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Thematic mapping of Burundi using geospatial data and satellite images processed by geoinformatics methods

Mapeamento temático do Burundi utilizando dados geoespaciais e imagens de satélite processadas por métodos geoinformáticos

Cartografía temática de Burundi utilizando datos geoespaciales e imágenes de satélite procesadas mediante métodos geoinformáticos

Cartographie thématique du Burundi à l'aide de données géospatiales et d'images satellitaires traitées par les méthodes de géoinformatique

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ABSTRACT

This paper presents the implementation of the integrated cartographic approach for environmental mapping of Burundi, East Africa. Monitoring different types of land cover in Africa by remote sensing is presented using GRASS SIG methods. The series of thematic maps of vegetation and habitat types, landscapes, topographic, geomorphic and geological context of Burundi is created in QGIS and GMT software. The methodological issues concerning the processes of cartographic scripting are discussed with commented snippets of programming codes using syntax of GRASS GIS. Several modules are used for satellite image mosaic, processing vector and raster data, and classification. The paper documents environmental features of Burundi, such as vegetation types, land cover patterns, geologic setting and landscape distribution using digital cartographic tools. A series of the thematic maps is proposed to support environmental policies on agricultural management in Burundi.

KEYWORDS: remote sensing; mapping; satellite images.

RESUMO

Este artigo apresenta a implementação da abordagem cartográfica integrada para mapeamento ambiental do Burundi, África Oriental. O monitoramento de diferentes tipos de cobertura de terra na África por sensoriamento remoto é apresentado usando métodos GRASS SIG. A série de mapas temáticos de tipos de vegetação e habitat, paisagens, contexto topográfico, geomórfico e geológico do Burundi é criada no software QGIS e GMT. As questões metodológicas relativas aos processos de script cartográfico são discutidas com trechos comentados de códigos de programação usando a sintaxe do GRASS GIS. Vários módulos são usados para mosaico de imagens de satélite, processamento de dados vetoriais e raster e classificação. O artigo documenta características ambientais do Burundi, como tipos de vegetação, padrões de cobertura de terra, cenário geológico e distribuição de paisagens usando ferramentas cartográficas digitais. Uma série de mapas temáticos é proposta para dar suporte a políticas ambientais sobre gestão agrícola no Burundi.

PALAVRAS-CHAVE: sensoriamento remoto; mapeamento; imagens de satélite.

RESUMEN

En este artículo se presenta la implementación de un enfoque cartográfico integrado para la cartografía ambiental de Burundi, África Oriental. Se presenta el monitoreo de diferentes tipos de cobertura terrestre en África mediante teledetección utilizando métodos GRASS SIG. La serie de mapas temáticos de vegetación y tipos de hábitat, paisajes, contexto topográfico, geomorfológico y geológico de Burundi se crea en el software QGIS y GMT. Se discuten las cuestiones metodológicas relacionadas con los procesos de creación de guiones cartográficos con fragmentos comentados de códigos de programación utilizando la sintaxis de GRASS GIS. Se utilizan varios módulos para el mosaico de imágenes satelitales, el procesamiento de datos vectoriales y raster y la clasificación. El artículo documenta las características ambientales de Burundi, como los tipos de vegetación, los patrones de cobertura terrestre, el entorno geológico y la distribución del paisaje utilizando herramientas cartográficas digitales. Se propone una serie de mapas temáticos para respaldar las políticas ambientales sobre la gestión agrícola en Burundi.

PALABRAS CLAVE: teledetección; cartografía; imágenes satelitales.

RÉSUMÉ

Cet article présente la mise en œuvre des approches cartographiques intégrées pour la cartographie environnementale du Burundi, Afrique de l'Est. Suivi des différents types de couverture terrestre par télédétection est présenté dans cet article par les méthodes de GRASS SIG. Les questions méthodologiques des scripts cartographiques sont discutées avec des extraits de codes de programmation utilisant la syntaxe de GRASS GIS commentés. Plusieurs modules de GRASS GIS sont utilisés pour la mosaïque d'images satellitaires, le traitement des données vectorielles et raster, ainsi que la classification. La série de cartes thématiques du Burundi, créée en utilisant le logiciel QGIS et GMT, comprend des cartes des types de végétation et d'habitats, des paysages, du contexte topographique, géomorphologique et géologique du pays. Ainsi, l'article examine les caractéristiques environnementales du Burundi, telles que les types de végétation, les modèles de couverture terrestre, le cadre géologique et la répartition du paysage à l'aide d'outils cartographiques numériques. Une série de cartes thématiques est proposée pour soutenir les politiques environnementales de gestion agricole au Burundi.

MOTS-CLÉS : télédétection ; cartographie ; images satellitaires.

INTRODUCTION

Since the development of remote sensing and geoinformatics techniques in the 1970s, a long tradition of geographical research has seen satellite images and geospatial data as both a source of information and a challenge for mapping methods: it is possible to use accurate and reliable data but using advanced and technically sound methods. Information from remote sensing and geospatial data is essential for environmental preservation. Their usefulness lies in their ability to map landscape dynamics, which allows representing vegetation cover at different scales of time and space. But the use of geospatial data, even by traditional GIS users, is still hampered by its methods and approaches (Robert and Gangneron 2015; Sellin et al. 2015).

Environmental monitoring can be carried out efficiently using satellite images. However, image processing is not efficient with conventional GIS methods due to the presence of a large number of manual operations. It is therefore preferable to adopt an autonomous approach to computer vision using automatic image processing algorithms. The question that arises is that when we see satellite images, we wonder whether they are images of objective landscapes and how the landscapes visible on the Earth's surface can be interpreted and correlated with other geospatial data, such as the geological framework, the hydrographic network, the relief and geomorphological processes, land use, regional variations in vegetation cover, etc. (Cabral et al. 2006; Diédhiou et al. 2020; Maswi and Mshiu, 2024).

In a geographical analysis, this issue becomes of paramount importance. On this occasion, the interpretation of data covering the study area in the integrated context is an essential approach for the analysis of environmental dynamics and the linkages between geological and geographical variables (El-Awady et al. 2016). Remote sensing has long been used for these purposes in various regions of Africa. However, the application of spatial data and remote sensing in Burundi is limited. It has mainly been used to map general land cover types using traditional GIS.

Using efficient processing of geospatial data, it is possible to represent the complexity of social and environmental systems. In this context, an additional ambiguity of the links between the elements of the systems arises. On the one hand, there are social developments such as demographic and nutritional transitions; on the other hand, landscape transitions (Cuq 2009). From the countryside to urban areas, we observe the dynamics of land covers visible from space using geospatial data.

Several aspects of the links between them can be distinguished: geological-geomorphological, environmental-vegetative, social-nutritional. The geological and geomorphological context determines the diversity of vegetation in the landscapes of East Africa. The regions of East Africa consist of coastal plains, tropical rainforests in the central regions, swamps and wetlands dominant in the mountainous regions, grassy and semi-deciduous forests in the central regions. The distinction between these different types of vegetation can be identified using remote sensing and geospatial data.

