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Dynamics of Spatio-temporal Occupation of Biological Soils Crusts Using RS and GIS Approach in the Saria Catchment, West-central Region of Burkina Faso

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

In the semi-arid environments of sub-Saharan Africa, the combined action of climatic factors and human activities degrades the vegetation cover, resulting in soils that are vulnerable to the risk of erosion. This is when micro-organisms of various kinds, known as biological crusts, colonise the soil surface, playing a part in the pedogenetic processes and combating soil degradation. The aim of this study is to investigate the spatio-temporal occupation dynamics of biological crusts in the Saria catchment using remote sensing and geographic information systems. The methodology is based on a geomatics approach that integrates the use of Landsat-8 OLI/TIRS satellite images, geographic information systems and fieldwork. The processing of Landsat-8 OLI satellite images and the pedomorphological and environmental characterization of soils have made possible to map mainly two types of soils i.e. leached tropical ferruginous soils and low-humidity hydromorphic soils with surface pseudogley. After this step, the field work enabled us to identify the land cover units in our study area from which the in-situ observations of soils surfaces revealed that biological crusts are more developed on the soils of the fallow plots (30% - 95%) than the bare (5% - 15%) and field soils (5% - 10%). The results of this study showed that the level of development of soils biological crusts is linked to the plots disturbance and its ages. In conclusion the use of remote sensing and geographic information systems is an effective and less expensive technique for mapping soil types and land cover units covered by biological crusts.

Keywords: Biological crusts; fallow land; Saria; remote sensing.

1. INTRODUCTION

Life depends on fundamental human resources such as soil and water (Economics of Land Degradation Initiative, 2019), but human pressures on soil resources are reaching critical limits (FAO and ITPS, 2015). Indeed, the soil source of agricultural production is increasingly threatened by multiple physical, chemical and biological degradations. All continents are affected by this phenomenon of soil degradation, hence the need to make soil conservation a major global project (Adams et al., 2000; Clément, 2020).

According to the Food and Agriculture Organization of the United Nations (FAO, 1994), soil degradation in the world is caused by two factors, namely natural and anthropogenic factors. In sub-Saharan Africa, soil erosion, loss of soil organic carbon, imbalance of nutrients in the soil, and loss of biodiversity are, in order of importance, the main threats facing soils (FAO and ITPS, 2015).

The degraded soils in the Sahelian countries are characterized by an insufficient water resource, the discontinuity of the plant cover and the modification of the physical properties (Malam, 1999). The work carried out by (Cornet, 1992; Valentin, 1994) shows that the discontinuity of the soil surface in the Sahelian regions is due to several phenomena. The adaptation of the plant cover to an optimal exploitation of water resources available for plants, the climate variation marked by two (02) severe droughts, i.e. the period 1972-1974 and the period 1982-1983, the progress of the Sahara Desert, the lengthening of the duration of the dry season, the irregularity of precipitation, the increase in the frequency of high intensity precipitation and the increase in strong winds (Girard & Girard, 1989).

In Burkina Faso, about 90% of agricultural production comes from extensive mining-type agriculture. Demographic pressure linked to population migrations has led to the elimination of land fallow and caused a change in cropping systems (Taonda et al., 1995; Ilboudo et al., 2023). Thus, the expansion of agricultural land coupled with unsustainable agricultural practices and climatic hazards have led to the degradation of soils in Burkina Faso which are frequently bare and crusted (Taonda et al., 1995; INERA, 2003; Sakandé et al., 2022).

According to Malam (1999), two (02) categories of crusts can be distinguished on these arid and semi-arid soils, namely the surface or physical crusts and the biological crusts. Biological crusts formed by microbial communities of diverse taxa, such as bryophytes, lichens, eukaryotic algae, cyanobacteria, fungi and/or bacteria, and their byproducts, are thin biological layer on the soil surface. Known also as microbiotic, cryptobiotic, cryptogamic, or microphytic soil crusts, or simply biocrusts, they are crucial components of terrestrial ecosystems because they play an essential role for aggregating mineral particles at the soil surface (West, 1990; St. Clair & Johansen, 1993; Evans & Johansen, 1999; Belnap et al., 2001; Belnap et al., 2003). According to the author, during the formation of these physical and biological crusts, three (03) major processes are involved. These are: (i) the disintegration of the soil structure under the impact of raindrops, followed or not by wind or water erosion, (ii) the deposition of particles by sedimentation, and (iii) the colonization of the soil by microorganisms. On biological crusts formation processes, some authors stressed that low-level montmorillonite (0.5–2 %; w/w) addition significantly increased the photosynthetic biomass by about 50% (indicated by Chlorophyll-a and gene copies) and promoted the accumulation of total nitrogen, nitrate nitrogen, ammonia nitrogen, and total organic carbon (Long et al., 2024).

During the process of soil degradation, when physical crusts are not quickly eroded, they become the site of colonization by microorganisms, which contribute to the formation of a living organic layer on the soil surface called a biological or microbial crust. These microorganisms are autotrophic, adapted to aridity, and in a dormant state during periods of water scarcity, becoming active again with the first rains.

Biological crusts not only play a physical role in stabilizing mobile surfaces and protecting the soil against erosion, but also facilitate the colonization, growth, and maintenance of vascular plants during succession and enrich the soil by providing nutrients, increasing the concentrations of various essential elements for the tissues of vascular plants (Evans & Johansen, 1999; Breen, 2006).

