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# Study and evaluation of the effects of vegetation cover destruction on soil degradation in Middle Guinea through the application of remote sensing and and geotechnics

Ibrahima Diogo Diallo [a,*], Amine Tilioua [b], Chakib Darraz [a], Amar Alali [c], Diaka Sidibe [d]

[a] Research team in Applied and Marine Geosciences, Geotechnics and Geohazards Laboratory (LR3G), Department of Geology, Faculty of Sciences Tétouan, Abdelmalek Essaadi University, Mhannech 2, BP 121, 93030, Tétouan, Morocco

[b] Research Team in Thermal and Applied Thermodynamics (2.T.A.), Mechanics, Energy Efficiency and Renewable Energies Laboratory (L.M.3.E.R.). Department of Physics, Faculty of Sciences and Techniques Errachidia, Moulay Ismail University of Meknès, B.P. 509, Boutalamine, Errachidia, Morocco

[c] Applied Geology Research Laboratory, Applied Geology and Remote Sensing Research Team, Department of Geosciences, Faculty of Sciences and Techniques Errachidia, Moulay Ismail University of Meknès, B.P. 509, Boutalamine, Errachidia, Morocco

[d] Minister of Higher Education, Scientific Research and Innovation, Former Higher Geology and Mines Institute, Ministry of State in charge of Higher Education and Scientific Research, Boké, Guinea

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ABSTRACT

Soil degradation in Middle Guinea is increasing over the years. While it's good to have precautions to deal with it, it's even more important to go back to the source of the scourge in order to lessen its effects over time, or even eradicate it. At the center of the factors that are often mentioned is the destruction of the vegetation cover, and the aim of this study is to clear it (in all its forms: trees, grass, savannah, etc.) by following its variation in time [1982 and 2021] and in space. The present study was conducted by combining the remote sensing and GIS results, developed with data from geotechnical survey data and laboratory tests. On the Mali Labé Linsan axis, between [1982 and 1992], 63 % of the territory explored was occupied by fresh vegetation cover, compared to 13 % of dry vegetation, as well as 12 % of sterile soil and 12 % of sand mineral soil. For the periods [1992–2002] and [2002–2012], these same parameters increased to: 67 %; 11 %; 11 % and 11 %. The period [2012–2021] was marked by changes of 73 %; 10 %; 9 % and 9 %, respectively. The bearing capacity of soils varies from one point to another. In all six boreholes presented, their maximum values are greater than or equal to 400 Kpa ($\geq$400 Kpa). The minimum values calculated for $2.1 \leq B(m) \leq 7.3$ fluctuate between 291 Kpa and 806 Kpa. The investigations carried out on this subject show that the overall movement of the positive variation of the vegetation cover in time (63 % < 67 % < 73 %) and very contrasted in space, would not be responsible for the degradations (which are local and mainly caused by erosion: wind and water). In addition, they open up to a (geoscientific and geotechnical) approach of a deep analysis, the purpose of which suggests the adoption of slab/concrete/grating foundations (depth of anchorage specific to each soil analyzed).

* Corresponding author.
*E-mail addresses:* dialloibrahimadiogo@gmail.com (I.D. Diallo), a.tilioua@umi.ac.ma (A. Tilioua), darraz@gmail.com (C. Darraz), a.alali@fste.umi.ac.ma (A. Alali), sidibediaka@cems-ismgb.org (D. Sidibe).

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## 1. Introduction

Soil degradation is a global problem. This degradation often has multiple causes, involving anthropogenic and meteorological factors, some of which are complementary. One of the most frequent causes is the destruction of the vegetation component. This situation, which can considerably disrupt the ecosystem, has an impact both on the climate and on the management of resources by local populations J. Quense [1]. This situation can have a significant impact on their socio-economic life. According to the United Nations [2], the world has experienced a crucial change in temperature in recent years. This change is expressed across the globe by very hot and very cold periods. There are a several of causes for this phenomenon, including: major industries (multidisciplinary and energy-intensive) that pollute the environment and cause global warming; the multiple and accelerated destruction of vegetation cover.

In Guadeloupe according to the work of J. JO and R. Defrance [3], the ilet de Caret is threatened with extinction due to the erosion of the sandbank at a rate of 12 m/year and the heavy use of the site, which has already lost almost ¾ of its original surface area. Among the development works for its perpetuation is the protection of the vegetation cover by the plantation of catalpas in addition to the coconut trees which are not very protective. While it's not theoretically possible (given the observed realities) to question the hypothesis that the destruction of vegetation cover may be a source of most of the environmental issues today, at the same time it is very difficult to make assertions without scientific basis. This is why it fundamental to ask what kind of vegetation cover is involved? This is an inescapable question that this paper aims to clarify, using as an illustration the variation in vegetation cover over time and space on the Mali Labé Linsan axis in Middle Guinea. With the development of digital technology, several geoscientific methods have been put in place to understand the real causes of soil degradation. The reality of this study is that there is a huge complementarity between them. In the Guinean environment, the present approach allows to conciliate GIS and Remote Sensing with pure Geotechnics in order not to limit the understanding of this scourge only in its temporal and geographical variation, or to give only degraded quantities (volumes). To guarantee durable structures, it is important to assess the response of the soil, in terms of its physics and mechanical behavior, to all these threats that invade it from everywhere. H. Xiong et al. [4] examined landslides in China using a combination of GIS and remote sensing. Their study produced 15 maps of landslide susceptibility compared with all the reforestation and urban development efforts. R. P. Quevedo et al. [5], through their literature review, explain how landslides could be increasingly related to human land use. Y. Gao et al. [6] remind us how important the understanding of the tensile strength of soils can be in their stability, and therefore in the stability of the structures they could support. For this, they make a study on a mixture of sand, clay and silt. W. Hassan et al. [7] developed a link between spatial mapping and geotechnical depth data. A method is certainly " heavy " which could be used as a guide once georeferenced and framed for any activity in the areas concerned and the targets of the themes to be carried out. P. Tarolli et al. [8] highlighted certain factors that can weaken agriculture in steeply sloping environments. Indeed, these areas often have historical, cultural, economic and even security (food) value, but they are also exposed to high risks of profitability often caused by humans (anthropogenic), but also by climatic effects (meteorological, often hydrological) that can affect their soils. J. Il et al. [9] reported a significant limitation in the understanding of structural instability in mines. They exposed the extent to which remote sensing is intended to map structures that are often difficult to suspect of being the cause of the geological accidents that often occur in this sector, and which put the safety of workers at risk. However, it is clear that in order to understand certain ruptures, far from any slopes, it is imperative to call on a mineral, microstructural analysis. Indeed, the other vision of soil degradation is based on the same logic of microstructural analysis, particularly in Conakry where incidents are most frequent. The mineralogical composition can be a factor with different sensitivities to the factors that can invade the geological material. In order to understand these factors, it is important to anticipate degradation with a strong precaution. N. Efthimiou et al. [10] deals with a problem that most countries with forests, including Guinea, have: forest fires. In addition to the social, economic and environmental consequences of such actions, the impact of the fire on the forest of Mati in Greece would have led to 102 deaths and accelerated the process of erosion. One of the most disturbing reasons for addressing the issue of vegetation cover change in Lower Guinea, Middle Guinea, Upper Guinea, and Forest-Guinea, both spatially and temporally, is to understand the true causes and magnitude of this scourge, so that it can be assessed, prevent it, and take steps to avoid its fallout, which can be very critical to all development sectors on which people rely for their livelihood. A. Abuelgasim et al. [11] have examined soil salinity as a facet of social and economic life. Whether of human or climatic origin, they estimate that it can induce uncommon agricultural consequences. To follow the variation of this element in space, they consider remote sensing as a very useful and advanced tool.