There is no doubt that satellite images have contributed greatly to the study of East Africa, improving the understanding of environmental complexity at continental, regional and local levels. The analysis and understanding of East African landscapes in the context of the complex geological setting deeply linked to the East African Rift, with a variety of regional soil and vegetation features, has been supported by the results obtained from the visualization of cartographic data, initially composed of maps and later (since the 1970s) of images obtained from continuously operating satellite missions, such as Landsat.

The objective of this study is to integrate satellite images and geospatial data in vector and raster formats in Burundi using several cartographic software tools. Three software were used for data processing. The main software is GRASS GIS which is used for processing Landsat satellite images. Generic Mapping Tools (GMT) software is used for a topographic map, and Quantum GIS (QGIS) software is used for GIS applications. A procedure is developed to combine multi-source data including geological, landscape, vegetation and geomorphological data with classified satellite images processed in mosaic form.

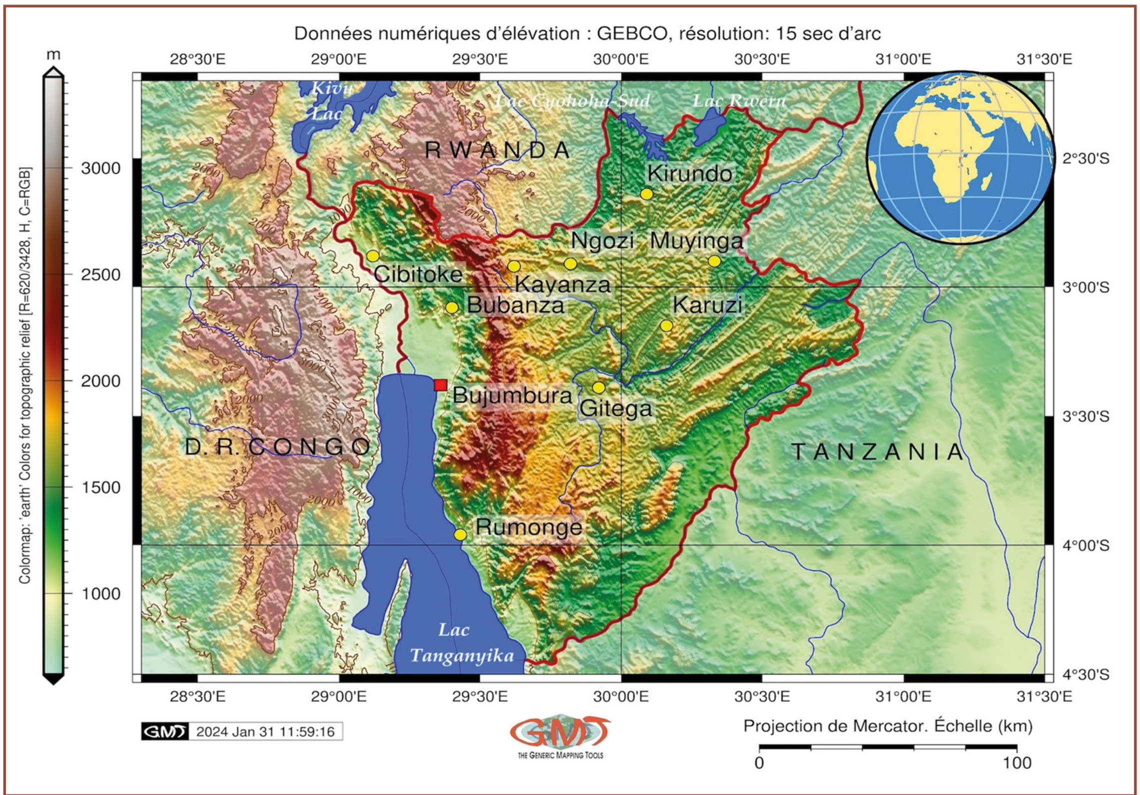
The variety of data used as thematic layers allows incorporating information on the environmental properties of East Africa. The performance of satellite image classification was presented by scripting methods and described with comments on the functionalities of selected GRASS GIS modules. GRASS GIS programming and mosaic techniques of multiple satellite images are explained. Integrated information on Burundi, derived from data collected, presented, analyzed and visualized using cartographic techniques, is evaluated to understand the links between the geological and environmental parameters of the country. Therefore, this study provides a description and visualization of land cover types, habitat and vegetation patterns of landscapes, and thematic maps of Burundi. The geographical analysis of Burundi using remote sensing data and cartographic information, presented in this study, contributes to the environmental monitoring of East Africa.

In the remainder of the paper, after a brief discussion on the particular nature of the landscape in Burundi and the current environmental problems related to geology, environmental and climatic context, and anthropogenic activities, we will develop the working steps for spatial data analysis using GRASS GIS and explain the methodology using its programming modules with examples of scripts provided. The selected functional codes were based on existing works with examples from GRASS GIS. We used GRASS GIS scripts to process medium-resolution Landsat satellite images with a case study of the Burundi region.

GEOGRAPHIC LOCATION OF STUDY AREA: BURUNDI, EAST AFRICA

The study is located in Burundi, East Africa. The country is bordered by Rwanda to the north, Tanzania to the east and the Democratic Republic of Congo to the west, Figure 1. Lake Tanganyika which belongs to the African Great Lakes forms the southern border of the country.

Figure 1 – Topographic map of study area: Burundi



Source: author.

Recently, socioeconomic and demographic processes in Burundi have led to environmental challenges that affect biodiversity, ecosystem habitats (El-Hassanin et al. 1993), trigger land cover changes (Hennebert et al. 1996) and cause fragmentation of landscape patches (Nyirarwasa et al. 2024). Land cover and vegetation in Burundi have undergone rapid changes in recent years due to environmental and climatic impacts, as well as human activities.

The food crisis and the consequences of climate change, such as droughts and environmental scarcity, have led to overexploitation of local farmers' resources in order to preserve crops and ensure food security (Ejigu, 2009; Bununu et al. 2023). Due to climate change and poverty of the population, food insecurity is becoming one of the major challenges in Burundi, especially in rural areas (Niragira et al., 2022). However, land degradation and deforestation have been driven by uncontrolled agricultural activities, as reported in previous research (Ndagijimana et al., 2019; Jacques et al., 1993).

Recent environmental challenges in Burundi include increasing pressure on land and natural resources due to rapid population growth and uncontrolled and unsustainable land use. According to Placide and colleagues (2021), population growth in Burundi is 11%, which implies increased pressure on natural resources and agricultural activities in Burundi: rural poverty increased by 70% and malnutrition by 67% in Burundi, making it one of the poorest countries in the world.

The geological peculiarity of Burundi lies in its location in the Albertine Rift Valley with Holocene alluvial deposits in the valley bottoms (Chuwa et al. 2023). In addition, it is a western extension of the East African Great Rift, which defines its rich geological setting (Evans, 2015) and its heavily vegetated terrain. Petrology and geochemistry are distinguished by complex mineral compositions including crystallized rocks and outcrops from the area between the Kibaran Belt and the Tanzania Craton (Midende et al. 2014). Among other geological resources, Burundi is distinguished by its deposits of rare earth elements (Buyse et al. 2020). For example, rare earth element mineralization in the Neoproterozoic Gakara in Burundi is located along fracture zones and in the upper crust of Mesoproterozoic sediments of the Gikoro Group, overlain by gneissic basement rocks (Decrée et al. 2015).