For the fight against land degradation in arid and semi-arid areas, and more particularly in Burkina Faso, rural and modern strategies for the conservation/enhancement of plant and animal biodiversity, the restoration/conservation of soil fertility, and the reduction of soil erosion have been proposed and implemented (Lompo, 2003; IRD, 2010; Hien et al., 2012; MAAH, 2019; Sakandé et al., 2022).

The inventory of soils by lands cover units is one of the keys to the management of soil resources and the control of desertification in arid areas. However, the traditional methods of soil mapping are time consuming, expensive and cannot meet the urgency of the necessary decision-making. Spatial technologies, particularly remote sensing through the processing of satellite images and geographic information systems (GIS), are effective, precise and reliable tools for soil mapping (Boulahouat & Naert, 1995; Canadian Centre for Remote Sensing, 2024).

In view of the importance of biological crusts in the fight against soil degradation and in view of their microscopic characteristics, it was considered necessary to focus on improving the methods of studying biological crusts. The present study aims to provide a response to the issue related to the spatio-temporal monitoring of biological crusts. The main objective is then to study the dynamics of spatio-temporal occupation of biological crusts in the Saria watershed using remote sensing and geographic information systems.

The Burkinabe context lends itself easily to this, as the fight against soil degradation is a major challenge, as the soil resources that constitute one of the main bases of agrosylvopastoral production are affected by the loss of multiple potentials (Duchaufour, 1999; Sawadogo et al., 2008).

2. METHODOLOGY

2.1 Description of the Study Site

The Saria watershed is a sub-watershed of the Mouhoun with an area of 57.4 km2 and a perimeter of 46.92 km. It is located in the Central-West region between longitudes 2°10'30" West and 2°6'0" West and latitudes 12°12'0" North and 12°19'30" North. Our study area is located 70 km from Ouagadougou and 24 km from Koudougou and covers the communes of Poa, Niandiala, and Koudougou.

The climate of our study area is of the northern Sudanian type (Guinko, 1984), characterized by two (02) seasons, a rainy and a dry season. The annual precipitation varies constantly and is between 600 and 900 millimeters (mm). The vegetation in the Saria watershed belongs to the North Sudanian phytogeographic domain characterized by a savannah with annual grasses, shrubs and trees. The Saria watershed is located within the Koudougou square degree. According to Castaing et al. (2003), the geological formations are made up of granites, porphyroid granites, gabbro-diorite, dolerites and alluvium. The relief is almost flat marked by a few mounds over the entire extent of the territory.