Further on, it is necessary to note that the other reason of salinity not mentioned is the effect of geological formation, whose deep analysis can be important in the progressive degradation of soils and the pollution of their environment (especially water). F. A. Abija et al. [12] combine geotechnical surveys and remote sensing to assess areas at risk of landslides in the Edim Otop area. They reach the conclusion that three zones (high, low, and medium susceptibility) are possible. For this, they believe that the slope (its orientation), soil (type, cohesion, friction angle, hydraulic conductivity, drainage and use), land cover, normalized vegetation, etc., could be essential factors in understanding these susceptibilities. G. Sreenivasulu et al. [13] showed how coastal environments can be invaded by agricultural activities, urbanization, and industrialization. A land use study that owes its content to combined geoscientific techniques, such as GIS and Remote Sensing (RS). The combination of GIS, RS and geotechnical techniques enables variations in degradation over time and space to be monitored, quantified and characterized. B. Lakshmanna et al. [14] used GIS and remote sensing to understand the dynamics of the Krishna River mouth, India. A dynamic, which once again, raises the importance of the combination of the two disciplines on the study of the spatial evolution of the different entities on the surface of the earth. C. Kutir et al. [15] examined the migration and land use along the Ghanaian coast. Using GIS tools and development, combined with remote sensing, they conclude that flooding, erosion, and human activity (including destruction of vegetation cover) have large impacts on land area change in this environment. Z. Ijaz et al. [16] detected hazard zones in basements using vertical mapping and laboratory analysis. This is a salutary approach as the most known and usual mapping is generally superficial and does not project much into the geotechnical hazard zones. However, a well done lateral and vertical cartographic study is a successful operation in advance of the exact definition of the foundation adapted to any planned structure. J. N. Kpoha et al. [17], by combining GIS and Remote Sensing manipulations, reach the conclusion that in the Allada Plateau of Benin, there would have been, between 1986 and 2020: a growth of 25.97 % of the areas of the mosaic/crop/fallow classes and 10.51 % for habitats/bare soil; against a decrease of −5.82 % for forests/galleries/swamps, −0.13 % for plantations and −0.25 % for water surfaces. These variations would have strong links with anthropogenic factors. C. Valdivieso-Ros et al. [18] have carried out land cover classification in semi-arid zones. An operation that requires background processing and regular calibration of data, with indispensable error margins. Very far, over the last 40 years, the work of ELD Initiative & UNEP [19] states that 33 % of the planet's surface has been affected by desertification (45 % of Africa's surface is affected and 55 % is at high or very high risk of degradation). Erosion has destroyed nearly 2/3 of the world's arable land (…) and its main factors are water, wind, acidification, salinization, compaction, etc. These factors are said to be amplified by the destruction of vegetation cover. After a long and thorough investigation throughout the world (Australia, Ethiopia, Bhutan, India, Namibia, Turkey, Rwanda, etc.), the work of United Nations, World Future Council et Green Cross [20] highlights several state policies for soil management, the fight against soil degradation and the collective confrontation of erosion. At the heart of the measures to be taken is the safeguarding of the vegetation cover and its restoration. In a work described by the authors as unique, FAO and ITPS [21] and L. Montanarella et al. [22] discusses soils in the context of food security and sustainable development, but points out the responsibility of erosion; salinization; acidification; compaction; chemical pollution and, above all, the loss of soil organic carbon as the main factors. -In trying to situate land degradation in Africa, P. Brabant [23] highlights the importance of erosion (hydric: 46 % and wind: 38 %) and situates anthropogenic, physical (4 %) and chemical (12 %) factors. Spontaneous deforestation or clearing of vegetation (14 %) could be the primary cause of all other anthropogenic factors (inappropriate agricultural practices: 24 %; overgrazing: 49 %; overexploitation of trees and shrubs: 13 %; bioindustrial activities: 0.4 %). Out of 90 % of the world's exploitable land, 74 % would be in Africa (68 % arable), while 85.4 % would be undegraded or slightly degraded. In a rather limited context, E. Roose et al. [24] believes that soil degradation is due to land clearing; (bush?) fire; overgrazing and others. This would lead to dead layers (topsoil) having a very important role in the development of biomass (roots, microfauna, microflora etc.), an essential element of soil balance. Erosion, an essential element in the accentuation and mobilization of the resulting products, includes several forms (sheet, linear, mass, mechanical and wind), several causes (raindrop energy, runoff, gravity, etc.) and various deposits (selective, non-selective, dunes, clouds, etc.). He believes that if the vegetation cover is complete, the weathering and erosion factors would be negligible. It's from an ecological point of view, whose non-management could affect the livelihoods of millions of people, that Publications Professionals LLC, Global Environment Facility [25] refers to the degradation of 500 million hectares of land in drylands. Eligible activities (technical assistance and capacity building) to address this issue include restoring or improving rangeland management to restore native vegetation (among others). In studying the impact of anthropogenic and climatic activities on vegetation and land use in the Bouregreg Basin (Morocco), Z. A. Tra Bi et al. [26] highlights a considerable drop in plant productivity following an accentuated degradation of the environment. The cause? He points to agro-pastoral activities and climatic variations which, according to him, under the same conditions, could cause the rain-fed agricultural production system to disappear beyond 2050. In the Isser basin (Algeria), M. Boughalem Kasmi [27] describes the vegetation cover as a protector against erosion. The studies conducted by M. Ouadraogo [28] in the Toussiana region (Burkina Faso) mention the destruction of the vegetation cover as a real problem in the ecosystem whose vulnerability is a real brake on economic development. In analyzing soil capital and institutional arrangements in agrosystems in northern Cameroon, O. Balarabé [29] mentions the importance of the dynamics of the organic matter stock in the context of the study of stationary states. In the Congo Basin (the second largest forest massif in the tropical zone after the Amazon), B. Tchatchou et al. [30] shows that the latter experienced a deforestation of 0.09 % between [1990 and 2000], or 0.17 % between 2000 and 2005. This increase would be due to: the opening up of certain regions for the establishment of infrastructures (Gabon and Equatorial Guinea); the development of agriculture (in Cameroon); logging; mining (943, 725 ha destroyed in Cameroon) etc.