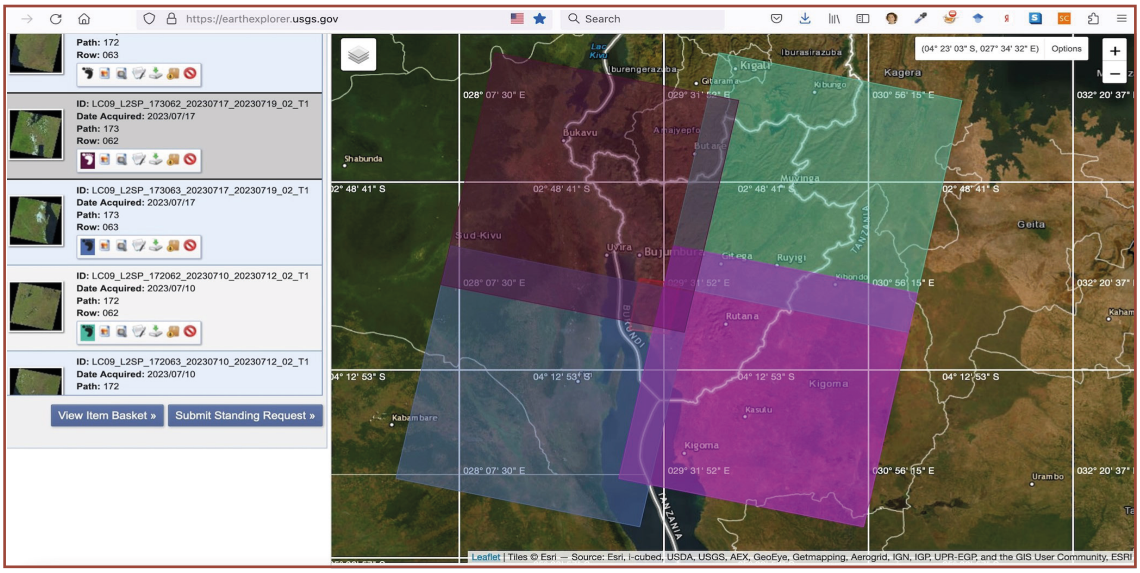
DATA AND METHODS

Variables, data and procedures for spatial environmental analysis

The advantage of using multi-source data (Figure 2) lies in their comparability and compatibility. Satellite images were exported into a GRASS GIS environment to create a geospatial data mosaic that was enhanced by the addition of topographic data (localities, roads, hydrographic network and country boundaries), land cover map based on spatial data from the Food and Agriculture Organization (FAO) and geological maps.

During geospatial analysis, satellite images and thematic maps can be compared to distinguish correlations between geological and environmental settings: distribution of vegetation types, geomorphological forms, tectonic structures such as the East African Rift. These correlations have been discussed earlier in the geological settings that are reflected in the landscape (Emishaw and Abdelsalam, 2023; Lemenkova and Debeir, 2023a).

Figure 2 – Overlaid Landsat multispectral satellite images covering the territory of Burundi



Source : USGS. Compilation : author.

Goals and motivation

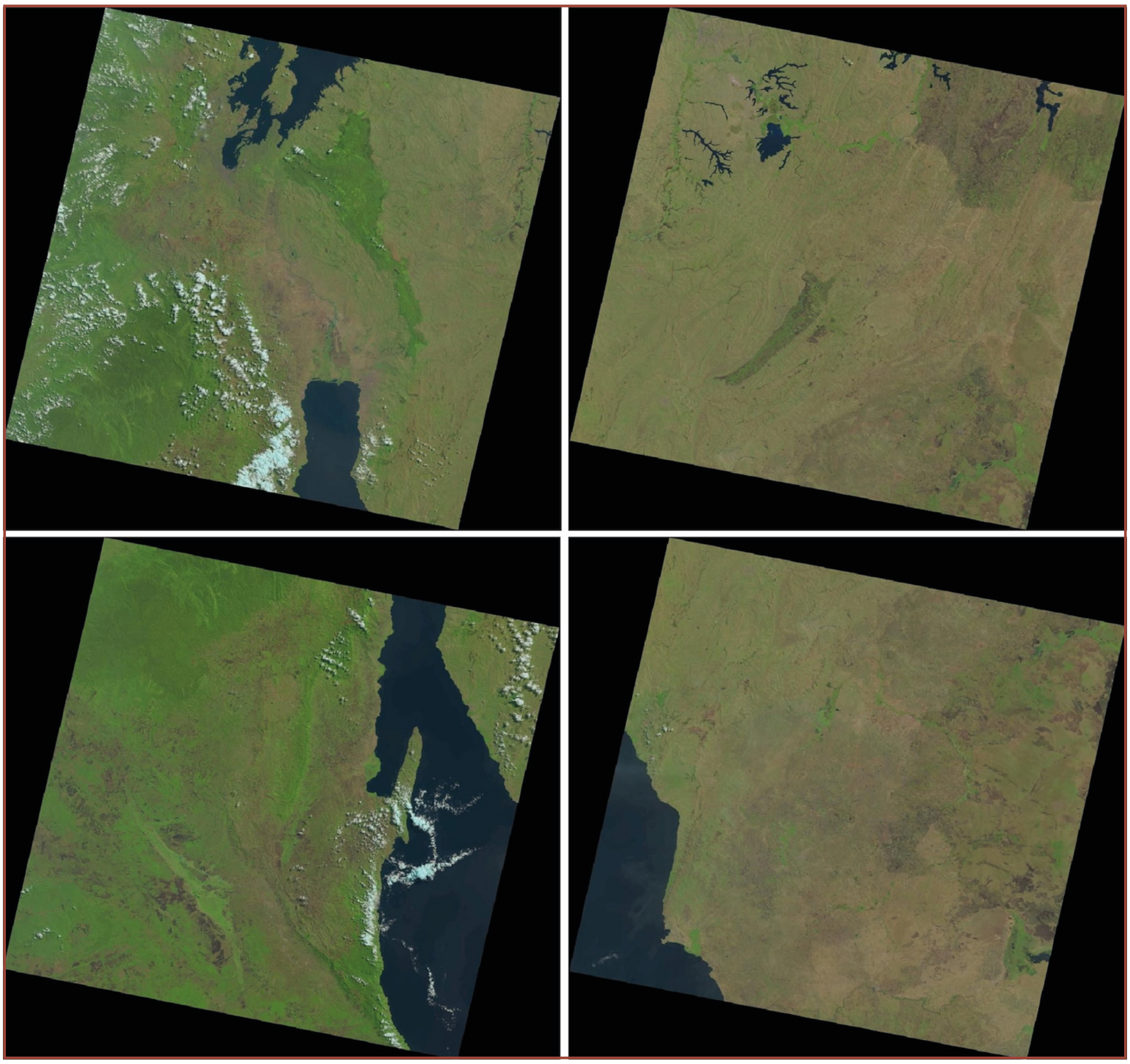
In this study, the GMT scripting toolset was used to map Figure 1; QGIS for the preparation of thematic maps in Figures 2, 3, 4, and 9; and GRASS GIS software for processing satellite images (Figures 7 and 8). For satellite image processing, we used Landsat 8-9 OLI/TIRS images covering Burundi from the USGS website. The advantages of remote sensing data for environmental mapping and land cover type distinction lie in their reliability and objectivity, as discussed in many previous works (Lemenkova and Debeir, 2022b, Lemenkova, 2024).

