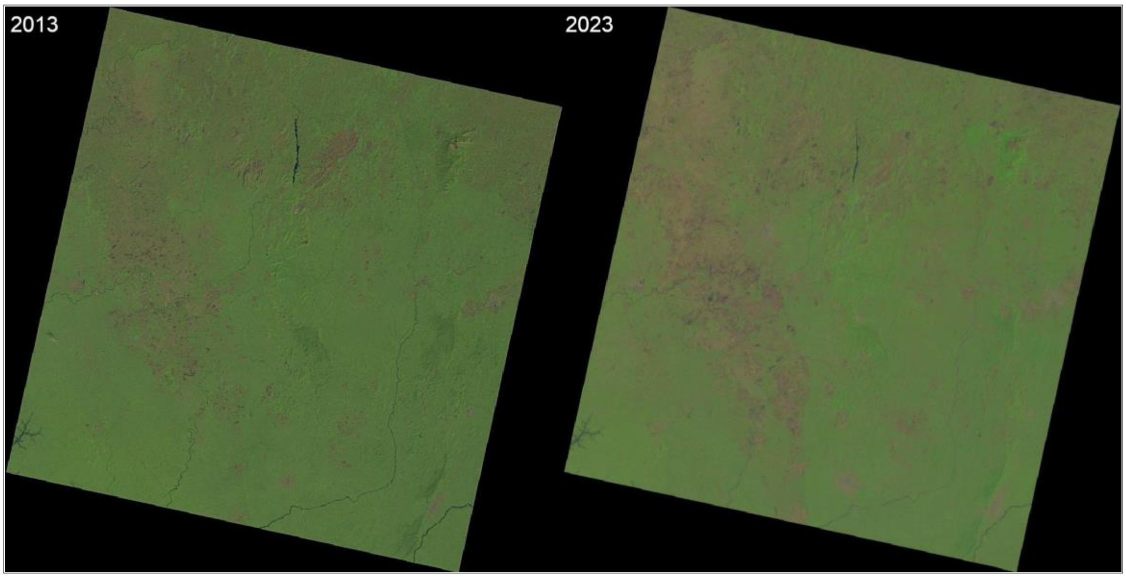

Figure 4: Satellite images Landsat 8-9 OLI/TIRS covering Sierra Leone in natural colors as raw data with a 10-year time gap. (a): 24 December 2013; (b): 27 February 2023.

Then, the categories of the raster file were checked to explore the range of values contained in the original map layer. This was done using the commands “r.category L_2013_cluster_classes” for a quick reference and “r.describe L_2013_cluster_classes” for a more detailed description of the file content and its categories. The rasters contained classes from Class 1 to Class 10, undetermined. Therefore, the classified images were examined and the classes assigned using the following code: “echo” 1 = 1 water 2 = 2 agriculture 3 = 3 shrubland 4 = 4 savannah 5 = 5 herbaceous 6 = 6 forest 7 = 7 grassland 8 = 8 bare soil 9 = 9 cropland 10 = 10 urban “> landuserecl.txt”. Hence, the file with descriptors “landuserecl.txt” was then used for reclassification and renaming the categories. The category “forest” was then used in the next step for computing fragmentation of forest areas and assessment of deforestation from 2013 to 2023. The reclassified maps are shown in figures 5 and 6.

The reclassification was performed by “r.reclass” module of GRASS GIS using the following code: r.reclass input=L_2013_cluster_classes output=SL_LCC_2013 rules=landuserecl.txt title=“LCC 2013”. The areas of forests were selected on both of the maps using map algebra and logical queries which selected target class from all the categories as follows: “r.mapcalc” “orests2013 = if(L_2013_cluster_classes == 6, 1, null())” “--overwrite”. The resulting maps showing only the areas of forests are shown in figure 7.

Afterwards, the landscape analysis was performed using r.li series of GRASS GIS modules. First, the definition were created using g.gui.rlisetup. Then, mean patch size (MPS) was computed using the following code which applied ”r.li.mps” module: “r.li.mps input=forests conf=movwindow7 out=forests_mps_mov7”. Uplon execution, the data were checked using the “r.univar” module as follows: “r.univar forests_richness_mov7”. The maps of MPS are visualised in this research in figure 8 for comparative analysis of 2013 and 2023.