In Guinea (1998), M.O. Bah et al. [31] reported that the vegetation areas and their proportions were: mangroves (250,000 ha, 1.02 %); dense humid forest (750,000 ha, 2.85 %); dense dry forest and open forest (1,600,000 ha, 6.51 %); wooded savannah (10,636,000 ha, 43.25 %); crops (1,500,000 ha, 6.10 %); fallow land and shrubby savannah (7,500,000 ha, 30.51 %) and others (2,400,000 ha, 9.76 %). This makes a total of 24,586,000 ha over the whole of the national territory. In Forest-Guinea, the dense humid forest has been cleared to such an extent that only 112,300 ha remain (Ziama forest); 64,000 ha (Diecké forest) and a few forests that are not very accessible or protected by custom. In Upper Guinea, between Faranah-Dabola-Kouroussa (Mafou forest) and Dinguiraye-Siguiri (Tinkisso valley), there are dense forests that are very sensitive to bush fires and difficult to regenerate. In the old agglomerations of Kankan and Faranah, as well as at the axes of circulation (road and river), the forest is cleared and the savannah burns more and more over time for several reasons (hunting, livestock, use of wood, local customs etc.). Middle Guinea, a very controversial region where it is very difficult to generalize about the degradation of vegetation cover. Similarly, it is not possible not to mention it, especially since in some areas the phenomenon is present. In Lower Guinea, the remaining forest on the coastal plain is found only in Forécariah (in Kaméléya) and the savannahs are often subject to large fires. The mangrove is threatened by rice cultivation, which could accelerate coastal erosion processes, irreversible soil acidification, etc. To address desertification, Ministry of Agriculture, Livestock and Forestry [32] is implementing a varied program adapted to each of Guinea's natural regions. At the heart of the proposals is the idea of restoring vegetation cover in degraded areas. -One of the programs aimed at restoring the damage done to nature in Guinea, notably the Tinkisso dam (Upper Guinea) which is said to have silted up considerably, is that of UICN [33]. This is a concrete case illustrating the consequences of soil degradation on structures. Deforestation, erosion, bush fires, internal dysfunctions (lack of water depending on the season, invasion by lake sand, decrease in flow rate, etc.) and external dysfunctions (disruption of ecosystems in the downstream floodplains) are the main causes of the dam. To complete this study and clarify the problem, Landsat data covering a period of 41 years [1980 to 2021] are used. Using remote sensing tools, GIS tools and manipulations, the variation of vegetation cover over in time and space are monitored. This allows accurate percentages of the subject's occupation and its temporal variation. The main characteristics of the soils are then elucidated using the geotechnical data collected for this purpose. This approach provides an effective basis for assessing the mechanical behavior of soils in relation to all the anthropogenic and meteorological stresses to which they are subjected.

The present study is divided into three main parts:

– The first part deals with the overall presentation of the subject, as well as the exploitation plan.
– A second part: which explains the scheme undertaken to achieve reliable and concrete results.
– A last one: which will allow to have an overview on the outcome of the work, its contribution, its projections, its magnitude and its singularity. It is also the place where, in a concise manner, all the ambiguities that undermined the issue will be removed. It will also be an opportunity to take stock of all the shortcomings that the subject might face for conceptual and temporal reasons. Additional projections will be made in order to elucidate in detail all the magnitudes of impact of the destruction of the vegetation cover on the soil.

## 2. Methods and materials

After the remote sensing phase which is followed by the GIS phase. This was carried out in several essential steps. One of the most important tasks of this study was to draw up a complete inventory of all the vegetation trends in Fouta, particularly along the Mali-Labé-Linsan axis. It was found that these trends are grouped into two main categories. These are herbaceous and arboreal. In these both groups, it has been ensured that both fresh and dry passes are included. To create an appropriate contrast, an assimilation was made with other soil-related entities. This gave rise to nine classes: wooded forest, coniferous forest, dry vegetation, fresh grass, grassy areas, cemeteries, soil-sand-mineral compound, agricultural areas and all other forms of grass and trees. All these units were digitized. From the vectors, a series of manipulations followed. The literature review allowed to classify the subjects according to treatments similar to the study's problematic. To acquire LANSAT data (Table 1), ENVI software, combined with G. Explorer, was used.

It is a multitude of tasks that require certainty and relevance in the search for objects (29 folders, each with 7 strips) which, from the outset, must be well targeted and verified even once they are framed. The present approach consists of establishing a grid over the entire Fouta Djallon perimeter (which was used until the percentages of variation of each class of plant cover between 1980 and 2021 were obtained), from which the grid covering the work on the Mali-Labé-Linsan axis was extracted. This approach enabled a precise geocoding to be chosen (by downloading the appropriate KMLs), which automatically generated the precise working limits, as well as all the coordinates and projections that go with them. For better visibility, the data was used during periods not covered by atmospheric bad weather. In order to process the images and obtain the first results, GIS tools (Global Mapper, MapInfo and ArcGIS) were used. To succeed in this operation, a certain procedure must be followed, the steps of which are interdependent and cover: the composite phase (compressing all the LSTs into a single TIF); the RGB management phase (which is very important and defines the final appearance of the map to be drawn. It is necessary to choose the best combination of bands (which is the 7,4,2 for this case); the clipping phase (to reduce the study to the real perimeter to be exploited); the reclass phase (to allow to prepare clipped TIF to be subjected to all possible digitization). Without it, the rest is very difficult, or even impossible). The vectorization phase (it allows you to obtain your classes in separate ways and to be able to touch them). The attribute table management phase (this is the ultimate stage for obtaining the numerical attributes for each of your classes); The calculation phase (you have the possibility to calculate areas, perimeters and other desired factors for each of your classes) and the final phase is the establishment of the map (content, title, scale, author, legend, north, coordinate system and projection, as well as the grid). In-situ and laboratory geotechnical data are acquired by probes, a Casagrande device and an oedometer. The international standards related to the parameters cover: water content (NF P94-050); particle size analysis (NF P94-056); Atterberg limits (NF P94-068); specific weights, apparent and absolute densities (NF P 94-053/NF P 94-053, 94-064); direct rectilinear shears (NF P 94-071-1) and oedometer compressibility (NF P 94-090-1). All statistical management was carried out using a combination of ArcGIS and Excel. It consisted in the 2D representation of the variation in time of the physical quantities of each class.

**Table 1**
Landsat images used for mapping campaigns in Mali-Labe-Linsan axis.

| LANSAT | Images |
|---|---|
| LST 05 | LT05-L2SP-201052-19860112 |
| LST 07 | LE07-L2SP-201051-20000111 |
| | LE07-L2SP-201051 |
| | LE07-L2SP-201052 |
| | LE07-L2SP-201053 |
| LST 08 | LE08-L2SP-201052-20210317 |
| | LE08-L2SP-201052-20210328 |
| | LE08-L2SP-201052-20210402 |
| | LE08-L2SP-201052-20210409 |