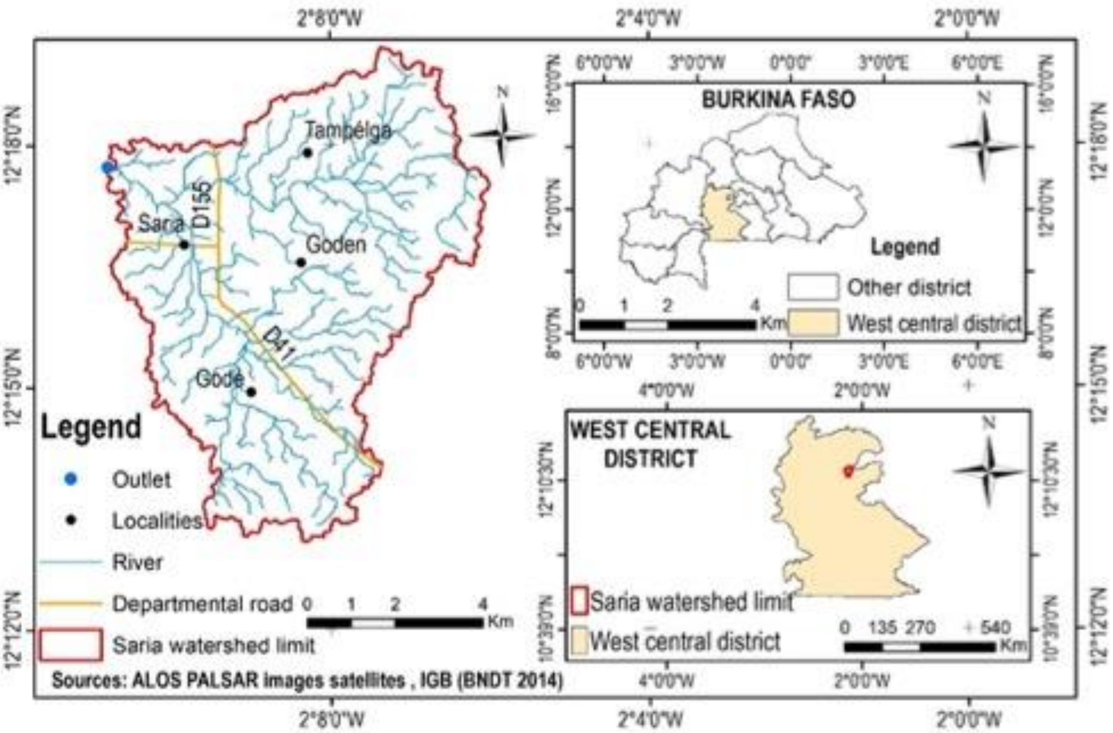

Fig. 1. Localisation map of the study area

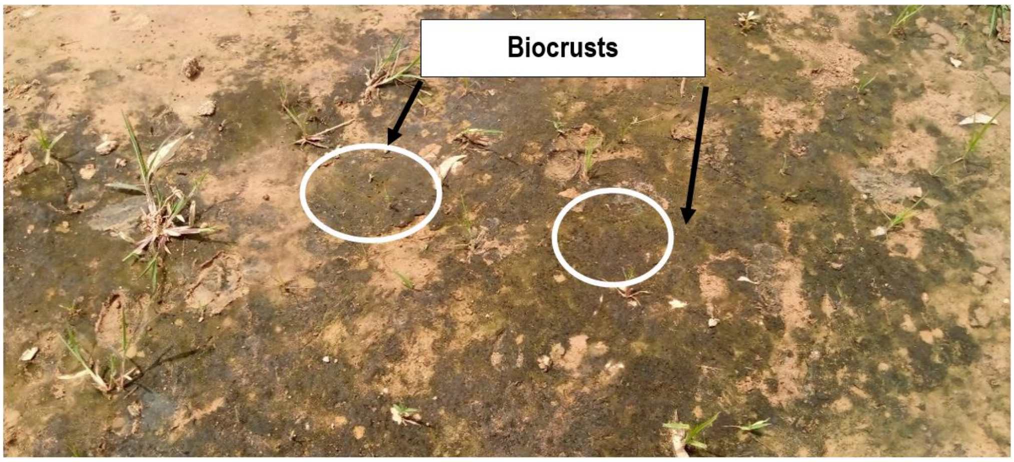

Fig. 2. Soil biological crusts

2.2 Experimental Details

2.2.1 Material

The material used consists mainly of biological material, field equipment, mapping data, and software.

The biological material of our study is the biological soil crust.

The field equipment, mapping data, and software are:

- a Garmin Map 66s GPS receiver to record the geographical coordinates of the observed encrusted surfaces, soil types and land use units;
- the Munsell color chart or code for determining the colors of soil horizons;
- a camera for taking pictures of the observed units;

- the Survey forms to collect information on the fallow plots of the Saria agricultural research station;
- a knife for sampling the biological crusts on the ground;
- a 1 m2 metal device for in situ observation of biological crusts;
- Microsoft Office 2019 software for data entry, creation of various graphs and statistical analysis of the results obtained;
- ENVI 5.1 software for processing Landsat-8 OLI satellite images;
- ExpertGPS software for the transfer of geographic coordinates of data collected by GPS;
- ArcGIS 10.8 software for cartographic production and spatial data analysis.

2.2.2 Methods or data acquisition

The data used was classified into two (02) categories : satellite and auxiliary data. The satellite data used are Landsat-8 OLI/TIRS and ALOS PALSAR radar satellite images. About the images, supervised classification was used for the images processing and then the field work allows to map the lands cover units of the study area. Alos palsar are japanese images used to extract the Saria watershed. Satellites images processing follow these steps :

1. Colored composition of the three index color IB, IC and IF ;
2. Choice of the lands cover units ;
3. Supervised classification ;
4. Fieldwork ;
5. Validation of the classification ;
6. Vectorization with a GIS software ;
7. Lands cover units mapping

The auxiliary data used in this study are tabular and vector data from our study area. The method is based on the joint use of remote sensing and geographic information systems (GIS). We used Landsat-8 OLI satellite images for image processing to discriminate soil types. From the different stages of satellite image processing, we were able to produce a map of soil types over the entire Saria watershed. Image processing focused on the specific processing of the bands in order to characterize the types of soils covering the Saria watershed. The different stages of digital mapping of soil types from Landsat-8 OLI satellite images are defined. Three (03) indexes were calculated: the gloss index (IB), the coloring index (IC) and the shape index (IF).

Sites visited in the field were chosen based on the colored composition of the IB, IF and IC index. The choice of sites to visit was based not only on the topo-sequence but also on their presence within the Saria agricultural research station. The geographic coordinates of the chosen sites were entered into a GPS receiver for field work.

The land cover units considered for the observation of biological crusts are: bare soil, the cultivation area and the savannah. In total, twelve (12) soil surfaces were observed depending on the types of land cover units. Three (03) surfaces were observed on bare soil, or 25% of the surfaces observed. Three (03) surfaces were observed in the fields, or 25% of the surfaces observed. Three (03) areas were observed on recently fallow plots and three (03) areas were observed on old fallow plots, i.e. respectively 25% of the areas observed.

Fig. 3. Metallic device for observing biological crusts on the ground

Table 1. Characteristics of Landsat-8 OLI/TIRS and ALOS PALSAR satellite images

Id images	Capteur	Scene (path/Row)	Date	Spatial Resolution (m)
LC08_L2SP_195052_20231226_20240104_02_T1	OLI/TIRS	195/052	December 2023	30
ALPSRP258610230	ALOS PALSAR	8	December 2010	12,5