Thus, this study illustrates various cartographic approaches to process and visualize multi-source geospatial data by different software. We used two types of geospatial data covering the Burundi region: raster data (satellite images and DEM topographic data) and vector data (thematic files on landscape, soils and administrative divisions).

Processing of remote sensing data

The geographic database is formed from Landsat image records with 30-meter resolution in multispectral channels that are presented in RGB colors in Figure 3.

Figure 3 – Four original Landsat 8-9 OLI/TIRS satellite images over Burundi



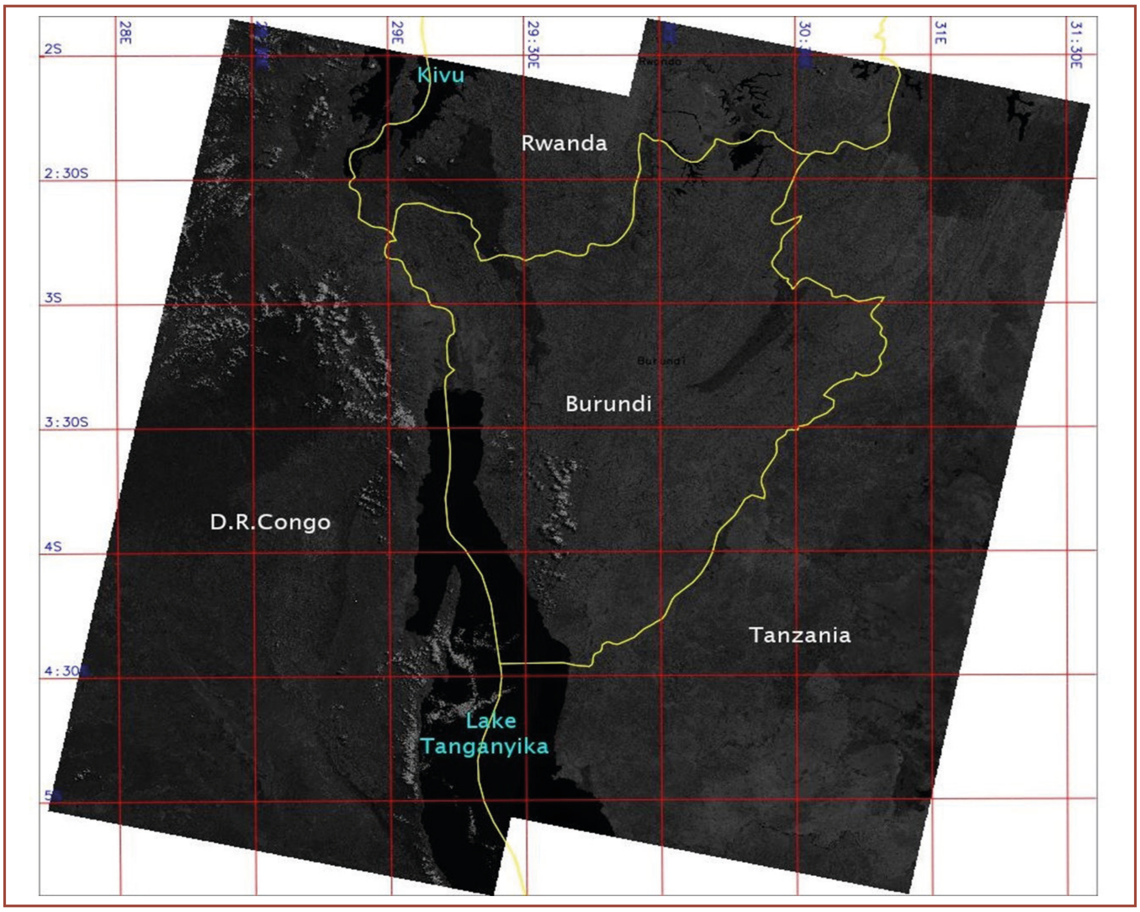
Source : USGS. Compilation : author.

The long history of Landsat sensors is one of the strengths of Landsat mission. Launched in 1982, it provides a valuable data source for environmental study in Africa. In addition, the open source availability of Landsat images is a complementary advantage. Finally, the 185 km band of Landsat images in multispectral cameras has the advantage of obtaining frequent global coverage. Such a large band of Landsat images is beneficial in regions of Burundi where clouds are a major obstacle to image acquisition in clear weather. In this context, satellite images, as accurate and current data, can be contrasted with descriptive data that may be subjective or outdated (e.g., old maps). Landsat multispectral imagery consists of spectral bands that are located in the visible and infrared spectra. The combination of three of these spectral bands is necessary for the constitution of RGB images or thematic classification.

Programming methods in mapping

The topographic map (Figure 1) was produced using Generic Mapping Tools (GMT) which can be defined as a computer scripting tool for storing, processing and representing geographic information using cartographic modules.

Figure 4 – Mosaic of Landsat 8-9 OLI/TIRS monochrome color satellite images, SWIR-1 and SWIR-2 bands, overlaid with vector data, covering Burundi



Source : author. Software: GRASS GIS.

The use of GRASS GIS modules plays a vital role in the processing of remote sensing data. The techniques used in the field of visualization are based on the algorithms that constitute the structure of the program. The satellite image processing process included the following steps. First, the satellite images were taken on the USGS site using a cloud mask of less than 10% for each image. The country of Burundi is covered by the four images. This requires a mosaic technique for representation by several merged images. This problem was solved by using the GRASS GIS module 'g.region', Figure 4.