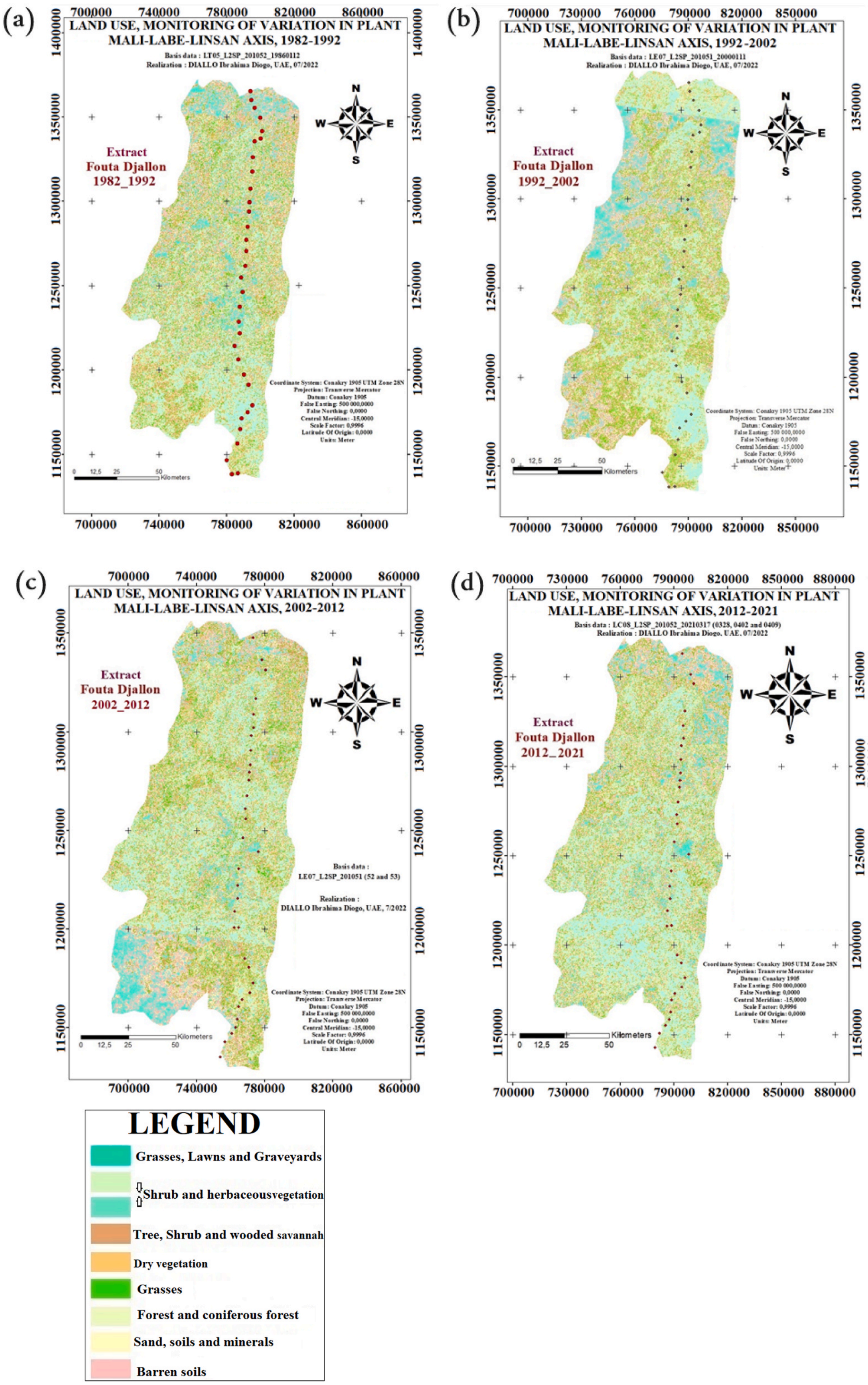


**Fig. 1.** Land use map on the Mali Labé Linsan axis. **(a)**: progress between 1982 and 1992, **(b)**: progress between 1992 and 2002, **(c)**: progress between 2002 and 2012 and **(d)**: progress between 2012 and 2021.

## 3. Results and discussion

### 3.1. Mapping the variation in time and space of the different classes

To understand the maps produced as a result of cartography, it is necessary to go back to the way they were acquired, and all the intermediate phases that followed their production. Each of these stages remains crucial and decisive. Remote sensing explorations are the starting point. They were carried out as meticulously as possible, with the aim of not missing a single detail. The initial images on which the manipulations were based were the object of consultation of data from several satellites. The final results were those of satellites LT05, LE07 and LE08, with all the annual ramifications that characterize them. These cover the entire perimeter to be treated, and include strips that are legible despite nature's inclemency over time. As the motivation behind the images was to extract all information relating to plant cover (herbaceous and arboreal), bands 1,2,3 then 1,4,5 and those 1,4,7 were examined. The last association was the most common. The combination of bands to obtain the R, G, B to be used next was 7,4,2. As well as producing enormous detail on vegetation in general, it brings to the fore several other entities, including soil, minerals or sand. It was on this basis that all map digitizing work was based for the remainder of the GIS manipulations.

The different classes processed by the remote sensing and mapping operations cover vegetation cover (fresh and dry, in all its possible classification); barren soil, as well as inorganic cover (soil, inorganic minerals and sand). These data are presented in a set of four maps (Fig. 1(a–d)) with the same legend, but with differences in attribute sizes.

### 3.2. Statistical study and temporal follow-up of the proportions of the different classes

The nine classes studied and condensed into four groups, show variable proportions in time and space. Their statistical representations are shown in Fig. 2(a–d).

### 3.3. Geological nature and geotechnical characteristics of some soils on the Mali Labé Linsan axis

In order to understand the quality of the land under the mapped vegetation covers presented in the previous paragraph, six geotechnical borings were carried out. The samples ($E_iS_i$) analyzed are taken from the depths requiring reinforcement. The different elements reflecting the geological natures and mechanical behavior of the soils are represented in the table below (Table 2).