Sources: www.glovis.usgs.gov ; www.alaska.gov

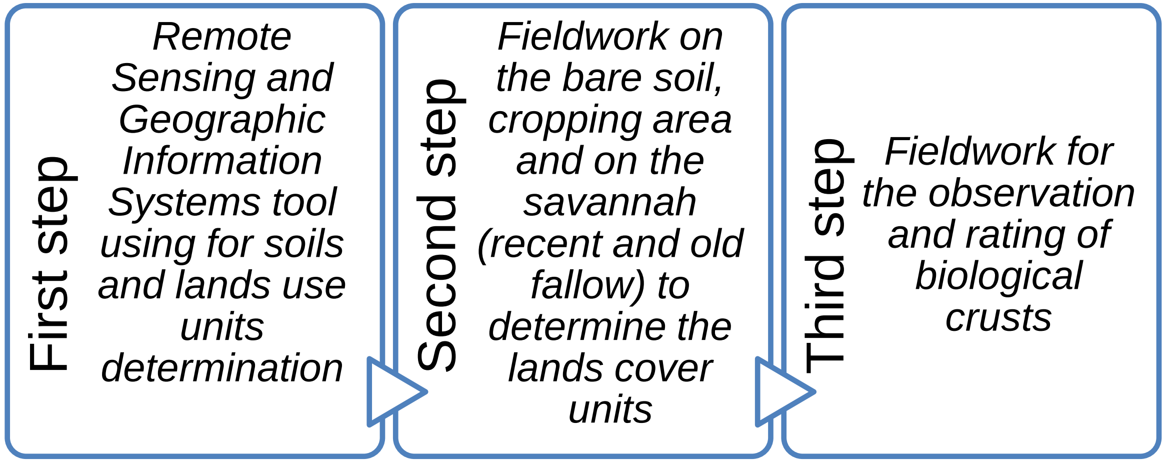

Fig. 4. Workflow on the essential steps of the methodology

3. RESULTS AND DISCUSSION

3.1 Processing Landsat-8 Satellite Images and Identification of Soil Types

The identification of soil types in the watershed was possible using the colored composition of three indexes color IB, IF and IC in the red, green and blue channels. Fig. 5 allows us to identify low-humid hydromorphic pseudogley surface soils (HPGS) in red and black coloring and leached tropical ferruginous soils (FLI) in varied purple, light green and blue coloring. These types of soils were mapped and confirmed during the field trip through the description of soils pedomorphological characteristics.

The soil types of the Saria watershed are not very diverse. A variation in soil types is observed depending on the topographical position. So, we have:

- at the level of the glacis (top of slope and average slope), leached tropical ferruginous soils;
- at the temporarily flooded lowlands (with the presence of a water table close to the surface), hydromorphic soils with little humus and surface pseudogley.

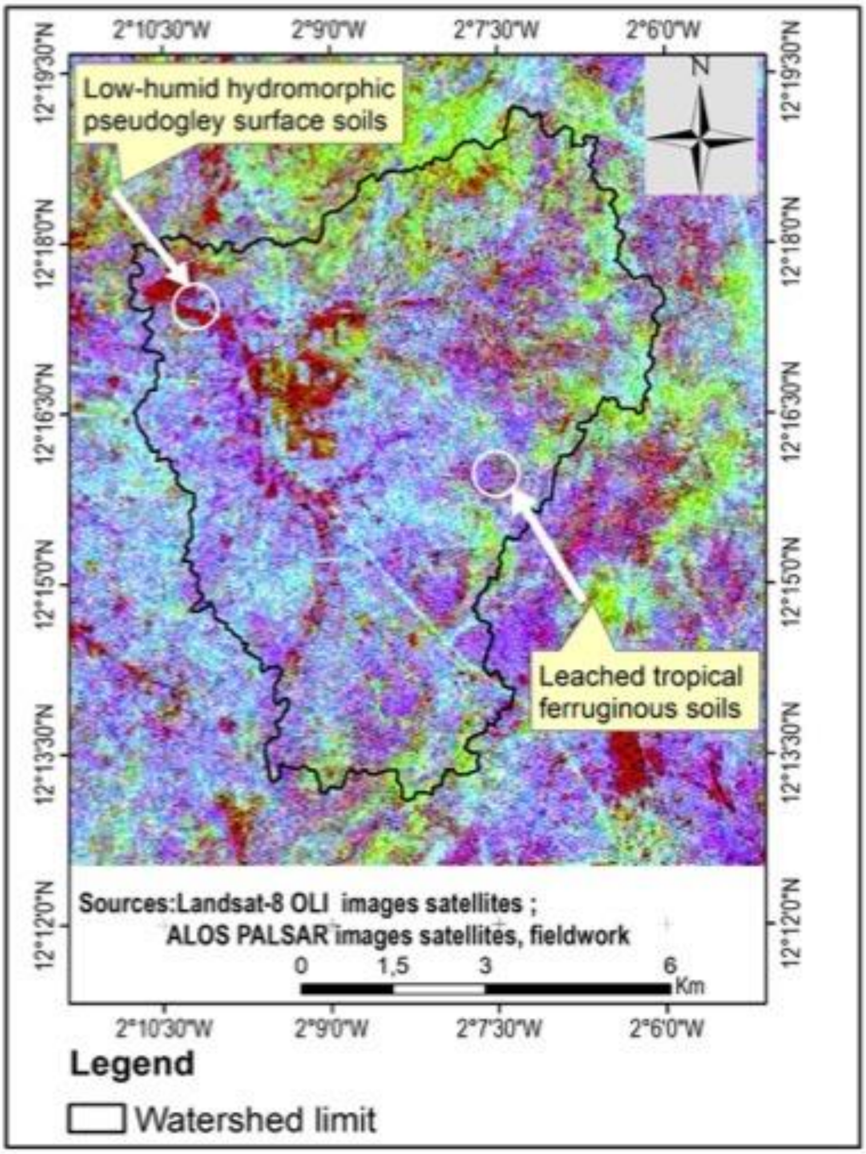

Fig. 5. Colored composition of Landsat-8 OLI satellite image indexes

The parent material of the soils is generally made up of granitoid (Castaing et al., 2003). Fig. 6 shows the spatial distribution of soil types in the Saria watershed. Our soil type mapping results are in agreement with those obtained by numerous authors who have worked in our study area. BUNASOLS (1991) carried out soil mapping work on plot number 31 located at the level of the average slope of the Saria agricultural research station. According to the CPCS classification (1967), the mapped soils are part of the class of iron and manganese sesquioxide soils and precisely of the group of leached tropical ferruginous soils.