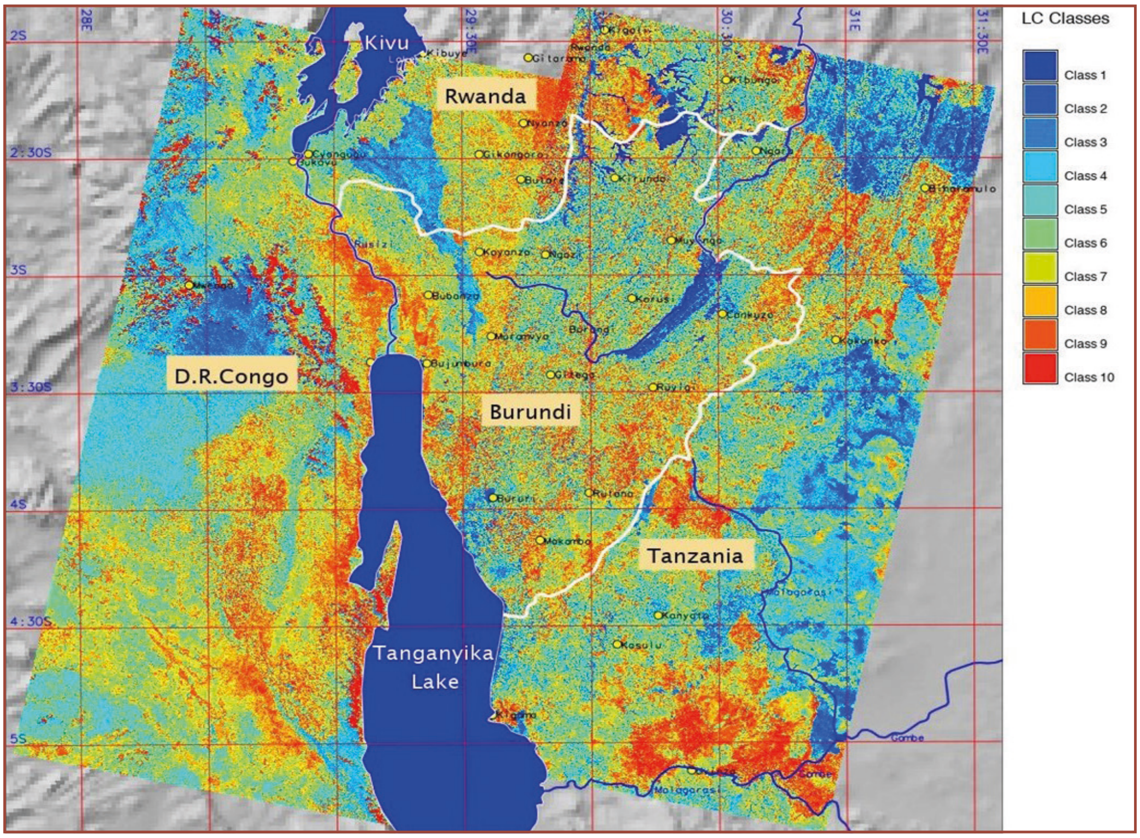
The images were imported into the program using the 'r.import' module using the code presented in Note 1. In a satellite image, the color information is decomposed into different spectral bands. But just as the representation of images is twofold, so is the interpretation: it is partly related to the identification and description of vegetation types, and partly to the precise detection of land cover types (Lemenkova and Debeir, 2023b).

Of course, the fact of processing satellite images and interpreting them by classification are not the same, but what we keep in mapping using remote sensing data is a classified image with the types of land cover detected and identified, and a representation of the perceived objects. However, this becomes more complicated when we have to take into account the seasonal and natural changes in land cover that are found first in the "wet" and "dry" seasons in tropical climates. Therefore, it is necessary to take comparable images covering the same period of the season for reasons of comparability. For this reason, we took Landsat images on the following dates: images 1 and 2 on August 19, 2023; image 3 on August 10, 2023 and image 4 on July 25, 2023 depending on the availability of the swath scene covering Burundi with minimal cloudiness (less than 10%), Figure 6. The mosaic of the 4 images is presented in Figures 4 and 5.

For countries with very small spatial extent and coverage, such as Burundi, the problem often arises when using satellite images. Some parts of the country may not be covered by the images and the country is located on the border of several images. Therefore, it is not possible in such cases to use a single image. Instead, it is necessary to stitch multiple images together using geoprocessing methods that analyze the coordinates of the target region.

1 'r.import input=/Users/path/grassdata/Burundi/LC08_<...>_02_T1_SR_B1.TIF output=L_2023a_01' Here, the example is given for band 1 of the image taken on August 19th. The same code, modified for the image name and file output name, has been used respectively for all Landsat multispectral bands and four images.

Figure 5 – Classification of Landsat 8-9 OLI/TIRS satellite images according to the 'Maximal Likelihood' method over the territory of Burundi



Source : author. Software: GRASS SIG.

In GRASS GIS, several approaches are possible to solve this problem. In this study, we used three possibilities to stitch satellite images together: 'g.region', 'i.image.mosaic' and 'r.patch', Figure 5. First, the coordinate extent was checked using the 'r.info' module, for example using the command 'r.info L_2023a_07'. The result is received as a geographic coverage for the west-east and south-north extent [2]. Another approach to mosaicking images can be achieved by using the 'i.image.mosaic' module which mosaics multiple images and extends their color palette [3].

Yet another way to stitch multiple images together is to use the 'r.patch' module which creates a mosaic of maps using bash syntax. Thus, it creates a list of maps matching a pattern, extends the region to include all of them,

2 In the same way, the coordinates of the four images were inspected and the area of greatest coverage comprising the four images was applied for the SIG GRASS project using the command 'g.region w=84585 e=345915 n=-204285 s= -596415'. The images were then visualized step by step as a mosaic of scenes.

3 SIG GRASS code for mosaicing satellite images: 'i.image.mosaic input=L_2023a_06,L_2023b_06,<...>L_2023c_06,L_2023d_06 output=mosaic_2023_SWIR1'.

and stitches them together to create a mosaic. In this approach, overlapping maps will be used in the order given. For this method, the following code was tested for all four images from (a) to (d): using the code in Note 4. Once the images were assembled using mosaic techniques, the vector data in ArcGIS '.shp' format was added as overlay layers.

So the file containing the country borders was imported using the import of vector files into GRASS GIS as presented in the note 5. Here, the command uses the 'v.in.ogr' module that allows importing vector data into GRASS GIS using the OGR (Open Source Geospatial Resources) library. Similarly, vector data has been imported for visualization of major geographic features, such as cities, lakes, rivers, text annotations, etc.

There are many approaches of two types of satellite image processing that can be used: supervised and unsupervised classification (Kim et al. 2013). In this study, we used clustering algorithms because they have reliable and simple methods used in many similar studies before. Therefore, image classification was performed using a combination of GRASS GIS modules "i.group", "i.cluster" and "i.maxlik" following the methodology described in previous studies (Lemenkova, 2023b, 2023c).

RESULTS

The environmental challenge in Burundi: agricultural development, food supply for population, and sustainable economy

Technically, this study offered us the opportunity to evaluate the results of the GRASS GIS programming approach in the processing of remote sensing data. The environmental study was used to monitor the biodiversity of different land cover classes in Burundi. These methods can be applied to study ecosystems in Africa using the GRASS GIS raster data format and scripting approach. Therefore, Landsat-8 OLI/TIRS data can be used in similar studies using the presented programming codes as a continuous data source for vegetation monitoring and geological mapping.