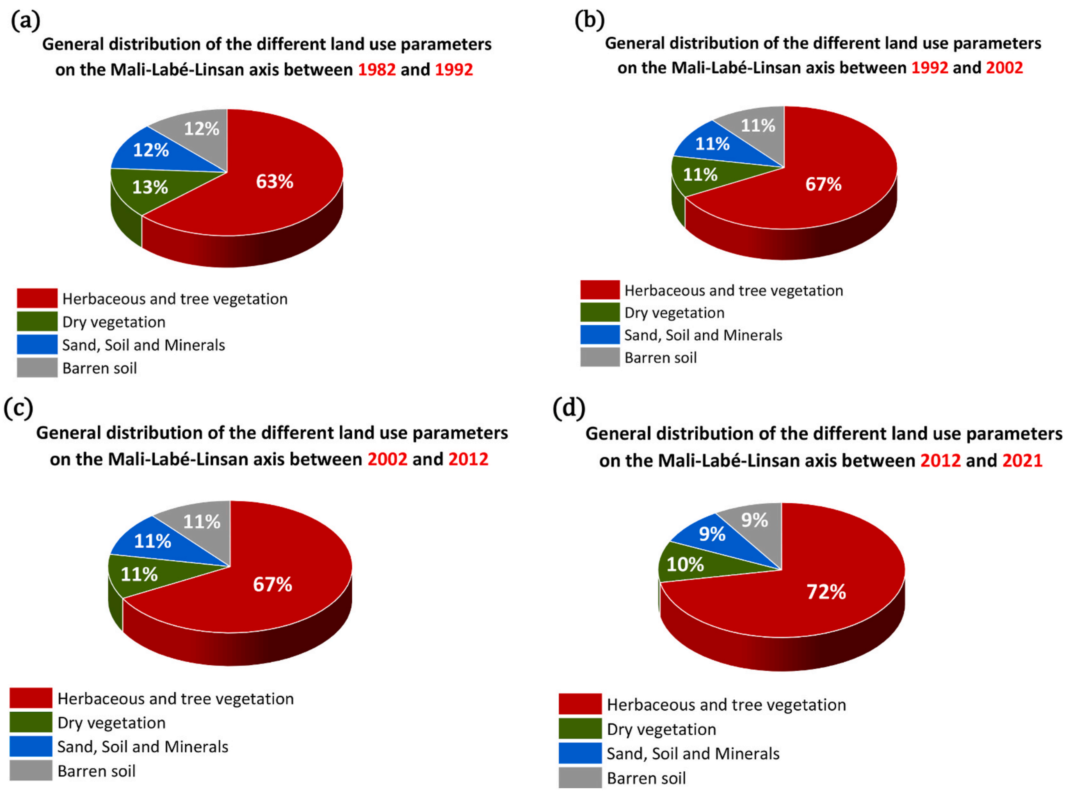


**Fig. 2.** Statistical distribution of the nine (9) land use study classes on the Mali Labé Linsan axis between 1980 and 2021 **(a):** Land use variation between 1982 and 1992; **(b):** Land use variation between 1992 and 2002; **(c):** Land use variation between 2002 and 2012 and **(d):** Land variation between 2012 and 2021.

### 3.4. Discussion

Several factors have been identified as contributing to soil degradation in Guinea. Broadly speaking, they fall into two categories: the first is meteorological impacts. The second deals with human impacts. Overall, it should be noted that in the first category, rainfall plays a considerable role. This often manifests itself in water erosion, as well as increased humidity, which has a huge impact on infrastructures, especially roads. In the second case, a number of human activities are encountered that could accelerate degradation. Among the most relevant of these are electricity infrastructure, with lines stretching for hundreds of kilometers, and real estate and land management not covered by the state. These factors impact biodiversity without any rehabilitation program. Further on, anthropogenic factors accelerate the effects of meteorological ones.

Over and above the contribution of variations in time and space, the present study provides broader specificities. Several researchers agree that remote sensing, GIS and geotechnology are today the best tools for identifying soil degradation and devising ways of counteracting or eliminating it. B.R. Evans et al. [34] presented a combination of the vegetation-geotechnical intersection to understand the degradation of salt marshes. Their approach exposes a number of scientific limitations. While on the Mali-Labé-Linsan axis, the emphasis is on geotechnical understanding of how variations in vegetation cover can adversely affect the physical properties of the soil, and hence its mechanical behavior, here vegetation is treated on a smaller scale. The presence of halophytes shows that vegetation type plays a considerable role in sediment stability. Shear strength is greater in vegetated areas. Bare and coarse areas are more exposed. Further on, the latter are more exposed to the hydric and wind erosion observed in Middle Guinea in general, and in the axis studied in particular. A. M. de Rosa Ferraz Jardim et al. [35] have demonstrated the extent to which the combination of land use, vegetation cover variation and climate change can have an impact on biodiversity. This study, carried out in the north-eastern Caatinga region of Brazil, shows that the combined use of remote sensing and GIS over time and space can provide instructive information for monitoring changes in vegetation cover (among other things). Between 1993 and 2019, several fluctuations were observed. In 2013, the area surveyed was 70.2 % covered, but by 2015 this had dropped to 67.8 %. The year 2015 will be marked by a constant 67.8 %. Over a large part of the area studied, rainfall was significant in 2013, with records of 480 mm, a minimum of 270 mm and an average. On 46.5 % of the area surveyed, a column of 410 mm was recorded. Rainfall in 2017 was among the lowest, with columns ranging from 200 mm to 340 mm. This is marked by low land cover, with vegetation cover only on a maximum of 25 % in almost 52.3 % of the surveyed area. This exposes the area to severe drought, with temperatures reaching 52oc in 40.5 % of the region in 2013. A closer

**Table 2**
Geological nature and mechanical parameters of some soil samples on the Mali Labé Linsan axis.

| S1 | S2 | S3 | S4 | S5 | S6 |
|---|---|---|---|---|---|
| E1S1: ]0.41m-3.40m[ Lateritic armour (sometimes laterite) | E1S2: ]0.31 m 4.00 m[ Lateritic armour blocks (sometimes clay laterite) | ]0.071m-6.00m[ More or less fractured lateritic armour | E1S4: ]0.121m-3.00m[ Gravelly laterite with blocks of armour. | E1S5: ]1.36m-1.66m [ Lateritic clay loam | E1S6: ]0.11m-4.00m[ More or less porous reddish lateritic armour with pockets of clay |
| E2S1: ]3.41m-4.71 m[ Low clay loam (sometimes lateritic concretions) | E2S2: ]3.41 m et 4.71 m[ Silty clay (lateritic concretion trends to compact silty clays) | | E2S4: ]3.01m-4.50m[ Clay with lateritic concretions | E2S5: ]2.01m-6.00m [ Lateritic armour with clay laterite | E2S6: ]4.01m-5.00m[ Clay with variegated lateritic concretions |
| E1S1: PL = 2.31 MPa et E = 187.52 MPa. E2S1: PL = 2.25 MPa et E = 24.34 MPa. | E1S2: PL = 2.30 MPa et E = 95.61 MPa. E2S2: PL = 1.68 MPa et E = 24.87 MPa. | PL = 2.26 MPa. E = 88.93 MPa. | E1S4: PL = 0.56 MPa. E = 10.27 MPa. E2S4: PL = 0.62 MPa. EL = 11.65 MPa. | E1S5: PL = 0.69 MPa. E = 3.24 MPa. E2S5: PL = 2.30 MPa. E = 142.98 MPa. | E1S6: PL = 1.72 MPa. E = 14.69 MPa. E2S6: PL = 1.38 MPa. E = 11.34 MPa. |
| E1S1: $\gamma_h = 2.00$ t/m$^3$; γd = 1.96 t/m$^3$ et C′(-MPa). Φ' (-MPa). E2S1: $\gamma_h$ = 1.77 t/m$^3$; γd = 1.75 t/m$^3$; C' = 19.33 MPa et Φ' = 35.30 MPa. | E1S2: $\gamma_h$ = 1.98 t/m$^3$ γd = 1.93 t/m$^3$. C′ (-MPa). Φ' (−). | $\gamma_h$ = 2.15 t/m$^3$ γd = 2.01 t/m$^3$. RC = 11,01 MPa. | E1S4: $\gamma_h$ = 1.92 t/m$^3$ γd = 1.88 t/m$^3$. C' = 20.43°. Φ' = 24.70°. E2S4: $\gamma_h$ = 1.89 t/m$^3$ γd = 1.81 t/m3. C' = 20.17 Kpa. Φ' = 28.60°. | E2S5: $\gamma_h$ = 2.3 t/m$^3$; γd = 2.24 t/m$^3$ et C' = 10.17 MPa. | E1S6: $\gamma_h$ = 1.93 t/m$^3$; γd = 1.90 t/m$^3$ et RC = 9.44 MPa. |
| E1S1: B (29° à 38°). A (18.4° à 26.8°). E2S1: B (29° à 38°). A (18.9° à 27.0°). | E1S2: B (29° à 38°). A (20.8° à 27.4°). E1S2: B (29° à 38°). A (20.6° à 27.3°). | B (35° à 46°). A (26° à 28°). | E1S4: B (29° à 38°). A (17.6° à 26.4°). E2S4: B (29° à 38°). A (18.1° à 26.7°). | E2S5: B (35° à 46°). A (26° à 28°). | E1S6: B (29° à 38°). A (20.6° à 27.6°). E2S6: B (29° à 38°). A (23.8° à 27.6°). |
| Minimum load-bearing capacity: E1S1 = 318 Kpa et E1S2 = 329 Kpa. | Minimum load-bearing capacity: E1S2 = 388 Kpa et E2S2 = 393 Kpa. | Minimum load-bearing capacity = 788 Kpa. | Minimum load-bearing capacity: E1S4 = 291 Kpa. E2S4 : 306 Kpa. | Minimum load-bearing capacity: E2S5 = 806 Kpa. | Minimum load-bearing capacity: E1S6 = 440 Kpa et E2S6 = 474 Kpa. |
| Net critical load-bearing capacity: E1S1 ≥ 250 Kpa. E2S1 ≥ 250 Kpa. | Net critical load-bearing capacity: E1S2 ≥ 250 Kpa. E2S2 ≥ 250 Kpa. | Net critical load-bearing capacity ≥ 400 Kpa. | Net critical load-bearing capacity: E1S4 ≥ 250 Kpa. E2S4 ≥ 250 Kpa. | Net critical load-bearing capacity ≥ 400 Kpa. | Net critical load-bearing capacity: E1S6 ≥ 400 Kpa. E2S6 ≥ 400 Kpa. |