3.2 Analysis of Satellite Images and Identification of Land Use Units

Landsat-8 OLI optical satellite images processed in 5-6-7 color composition were used to better discriminate land cover units in the Saria watershed (Fig. 7). The land use units identified are: bare soil and habitat, gallery forest, savannah, water body and cultivation area. The bare soils and habitats are mosaic of white and yellow coloring. Gallery forests appear in bright red color and savannahs in mosaic of light red and purple colors. Bodies of water appear black and crop areas appear green. Our results match with those obtained by the authors Assemian et al. (2018) and Tankoano et al. (2016). Assemian et al. (2018) used Landsat-7 ETM+ satellite images with an average spatial resolution of thirty meters (30m) to map land use units in the Marahoué region of Côte d'Ivoire. It was difficult to discriminate from image processing between fallow areas and tree plantations because of the similar plant cover densities and the large extent of the study area.

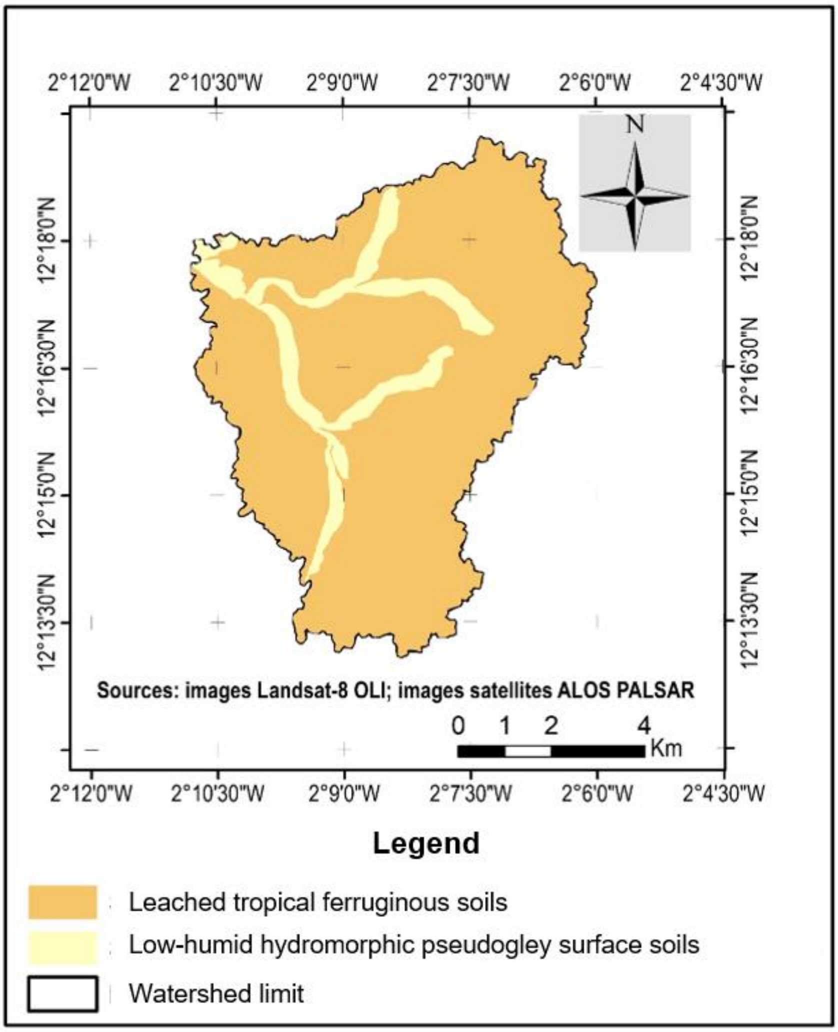

Fig. 6. Soil types in the Saria

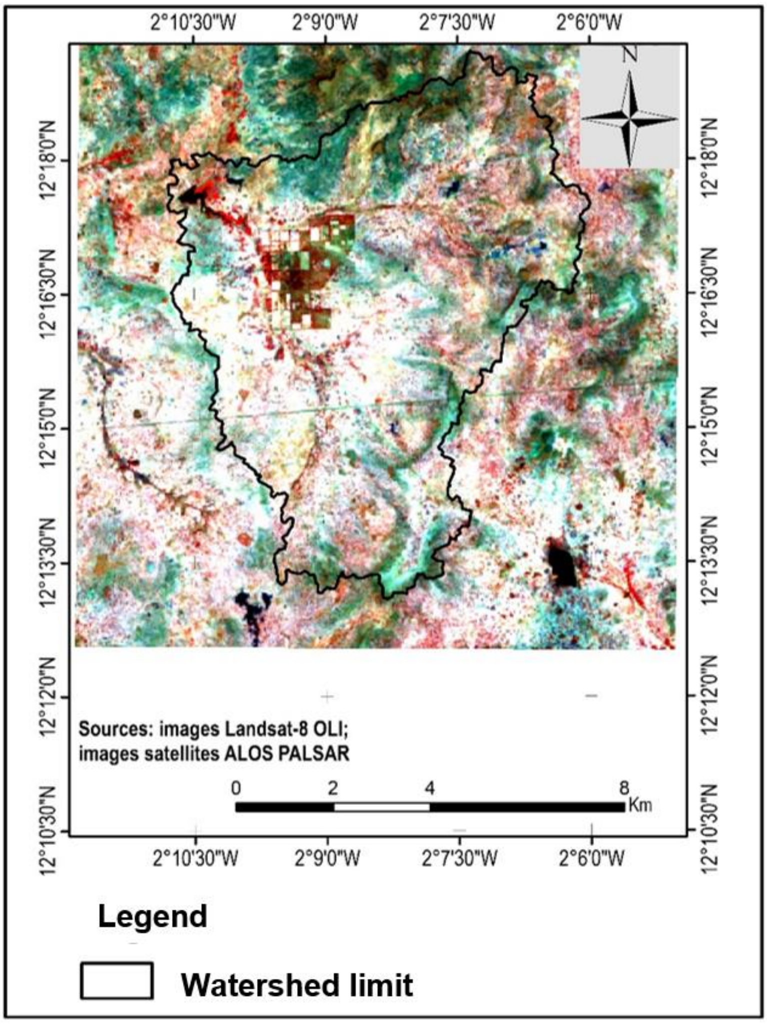

Fig. 7. Land cover units in the Saria watershed

3.3 Evaluation and Validation of the Classification

The classification supervised by the "Minimum distance" method was evaluated by the confusion matrix (Table 2) and the values of the overall precision and the Kappa coefficient.

3.4 Globale Precision (*Overall Accuracy*): 89,25%; *Kappa Coefficient*: 0,86