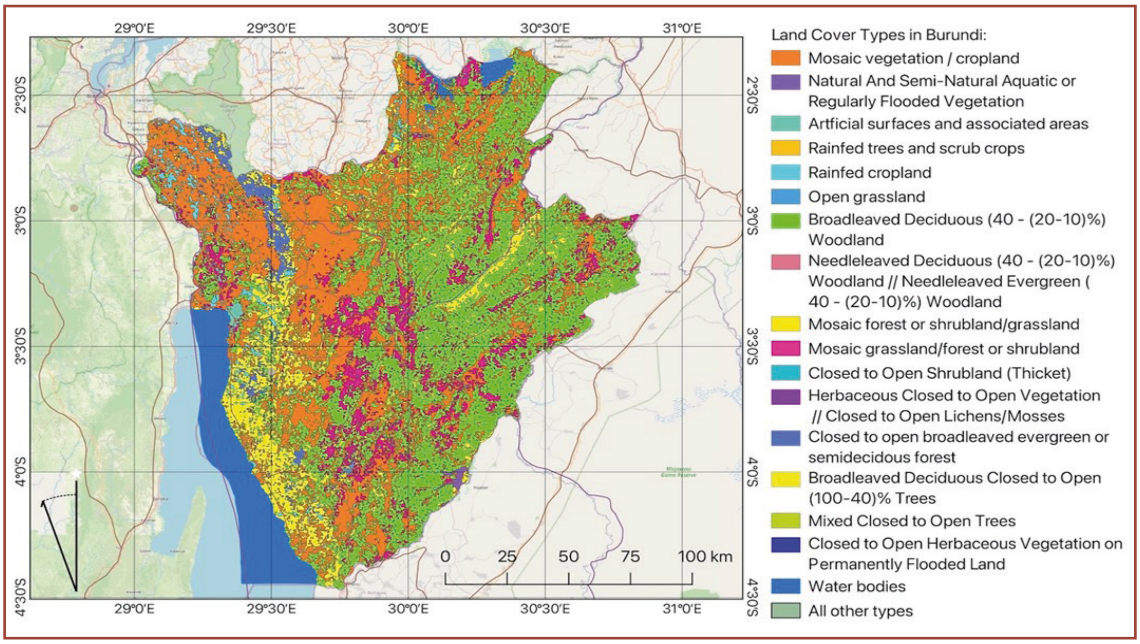
4 The code for merging several satellite images using r.patch ' module of SIG GRASS: "r.patch in=L_2023a_01,<...>,L_2023d_01 out=mosaic_2023_Burundi."

5 The code for importing country border data into SIG GRASS: "v.in.ogr input=/Users/<...>/ne_10m_admin_0_countries.shp output=world_countries -o".

Geospatial data analysis then allows us to detect important environmental challenges in Burundi. Food insecurity and climate effects such as droughts and environmental scarcity have led to overexploitation of local farmers' resources to protect crops and secure food resources. Increased by climate effects and triggered by the poverty of the population, food insecurity is becoming one of the major challenges in Burundi, especially in rural areas. Therefore, we also recall the importance of analyzing landscape change and land use planning processes, both from a social ethics and environmental point of view. This has led to land degradation and deforestation due to uncontrolled agricultural activities, as reported in previous studies.

The mapping was based on processed and visualized remote sensing data. The subregions of the coastal zone of Lake Tanganyika are visualized and compared using the mosaic of satellite images. The results indicate the different land cover classes automatically detected by GRASS GIS methods. The visualization of vector data was performed in GRASS GIS using the 'd.vect' module [6]. Land cover type classes for Burundi are presented in Figure 6.

Figure 6 – Map of land cover types

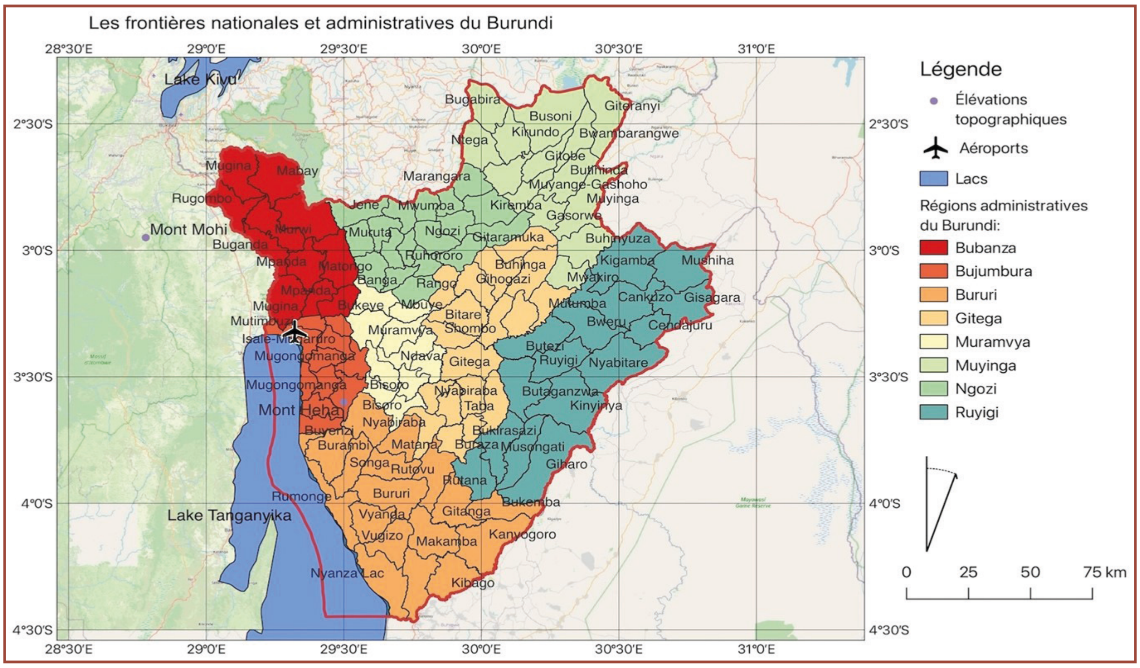


Source : author.

6 For example, Lake Tanganyika on figure 9 was visualized using the following code: "d.vect map=Burundi_lakes display=shape type=area color=white fill_color=blue width=1 attribut_column=name label_color=white". The grid in figures 7 and 8 was added using the 'd.grid' module with the command "d.grid -g size=00:30:00 color=red width=0.1 fontsize=10 text_color=blue".

For example, among the recent environmental problems of Burundi, there is increasing pressure on land and natural resources due to rapid population growth and an uncontrolled and unsustainable land use system. Population growth in Burundi suggests increased pressure on natural resources and agricultural activities in Burundi. Agricultural pressure is particularly notable in the provinces of Bururu, Bujumbura and Bubanza, Figure 7.

Figure 7 – Administrative division of Burundi



Source : author. Software: QGIS.

In addition, civil unrest and the recent war have had devastating effects on the economy of Burundi, with negative consequences on the population. In addition, there is an increase in rural poverty and malnutrition in Burundi, making it one of the poorest countries in the world. Such social indicators naturally push farmers to intensify agriculture and adapt more land to crops, leading to unsustainable development and land depletion, forming a vicious circle in socio-natural systems.