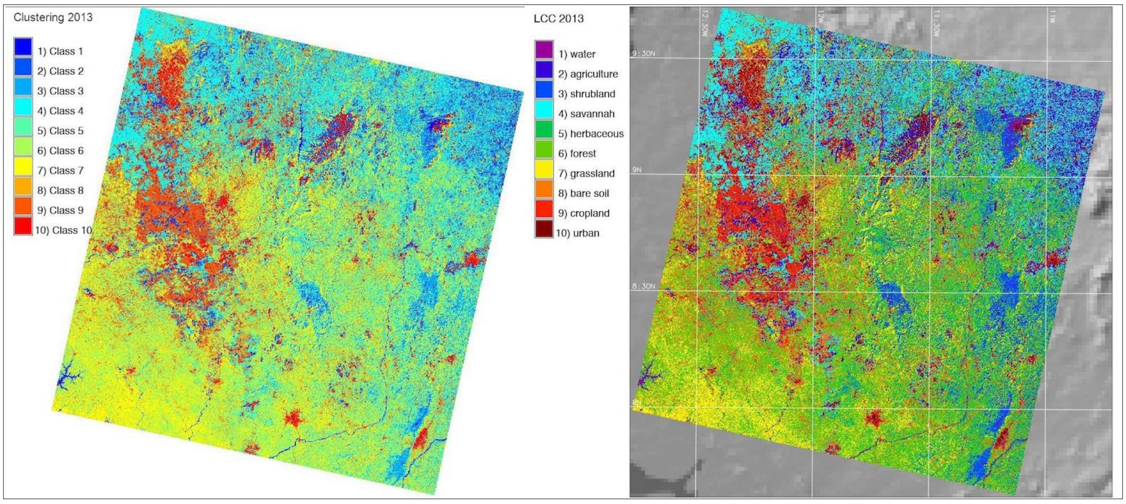

Figure 5: (a) Classification the Landsat 8-9 OLI/TIRS on 24.12.2013 of the coastal regions of Sierra Leone using clustering method. (b) Reclassified image Landsat 8-9 OLI/TIRS on 24.12.2013 with indicated 10 land cover types.

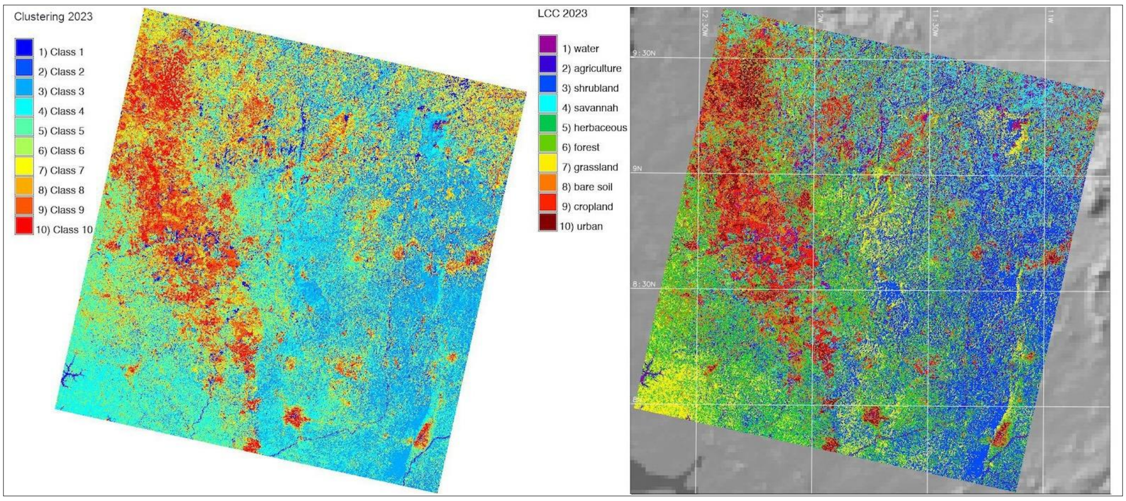

Figure 6: (a) Classification the Landsat 8-9 OLI/TIRS on 27.02.2023 of the coastal regions of Sierra Leone using clustering method. (b) Reclassified image Landsat 8-9 OLI/TIRS on 27.02.2023 with indicated 10 land cover types.