The analysis of this contingency table allowed us to note some confusion between the land use units during the supervised classification. Despite these confusions, the values of the overall precision (89.25%) and the kappa coefficient (0.86) made it possible to confirm the acceptable nature of the classification. The colored composition of the IB, IF and CI indices made it possible to better discriminate the types of soils in the Saria watershed, namely leached tropical ferruginous soils and low-humus hydromorphic soils with surface pseudogley. Classification of satellite images by the supervised classification method was used to determine soil units in the Saria watershed. The values of the overall precision (100%) and the Kappa coefficient (1) suggest a good classification of the pixels. According to Girard and Girard (1999) and Aka et al. (2022), an image classification is of good quality when the value of the overall precision is greater than 80% and that of the Kappa coefficient is greater than 0.75.

3.5 Land Use Units

A map of land use units in the Saria watershed was produced (Fig. 8). It presents the spatialization of land use units in the watershed. The land use units in the Saria watershed are: bare soils and habitats, gallery forests, savannahs, water bodies and crop areas.

Table 2. Confusion matrix of supervised classification of Landsat-8 OLI satellite image

Soil occupation units	Bare soils habitats	Forest gallery	Savannah	Water	Cultivation area
Bare soils habitats	**100**	0,00	0,00	0,00	0,00
Forest gallery	0,00	**45,45**	2,47	10,34	0,00
Savannah	0,00	54,55	**97,53**	20,69	1,72
Water	0,00	0,00	0,00	**68,97**	0,00
Cultivation area	0,00	0,00	0,00	0,00	**98,28**
Total	100	100	100	100	100