**NB:** TN: Natural Terrain; γh: Wet density; γd: Dry density; Rc: Simple compressive strength; C: Soil cohesion; Em*: Pressiometric modulus; Pl*: Limiting pressure; A and B: Soil classes assigned to their angles.

examination of the arguments put forward by Y.C. Wang et al. [36] reveals that the Mali-Labé-Linsan approach goes beyond its main stated objective. The large Fouta Djallon region that hosts the area of the present study is well known for its metalliferous potential. Among the most recurrent are iron, aluminium and gold. The exploitation of the latter has led to a considerable degradation of the vegetation cover in the Kounsitel area (part of the route studied). This activity is accompanied by the use of non-conventional products, considerably destroying biodiversity and increasing soil erodibility. An analysis of the variation in vegetation cover in this area is particularly relevant. Any lack of vegetation increases the degradation of nature, as well as the drying up of watercourses. During rainy seasons, metal drainage can cause enormous contamination. The presence of plants considerably reduces this effect. D. C. Refati et al. [37] provide an update on soil degradation, using a multidimensional scenario. The authors combined drought, anthropogenic factors through land use and land cover variation. In a semi-arid region of Brazil, they argue that human activities and meteorological effects have a considerable impact on soil degradation. To achieve this, they combine remote sensing images and GIS. The result is a loss of 9.33 % of the total vegetation cover in the analyzed area, and a low water availability of 2.24 %. As in Middle Guinea, particularly on

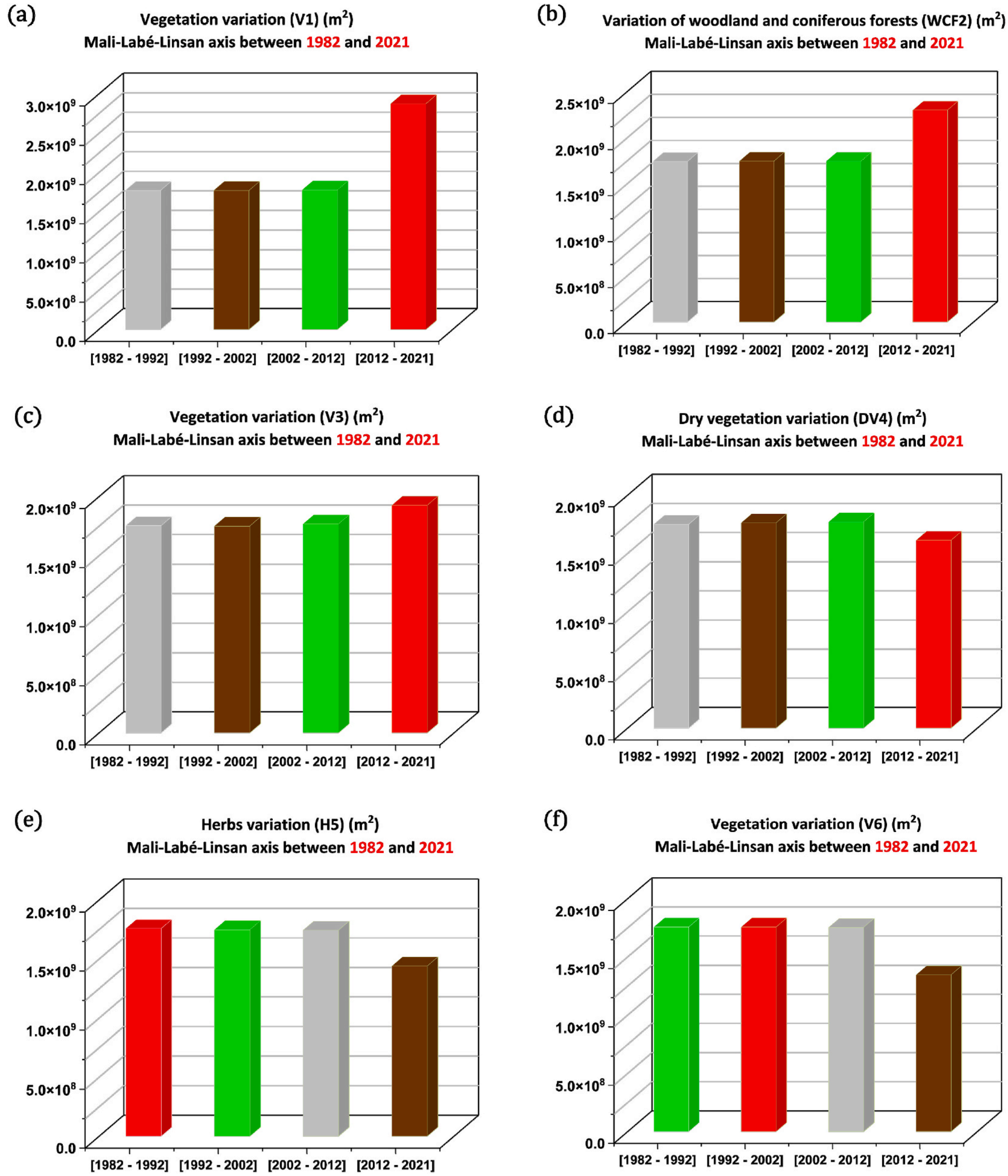


**Fig. 3.** Temporal variation of the different land use study units on the Mali Labé Linsan axis **(a)**: fresh vegetation; **(b)**: wooded and coniferous forests; **(c)**: other fresh vegetation; **(d)**: dry vegetation; **(e)**: fresh herbs; **(f)**: vegetation covers fresh; **(g)**: soils, sand and mineral; **(h)**: sterile soil cover and **(i)**: herbs, cemeteries, grass etc.