The geographical and geological framework of Burundi: the main tectonic formations, rock type and location

Burundi is distinguished by its location in the Albertine Rift Valley, as shown in Figure 8, which represents the western extension of the Great East African Rift. This explains its rich geological setting and its highly vegetated terrain. The geological setting of Burundi is presented by a wide distribution of sedimentary and granitic rocks belonging to the Karagwe-Ankolean belt, with

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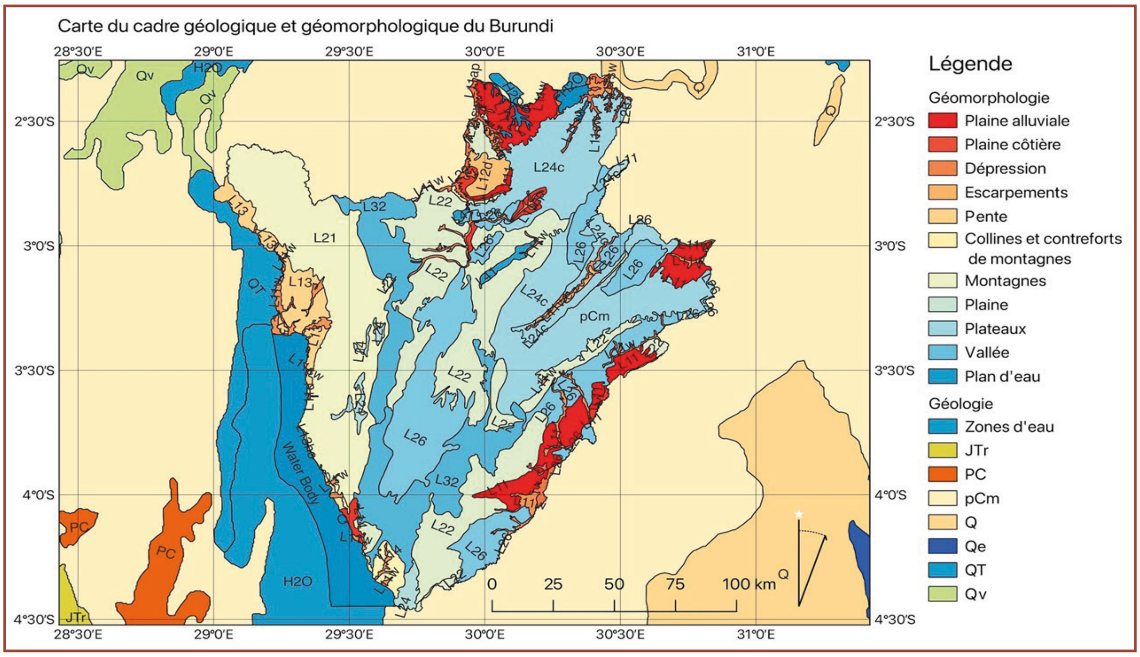
Holocene alluvial deposits in the valley bottoms. The crystallized rocks and outcrops of the area between the Kibaran belt and the Tanzania craton are complex mineral components that characterize the petrology and geochemistry of Burundi, Figure 8.

Figure 8 – Geological and geomorphological map of Burundi: reliefs, lithological types and general physical characteristics of rocks in Burundi according to the United Nations Africover Project



Geology: JTr - Jurassic and Triassic; PC - Permian-Carboniferous; pCm - Precambrian; Q - Quaternary; Qe - Holocene; QT - Cenozoic; Qv - Quaternary extrusive and intrusive rocks.

Source: author. Software: QGIS.

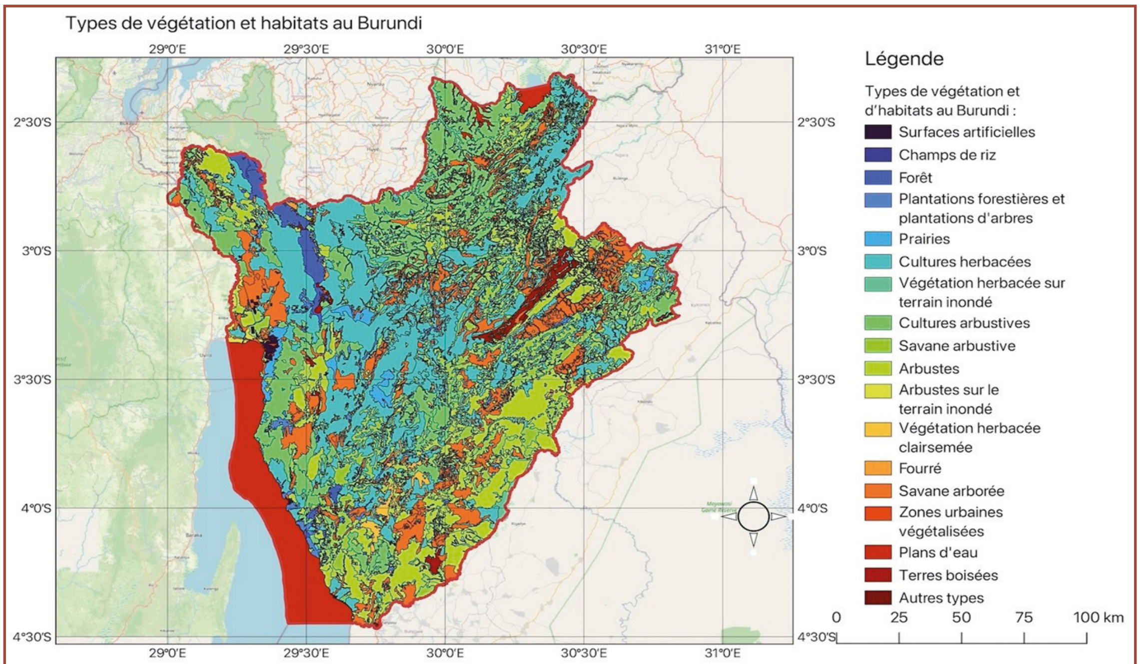
Burundi is distinguished by geological and mineral resources, including regional reserves of rare earth elements. The availability of rare earths can be an important economic factor for mining. Various applications of these elements as electronic components, magnetic materials and industrial processes can contribute to the economic development and wealth of the country. However, their proper geological exploration is lacking due to limited resources of Burundi.

The geological context of the country is strongly linked to the tectonic context. Consider the example of the rare earth element mineralization of the Neoproterozoic Gakara in Burundi, which is located along fracture zones and in the upper crust of the Mesoproterozoic sediments of the Gikoro Group, which are underlain by gneissic basement rocks.

The environmental and social framework of Burundi

The adaptive determination of the ecological and environmental context of the country by geographic maps is a new aspect of this study implemented using GRASS SIS scripts. Indeed, landscape monitoring using remote sensing and geospatial data is an important research topic for future studies on climate-environment relationships in Africa, because the automatic processing of satellite images using computer cartographic approaches is a very complex task. After describing the geological aspects and the geomorphological framework of the country, it is appropriate to define the plant diseases and types (Figure 4) and the agricultural human activities that relate to this geological factor of Burundi. They form, as just noted, a continuum of environmental factors within which regional distinctions must be made in Burundi and to determine what is related to regional environmental specificities, Figure 9.

Figure 9 – Terrestrial habitat map of Burundi



Source : author.

One of the smallest countries in Africa with a tiny territorial extent of Burundi (about 2° in the west-east and south-north directions), Burundi nevertheless has a great variety of landscapes formed under an equatorial climate. Plateaux and highlands cover more than half of the country, which affects the specific distribution of habitats such as mosaic vegetation types, broadleaf, herbaceous and deciduous forests. The major units have been identified as follows: urban area, forest, forest-savanna mosaic, savanna and steppe, aquatic vegetation and marsh (Henri 2009).