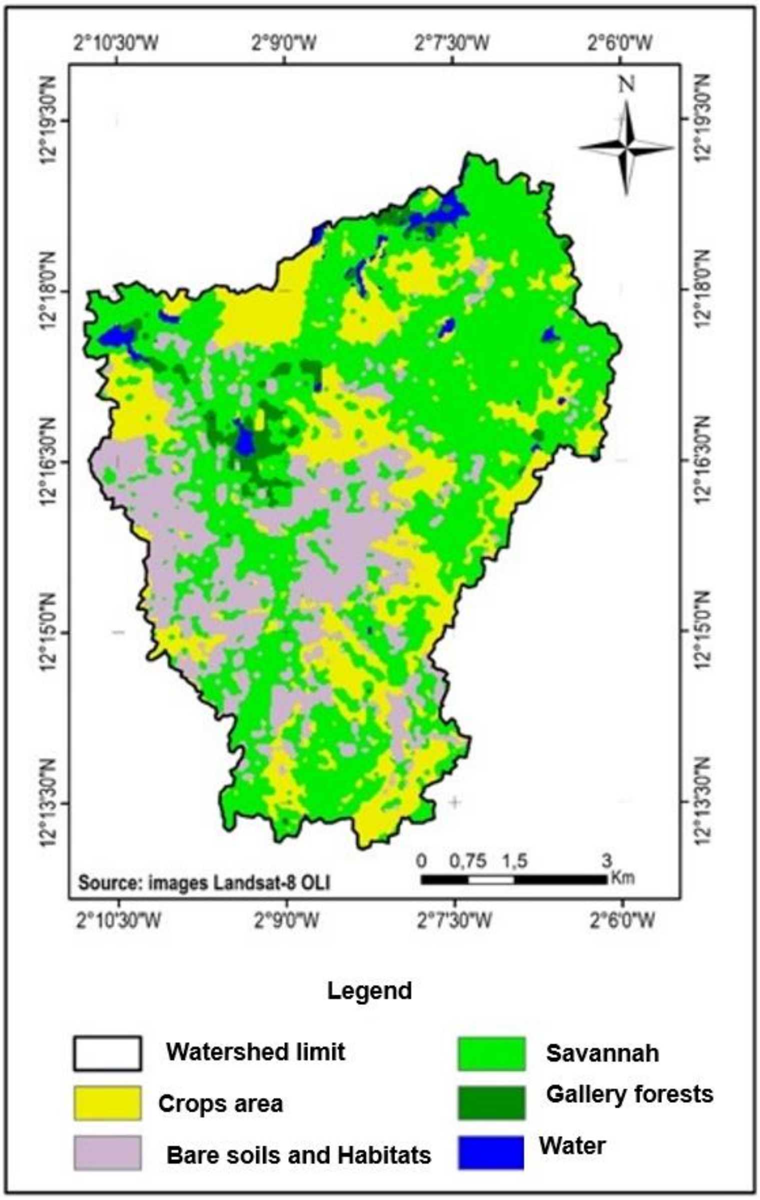

Fig. 8. Land use units in the Saria watershed

Table 3 presents the area and percentage of each land use unit in relation to the area of our study which is 57.4 km2. It presents the spatialization of land use units in the watershed. The land use units in the Saria watershed are: bare soils and habitats, gallery forests, savannahs, water bodies and crop areas.

3.6 Dynamics of Spatio-temporal Occupation of Biological Crusts in the Saria Watershed

The results of observations carried out on bare soils, in fields and in fallow plots (recent and old) chosen during our field work in the Saria watershed varied. The visual estimation of surfaces covered by biological crusts showed a coverage rate between 5% and 15% on the surface of bare soils. The coverage rate of biological crusts in the fields is between 5% and 10% of the surfaces observed. The coverage rates of biological crusts on fallow plots (recent and old) are considerably higher than those of bare soils and fields in our study area. Recent fallow plots (whose set-aside ages are between 3 and 10 years) have biological crust coverage rates which vary between 30% and 60%. Old fallow plots (the age of which was set aside is greater than 30 years) have the highest rates of biological crust coverage (between 75% and 95%) on their surfaces.

The installation of biological crusts evolves on land use units over time. The fallow plots chosen have biological crust coverage rates which vary between 30% and 95%. The evolution of the coverage rate of biological crusts on these fallow plots is linked to the age at which the plots were protected (Fig. 8). Thus, on the surface of recently fallow plots (age of protection between 3 and 10 years), the biological crusts have a coverage rate of between 30% and 60%. While at the level of old fallow plots (age of fallowing greater than 30 years) the coverage rate of biological crusts is between 75% and 95%. The coverage rate of biological crusts on old fallow plots is higher (between 75% and 95%) than the coverage rate of biological crusts on recent fallow plots (between 30% and 60%).

Table 3. Area and percentage of each land use unit

Soil occupation units	Area (Km^2)	Percentage (%)
Bare soils	12,43	21,66
Forest gallery	1,59	2,77
Savannah	29,14	50,77
Water	0,92	1,6
Cultivation area	13,32	23,2
Total	57,4	100

At the level of bare soils, the coverage rate of biological crusts increases when the soils are less disturbed over a long period by human trampling and grazing. Likewise in the fields, the coverage rate of biological crusts increases when work on the ground (ploughing, scarifying, ridging, Zaï) has not been carried out over a long period.