The edge density was computed using "r.li.edgedensity" module using the code: "r.li.edgedensity input=forests2013_SL conf=movwindow7 out=forests_ED_mov7_SL_2013". Afterwards, the data were inspected using modules r.univar, r.category and r.describe and plotted in figure 9 where the results are shown for 2013 and 2023. Forest fragmentaion has been calculated using "r.forestfrag" module of the GRASS GIS by using the following code: "r.forestfrag input=forests2013_new output=fragment_2013 window=7". The results of mapping are shown in figure 10.

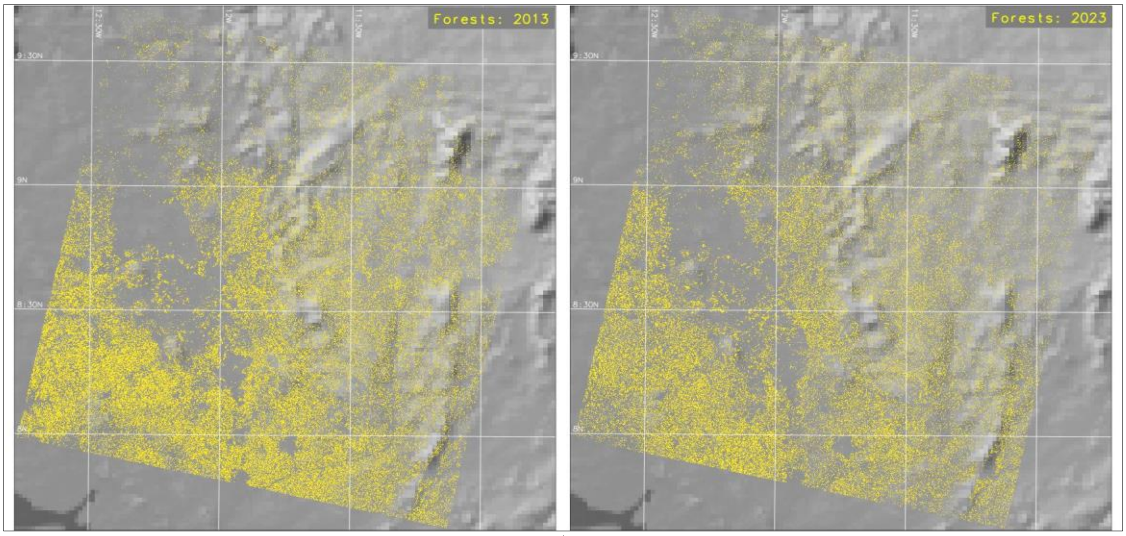

Figure 7: Distribution of rainforests in Sierra Leone. (a) in 2013, detected using classes "forests" in classified Landsat 8-9 OLI/TIRS image. (b) in 2023, detected using classes "forests" in classified Landsat 8-9 OLI/TIRS image by methods of map algebra, GRASS GIS.

The maps were then plotted using a series of cartographic commands used for visualization, as explained in previous works (Lemenkova, 2023a,b) using the following codes: d.mon wx0; d.rast shaded_relief; d.rast fragment_2013; d.grid -g size=00:30:00 color=white width=0.1 fontsize=10 text_color=white; d.legend raster=fragment_2013 title="Fragmentation 2013" title_fontsize=14 font="Helvetica" fontsize=13 bgcolor=white border_color=white; d.out.file output=Fragment_2013 format=jpg.

RESULTS AND DISCUSSION

Figure 8 shows the computed Mean Patch Size (MPS) in Sierra Leone which differs in the range from 0 to 4.4.