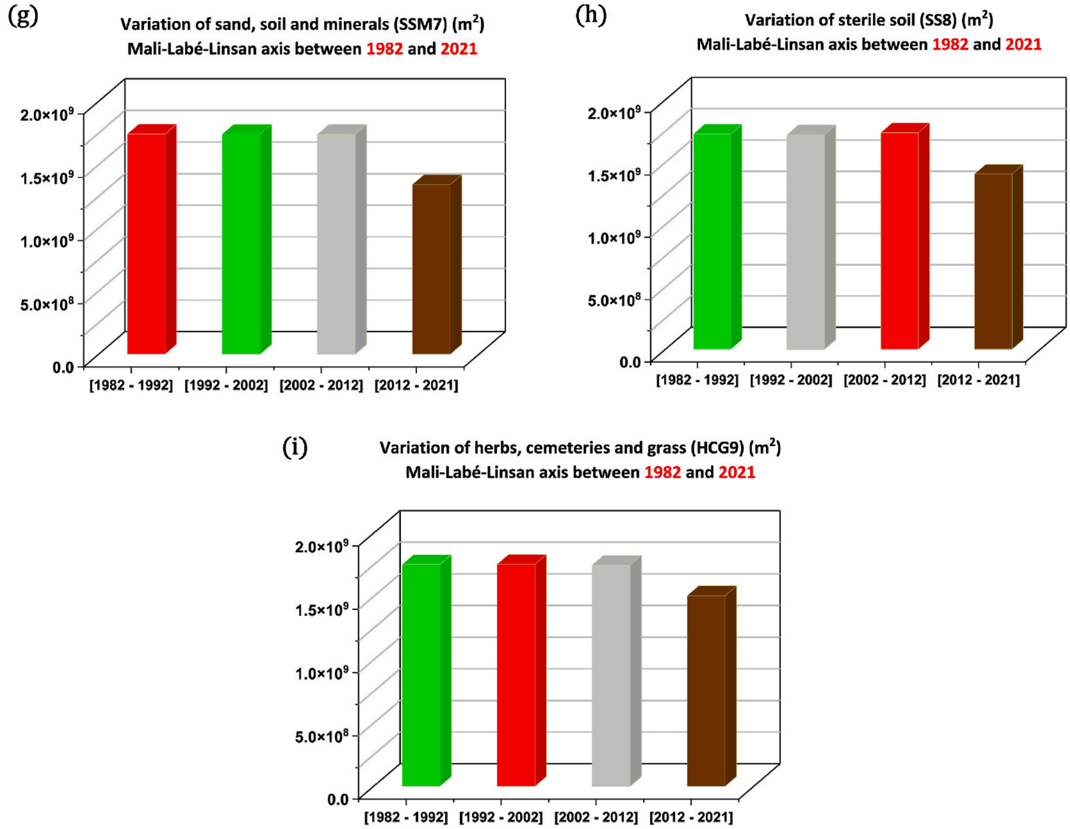


**Fig. 3.** (*continued*).

the Mali-Labé-Linsan axis, industrial activities (mainly electricity), agriculture, livestock farming and anarchic land use had a considerable impact on the variation in vegetation cover over time and space. Any deficiency in the latter would lead to optimization of erosive reasons, as well as water and wind. D. Cazzuffi et al. [38] presente a study on the treatment of vegetation as a geotechnical stabilizer. The Mali-Labé-Linsan axis is part of a considerable mountainous network, often with slopes. The understanding of the variation of vegetation cover in the exploited area allows to identify the areas subject to degradation factors, and possibly to envisage setting up a geo-stabilization program in the near future. Low slopes, as the authors point out, can easily benefit from vegetation cover campaigns to reduce the risk of landslides or erosion (water and wind). J. da Silva Cruz et al. [39] emphasize the digitization of land cover and land cover variation using the predictive curve. The authors proposed a predictive and very concise approach that tracks these parameters over time and space. They simulate their study over a 40-year period, starting in 2009. Their results show that, by calibration, several similarities in values were all greater than 50 % for the models in each basin. The Tapajós model was 40 % in spatial resolution of 255 m. Validation of the values will vary widely. It varies for a spatial resolution of 255 m, with ranges from 36 % to 76 %. In terms of forecasting, by 2024, they stipulate that the surface area of high CN will experience strong growth. This will be caused by due to forest conversion to pasture/agriculture, with a strong implication of larger runoff and flooding. It is also important to take into account the growth of urban areas. This work supports the present study on the Mali-Labé-Linsan axis. Digital technology is a powerful tool for monitoring land use and assessing any degradation that might accompany it. GIS and remote sensing are at the heart of this approach. P. M. Crivelari-Costa et al. [40] provide a carbon dioxide balance in relation to land use in the Amazon. The tool used to obtain these results is a combination of remote sensing and GIS. In this largest vegetated portion of the planet, $CO_2$ emissions and absorptions are anything but linear. These changes are strongly linked to variations in land use and land cover. Satellites are a very useful tool for assessing $CO_2$ variations. The authors agree that forests should absorb 211.05 TgC each year. However, there are a number of constraints to this assessment. These include partial conversion to other land uses, resulting in the loss of 135,922.34 $km^2$ of forest area. This will result in 5.82 TgC carbon less being absorbed. Pasture and agriculture, have strongly impacted land conversions, increased by 100,340.39 $km^2$ and absorbed 1.32 and 3.19 TgC less. Emissions increased twice as much in the area. An increase in $CO_2$ quantities was observed. It ranges from 2.2 to 2.8 ppm annually in BLA. Hotspots were also observed in the southeast of Amazonia. It should be noted that the decrease in vegetation cover is necessarily accompanied by an increase in the weight of water and wind erosion. An approach that uses more than 80 % of the logic used in Middle Guinea to assess soil degradation. Geotechnical differences and analyses of $CO_2$ variation provide an opportunity for further complementarity. In this region of Guinea, it would be useful to assess variations in the spatial and temporal uptake of carbon dioxide by vegetation, in order to monitor the rational variation of the latter, and to assess any soil degradation that might result. Placed at the heart of this multidimensional problem, the variation in plant cover that the present study is concerned with translates into plural detail. Nine entities have been treated, with the aim of not missing any sensitivities that might omit a real conclusion on the harm that human or climatic impacts might have on the soil. The realities dealing with the temporal and spatial evolution of the nine classes show a tendency to be very cautious before pronouncing on the different variables (Fig. 3(a–i)). A targeted and specific analysis of each of them is essential.

The present study will follow the pattern advocated, which presents a best approach to define each variable and attribute its true characteristics before placing it in its regional context.