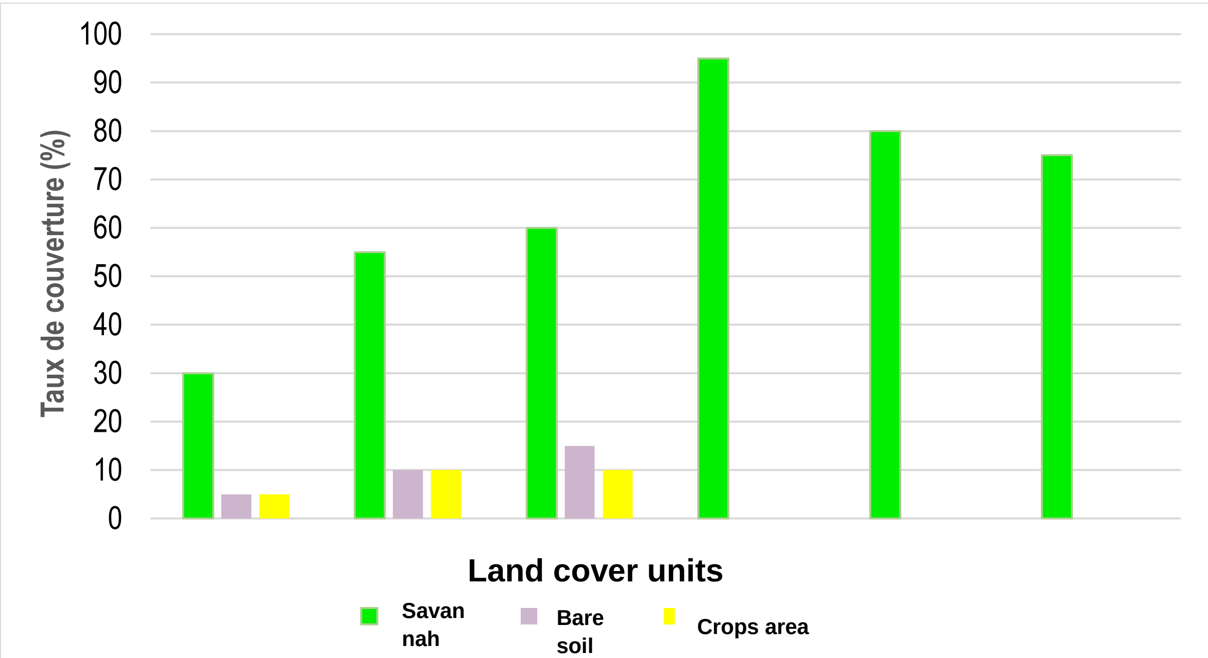

Fig. 9. Biological soil crusts on soils units

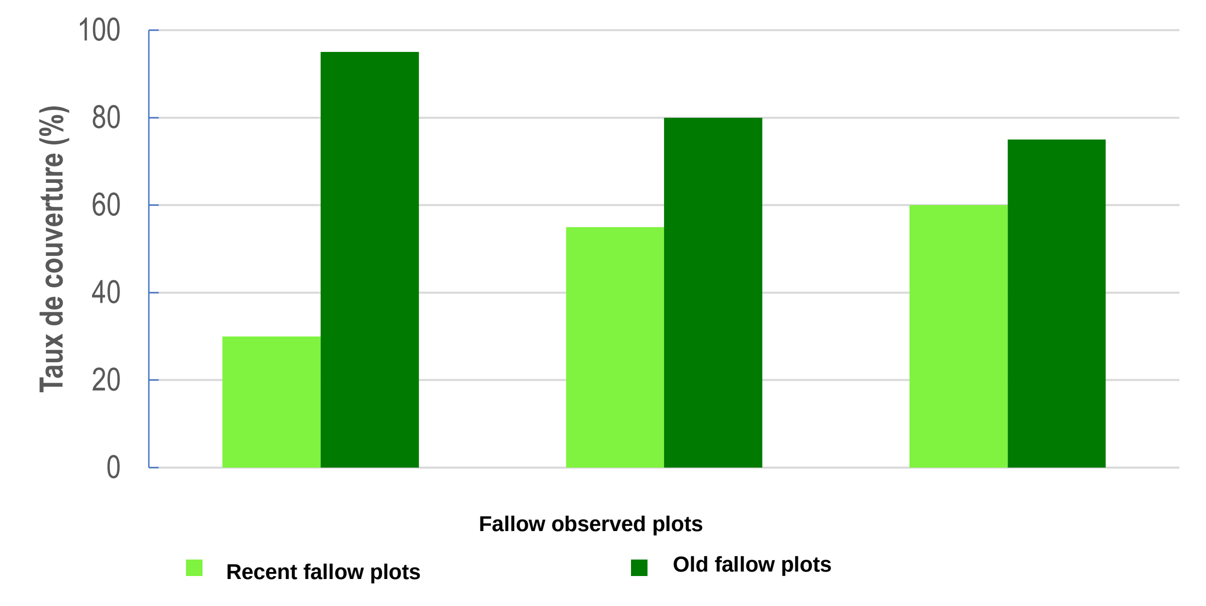

Fig. 10. Temporal evolution of the coverage rate of biological crusts on fallow plots

The biological crusts cover almost all environments. Our results match with those found by Mehda (2022) as part of his work on biological crusts on the ground in Algeria. The author states that crusts colonize almost all environments because they sometimes contain microbiological species (cyanobacteria) which have the capacity to resist extreme temperature conditions and to be resilient in unfavorable conditions. The biological crusts (cyanobacteria) were characterized on two (02) types of soils, namely salty soils and slightly salty sandy soils. The work showed the presence of a diversity of biological crusts which colonize almost all surfaces in this hyper-arid environment. Our results corroborate the conclusions of the research work of Malam (1999) who studied biological crusts in fallows and the tiger bush of Niger. According to the author, the biological crusts have a coverage rate which evolves depending on the age of protection of the plots and their association with herbaceous plants. According to their relative importance, the microscopic biocrust communities function ecologically to (i) stabilize soils, (ii) fix nitrogen and carbon, (iii) regulate water cycling in an out of soils, (iv) capture dust, (v) accumulate organic matter, (vi) supply nutrients to vascular plants, (vii) enhance and/or reduce seedling establishment, (viii) promote chemical and physical weathering, (ix) provide wildlife habitat, (x) and regulate soil food web interactions (West, 1990; Johansen, 1993; Evans & Johansen, 1999; Belnap et al., 2001; Johansen & Schubert, 2001; Shepherd et al., 2002; Zaady & Bouskila, 2002; Darby et al., 2007, Williams et al., 2012).

4. CONCLUSION

The main objective of the present study is to assess the dynamics of spatio-temporal occupation of biological crusts on the Saria watershed using remote sensing and geographic information systems. The processing of Landsat-8 OLI satellite images allows us to present an effective and less expensive technique which makes it possible to identify the units of soils and the land cover units on which biological crusts form. The study of soils by the approach of remote sensing and geographic information systems is therefore an effective tool which can help in the planning of development and protection actions for vulnerable environments. For more details on the acquisition of information on the state of soil resources, it would be interesting:

- Map the soil types of the Saria watershed using high spatial resolution (10 meters) Sentinel-2 satellite images;
- Characterize the soil types of the Saria watershed using radiometric airborne geophysical images.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models

(ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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