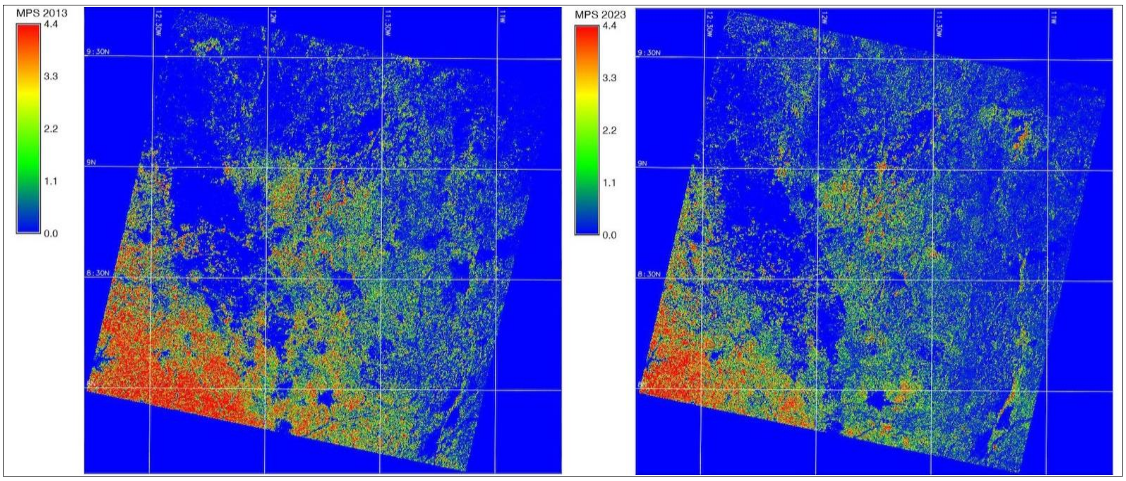

Figure 8: Computed Mean Patch Size (MPS) in the rainforests of Sierra Leone. (a) in 2013, detected using processed Landsat 8-9 OLI/TIRS image. (b) in 2023, detected using processed Landsat 8-9 OLI/TIRS image by methods of landscape analysis, GRASS GIS.

The maps demonstrate the average number of pixels of the patches in the coastal landscapes of Sierra Leone in 2013 and 2023 which visualise the difference. The comparison of the information on this landscape metrics in both maps reveals that patch size in the south-western region became smaller. Since this is the region corresponding to the lowland and wetland areas, it indicates that the decrease of landscape patches in wetlands is affected by fragmentation that is related to the decline of mangroves. This spatial attribute enables to examine the landscape structure and shows that higher MPS is related to the croplands.

Figure 9 shows the computed edge density which equals all edges in the landscape in relation to the landscape area in the study area of Sierra Leone for 2013 and 2023. The range of values differing from 190 to 1333 shows the difference in values calculated for all patches within forest land cover type indicating the length of edge per area of patch over rainforests. Tropical rainforests of Sierra Leone should be protected for conservation of flora and fauna, and as a precious source of commercial exploitation for timber. Nevertheless, the overexploitation of woodland and natural resources can lead to the deforestation and landscape fragmentation, as demonstrated in the maps. Increased forest fragments result from the activities of traditional landowners and local communities in Sierra Leone which can affect environmental sustainability of the country through unbalanced use of resources. Therefore, forest monitoring should be implemented with the aim of sustainable and reasonable use of natural resources that enable local population use resources in balanced way.