To protect rare species and conserve wildlife populations, two national parks have been created in Burundi: Kibira National Park, which preserves 40,000 ha of tropical rainforest in the northwest of the country, and Ruvubu National Park, located along the Rurubu River in the northeast of the country (Peyrot 1997). The park preserves the natural grassland ecosystem that covered the vast majority of the northeast.

The links between the geological framework and the environmental context of Burundi: challenges for agriculture and environmental dynamics

The location of Burundi near the margins of the Tanzanian Craton determines its geological setting and defines the mineral content of geological outcrops which are dominated by Precambrian basement rocks, mostly of Proterozoic age. Thus, sediments comprising mainly alluvial sands, silts, gravels and clays fill the main tectonic rift valley in western Burundi and descend to Lake Tanganyika. Such a geological setting leads to the distribution of acidic soils with “strong” to “very strong” acidity (pH ≤ 5.5). At the same time, acidic soils constitute a serious factor of land degradation that impacts agricultural productivity and sustainable agriculture.

As a result, agriculture in Burundi is limited to arable land in only half of the country, and only about a third is suitable for grazing. Agricultural plantations are occupied by simple crops such as beans, maize, cassava and sorghum, as well as some export crops (coffee, cotton and tea). The complex interrelationships between geological setting, cover and vegetation types result from the effects of rock and mineral geochemistry that affect soil content, plasticity, acidity and structure (Hicintuka and Masilya, 2013). In addition, regional geomorphology is expressed in the relief, curvature and steepness of slopes overlying crystalline rocks belonging to the geological structures of the East African Rift. Therefore, the geomorphological setting and exposure control soil stability and properties which, in turn, contribute to the distribution of certain vegetation types in the country (Nkunzimana et al. 2020).

Environmental monitoring of Burundi

In response to limited natural resources and growing population, Burundian farmers are adjusting and intensifying their agricultural activities to mitigate the impact of environmental scarcity and weather effects on crop yields. For example, they are diversifying crop types, using more productive and climate-resilient crops, adopting different farming practices and techniques to increase harvests through multiple cropping, supplemental irrigation, and high-yielding varieties (Niragira et al. 2021).

However, such intensification of agricultural activities leads to fragmentation of landscapes and overexploitation of land. In this regard, Turimubumwe et al. (2024) recently noted the need for land use and management planning through quantitative data for soil monitoring in Burundi. Therefore, it is necessary for geospatial data integrity to link the country's geological and environmental framework to produce integral analysis and monitoring (Lwasa 2019). This integrity is the data representation that receives in the form of satellite images and thematic mapping what comes from the environmental complexity of East Africa.

DISCUSSION

The study of land cover properties for landscape monitoring in Burundi involves cartographic visualization of data collected from various sources such as spatial imagery, vector and raster data, as well as a descriptive analysis of existing works. Examples of complex GIS approaches are presented in selected works that combine satellite images with geological, soil and vegetation maps (Lemenkova, 2023a) or climate data (Ge et al. 2008). Moreover, 'in situ' fieldwork is difficult in this country and data are scarce.

However, these studies use traditional GIS mapping methods for data analysis and visualization. To continue and extend these studies, this work presents the application of script mapping techniques for integrated mapping that uses various data for a comprehensive analysis of the environmental context of Burundi. By continuing this study, it is possible to achieve a graphical representation of land use changes using classification. For example, the upcoming study could explore segmentation techniques that could be used to analyze satellite images at different scales. The development of this method could include automatic object discrimination, segmentation, and feature extraction of land cover types in Burundi landscapes.

Land monitoring and an effective landscape management system can contribute to the development of a more efficient agricultural system. For example, using multi-temporal image sequence, the dynamics of Burundi landscapes can be analyzed in more detailed spatio-temporal aspects. The content of this information can be derived from satellite imagery for the analysis of suitable and sufficient features for landscape monitoring.

In this context, this paper highlights the importance of integrating programming algorithms, scripting techniques and GRASS GIS computational methods for spatial data analysis in landscape studies. Furthermore, it offers opportunities for the development of new methods that could complement classical cartographic tools. Furthermore, this study applied interactive spatial data analysis combining logical queries on raster data regarding various landscape characteristics, with exploratory and confirmatory analysis, and cartographic visualization by GRASS GIS scripts. Considering this, this paper contributed to the thematic mapping of Burundi through the presentation of a new series of maps based on multi-source geospatial data and satellite images.

CONCLUSION

This article presented the environmental analysis of Burundi as well as the principles of using various GIS software, to see the differences between cartographic applications through multiple geospatial data on Burundi. So, the different ways of approaching the visualization of geospatial data and satellite images via QGIS, GRASS GIS and GMT software are analyzed. As for the best software in this study, our choice would be GRASS GIS followed by GMT. Even if it does not show completely easy approaches, it is categorically faster thanks to the programming algorithms used for processing cartographic and remote sensing data. So, the use of scripts in the context of environmental monitoring can be considered a very great advantage.

On the one hand, the integration of geospatial data and satellite images using GRASS GIS scripts and traditional GIS approaches aimed to support a geographic analysis process with the aim of assessing environmental dynamics in East Africa. On the other hand, the demonstrated cartographic capabilities of the scripts executed in GRASS GIS contribute to the development of technical methods of geoinformatics and cartography. Thus, this paper achieved the dual objective of this study by combining the technical processing of cartographic data by scripts and the environmental analysis of landscapes.

In addition, this paper illustrates the importance of applying programming for remote sensing data processing using spectral and texture feature analysis of satellite images. The programming approach has yielded relatively good results on Landsat-8 OLI/TIRS images with simple color texture covering the territory of Burundi. Satellite image analysis and thematic mapping are advantageous for environmental monitoring, and the integration of cartographic and programming approaches allows to extract maximum information from these data. The classification of Landsat 8-9 OLI/TIRS satellite images performed using GRASS GIS software is useful for learning Burundi landscape patterns in the form of geospatial structures detected and identified by the script algorithms.

The social development of the country is generally strongly linked to its natural geographical setting and available land resources. This is particularly true for Burundi whose limited economic potential is affected by the extent of the landlocked and small country. For example, the existing relationship between land productivity and farm size, which is affected by the fragmentation and heterogeneity of the landscape. At the same time, a good understanding of the environmental and geological context of the country helps to reveal the potential of its resources. For example, geological mapping is useful for modeling regional hydraulic parameters and discovering the thickness of the aquifer. In turn, this is useful for the analysis of the groundwater resources of Burundi which are essential sources of drinking water for the population. In this regard, the production of new maps using reliable geospatial data and advanced methods contributes to a better understanding of the country's natural and environmental resources. Several authors have highlighted the successful applications of programming and data integration methods for environmental and geographic analysis (Fikadu and Olika 2023; Cloete et al. 2024). In the presented study, such integrated environmental analysis fills the gap in the existing literature on Burundi that lacks approaches on programming cartographic techniques used with GIS software. ●

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