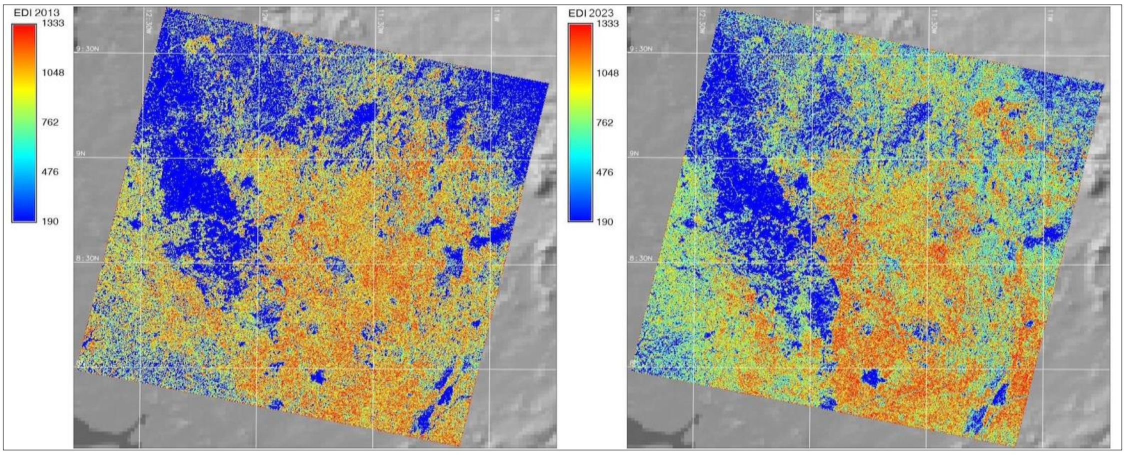

Figure 9: Edge density index computed on two raster maps using methods of landscape analysis in module r.li.edgedensity of GRASS GIS. The analysis includes the rainforests of Sierra Leone. (a) in 2013, using Landsat 8-9 OLI/TIRS image. (b) in 2023, using Landsat 8-9 OLI/TIRS image.

The specific features of edge density index of landscape patches are that it presents a class-level metric which is useful for quantification habitat network. Hence, for biodiversity analysis, it can be applied for monitoring migration ways of species within an area that use ecological corridors for habitat changes of rainforest in Sierra Leone from 2013 to 2023. In view of this, the results of the performed landscape analysis and computed edge density index contribute to the environmental monitoring of Sierra Leone through presented landscapes analysis based on remote sensing data. The comparison of the regions occupied by forests in 2013 and 2023 indicated their decline which pointed at continued deforestation in the eastern regions of Sierra Leone. Such results confirm previously reported studies on deforestation in Sierra Leone (Karg et al., 2020; Mansaray et al. 2016; Kim et al., 2015) and contribute to the environmental monitoring of tropical rainforests.

Figure 10 shows dynamics of landscape fragmentation in Sierra Leone from 2013 to 2023 which indicates disintegration of continuous habitat areas into smaller clusters of patches. Here, six levels of fragmentation are detected as follows: 1 exterior, 2 patch, 3 transitional, ; 4 edge, 5, perforated, and 6 interior. These level indicate changes landscape structure such as physical discontinuity and increased discrepancy in the landscape mosaic which is caused by construction of urban or transport network, expansion of agricultural fields that replace natural communities and increased heterogeneity and division of landscapes in Sierra Leone.

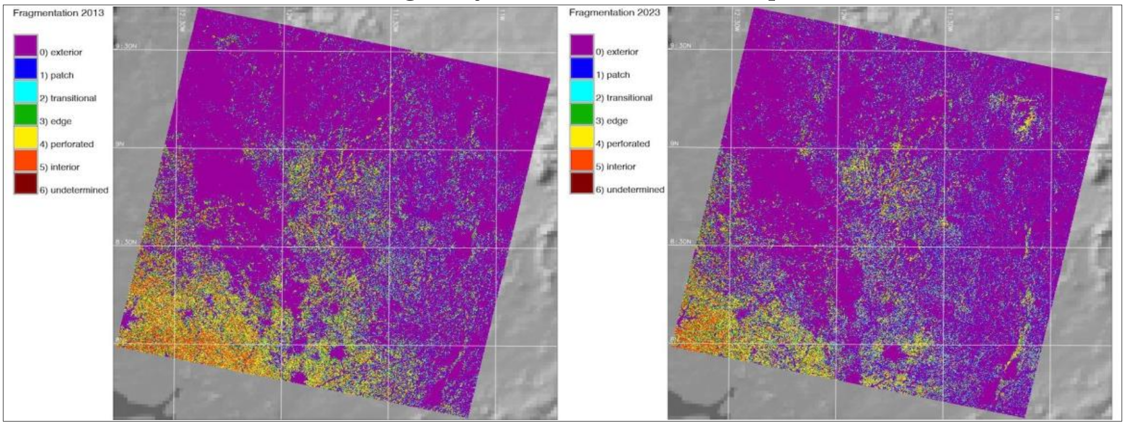

Figure 10: Landscape fragmentation with six levels of fragmentation: 1 exterior, 2, patch, 3 transitional, 4 edge, 5 perforated, and 6 interior. The analysis includes the rainforests of Sierra Leone. (a) in 2013, using Landsat 8-9 OLI/TIRS image. (b) in 2023, using Landsat 8-9 OLI/TIRS image by methods of landscape analysis, GRASS GIS.

Hence, increased landscape fragmentation within forests shows that parts of a habitat are destroyed, leaving behind smaller isolated areas of rainforest patches. This occurred both naturally and also due to human activities. Tropical rainforests form an essential element in the natural ecosystems in Sierra Leone. The complex matrix of their landscapes is characterized by a mosaic of fragments of patches. Local communities of Sierra Leone use diverse types of landscapes to maintain their livelihood (cotton, baobabs) and as a source of diverse products: wood, biomass fuel, nutrition (rice plantations, fruits, nuts, cocoa, coffee beans, and leaves), as well as for traditional medicine. Some products are used for export and therefore have an international commercial value, for instance, such as cocoa which is the biggest export product of Sierra Leone. At the same time, maintaining the balance of environmental sustainability and economic prosperity is important for ecosystems. In view of this, keeping a sustainable mosaic of agriculture-forest landscapes in Sierra Leone is essential due to the diverse and multi-facetted benefits of biodiversity and ecosystem services. In this regard, environmental monitoring using data visualization and analysis is important for nature resource management in agroforestry systems of Sierra Leone.

Landscapes of Sierra Leone include rainforests that present an essential part of Upper Guinea forest ecosystems in West Africa. Therefore, protecting valuable tropical forests in Sierra Leone has a high priority for nature conservation which can be performed through measures on habitat restoration. Mapping landscape dynamics and implementing landscape analysis in Sierra Leone can be assured by detecting changes in rainforest patches and analysis of landscape fragmentation using remote sensing data and advanced cartographic techniques. Such methods are presented in this paper, which applies GRASS GIS advanced scripting cartographic software for processing satellite images covering Sierra Leone.

CONCLUSIONS

This article has demonstrated how rainforest areas and fragmented patch sites in the landscapes of Sierra Leone can be mapped and analysed using GRASS GIS approach of scripts. Moreover, the satellite images used for mapping demonstrated their potential for identification of rainforest areas through map algebra used for analyses of diverse vegetation patterns by spectral signatures in the multispectral bands of Landsat 8-9 OLI/TIRS images. Complex vegetation mosaic which is formed by different landscape patches within rainforests and diverse land cover types of Sierra Leone were identified using scripting methods of image analysis implemented in GRASS GIS. These features are essential elements of the landscape structure which was analysed using distinct patterns of patches detected on raster images.

Deforestation of rainforests in West Africa indicate decreased connectivity of patches which is essential for globally important wildlife species. Recorded from the analysed satellite images and visualised using GRASS GIS scripts, maps of landscape patch distribution can be used to analyse the areas with high level of landscape fragmentation and deforestation. In turn, detected endangered regions can be selected as protected areas for conservation of landscapes to mitigate the consequences of landscape transformation through agriculture field expansion. Hence, this study contributes to the practical development of cartographic methods on mapping and data visualization to achieve these goals. Technically, the data were processed using scripting approach of GRASS GIS applied for landscape analysis in Sierra Leone using Earth observation data. Processing Landsat 8-9 OLI/TIRS by GRASS GIS methodology proved to be a powerful tool for detecting deforestation and land cover classification to evaluate landscape fragmentation in Sierra Leone using modules of landscape analysis (“r.li.edgedensity”, “r.li.mps”, “r.forestfrag”) and raster calculation by “r.mapcalc”.

Streamlining existing GIS techniques is invaluable to process and model geospatial data such as satellite images in order to retrieve information regarding land cover types using raster analysis and computational map techniques. Scripts written using GRASS GIS syntax targeted for automation of data processing facilitates cartographic workflow. Such approach is essential for implementing landscape analysis in areas of highly heterogeneous landscapes. At the same time, evaluating distribution of forest, tree canopies, and wetlands helps to detect areas for land cover protection. Detecting land cover changes and fragmented landscapes using advanced GIS approaches is useful for selecting areas of priority landscapes to secure endangered habitats. Complementary cartographic approach included image analysis through classification and landscape analysis supported by visual interpretation. Demonstrated GRASS GIS techniques of image processing support environmental monitoring in tropical landscapes of Sierra Leone, West Africa.

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