- This's a total of 177,257,3345 ha that were covered by crops between [1982–1992]. This value reached 177,271,8081 ha between [1992–2002], an increase of 14,4736 ha. This coverage will drop sharply to 177,818,9145 ha between [2002–2012], representing a decrease of 547,1064 ha. The period between [2012–2021] is marked by an occupation of 287,598,5975 ha, marking a surplus of 109,779,6830 ha. Overall, there are two positive periods (2002 and 2021, which could be explained by the social, state, associative and NGO involvement in regional agricultural development programs, notably cash crop production covering mainly potatoes, onions and tomatoes, in Timbi Madina, Dalaba, Labé, etc.) and one negative one (2012).
- Mangrove coverage was 175,608,4697 ha [1982–1992], compared to 175,610,7127 ha [1992–2002], an increase of 2,2430 ha. The period [2002–2012] reached 175,272,5071 ha, marking an increase of 338,2056 ha. The period [2012–2021] saw a drop of 40,760,0465 ha to 134,512,4606 ha. These trends reflect two phases of growth (2002 and 2012) and a very marked decrease (2021), which could be explained by the sudden invasions of the rivers and the flagrant changes in their regimes recorded in recent times on the axis. This is the case in the Kounsitel gold zone where the only traces of water remaining are reddish with the almost total disappearance of the trees that bounded them.
- Fallow land has fluctuated remarkably between 1982 and 2021. They covered 175,275,9917 ha between [1982–1992]. This trend will decrease between [1992–2012], reaching 174,998,8957 ha, a decrease of 277,0960 ha. A curve that will completely reverse from 2012 to 2021, since it will cover 176,746,0863 ha [2012–2002], with a growth of 1,747,1906 ha, against a coverage of 192,581,0633 ha between 2002 and 2021, for an increase of 15,834,9770 ha.
- Woodland and coniferous forests occupied 174,402,4661 ha between 1982 and 1992. They increased by 528,8396 ha between 1992 and 2002 to 174,931,3057 ha. This trend will be reversed between [2002–2012], with an occupation of 174,675,6317 ha, marking a decrease of 255,6740 ha. The period between 2012 and 2021 saw a very positive trend, reaching 230,064,0807 ha, reflecting a growth of 55,388,4490 ha.

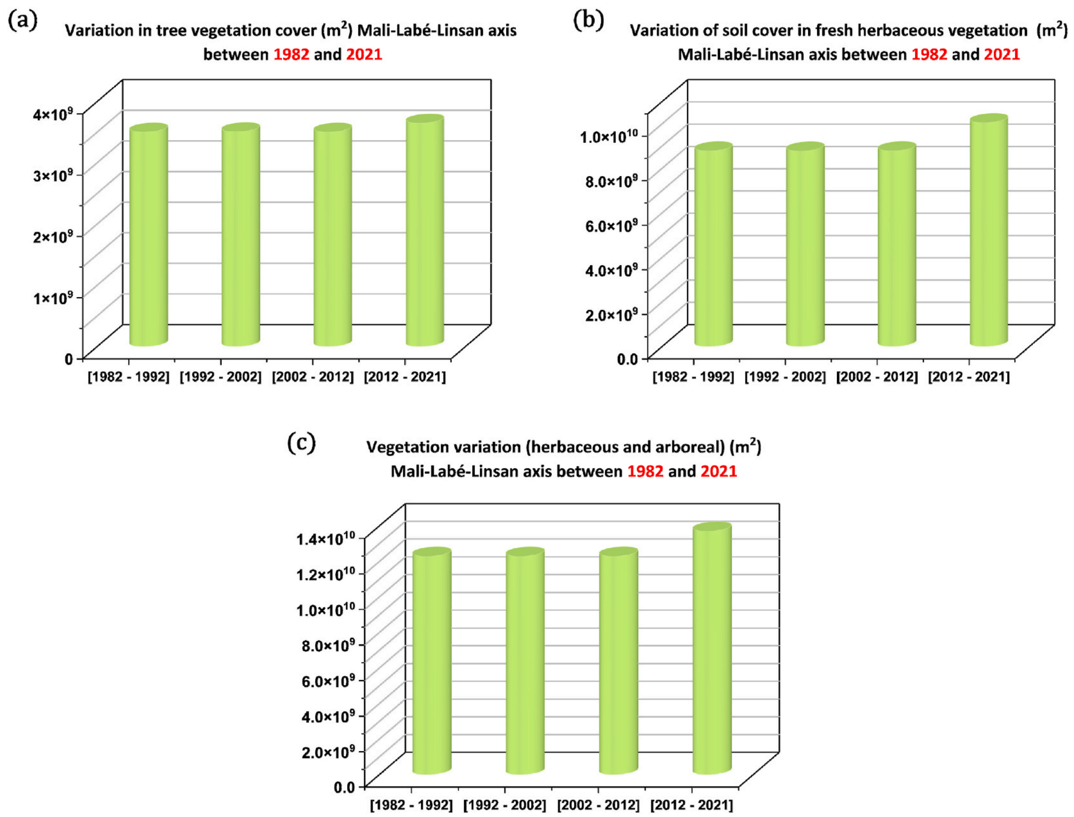


**Fig. 4.** General trend in vegetation cover on the Mali Labé Linsan axis, between 1982 and 2021.

– Dry vegetation was 174,901.8783 ha between [1982–1992]. It reached 176,193.5058 ha between [1992–2002], an increase of 1291.6275 ha. Between [2002–2012], it increased to 176,974,2402 ha, or 780,7344 ha. This encouraging pace will decrease in the horizon [2012–2021] and reach 161,171 8244 ha, i.e., a decrease of 15,802 4158 ha.
– While between [1982–1992] grasses covered 175,815.8062 ha, for the periods [1992–2002]; [2002–2012] and [2012–2021], they occupied respective coverages of 174768.7815 ha; 174,312.6717 ha and 144,038.2593 ha, with respective decreases of 1047.0247 ha; 456,1098 ha and 30,274.4124 ha.
– The sand, soil and mineral complex covered 174,181.3970 ha between [1982–1992]. This will decrease to 174,048.6045 ha visible, or 132,7925 ha camouflaged by [1992–2002]. This could be explained by the fact that the majority of plant variants grew in this period (2002) and covered their supports. Then, the same trend continues between [2002–2012], it approaches 1,738,252,268 $m^2$, a second decrease of 2,233,777 $m^2$ that prevents its outcrop. Between [2012–2021], the most significant decrease in the lot is observed which results in an occupation of 134,182.7907 ha and a decrease of 39,642.4361 ha.
– The cover occupied by barren soil has fluctuated several times. Between [1982–1992], it occupied 172,658.8462 ha of the axis. A value that will fall between [1992–2002] to reach 172,121.0470 ha and reflect the 537.7992 ha decrease. The period [2002–2012] saw an increase in coverage to 173,727,3033 ha, a surplus of 1,606,2563 ha. Between [2012–2022], a second decrease, this time exponential, is recorded and materializes in 140,581 6828 ha, for a difference of 33,145 6205 ha.
– The other components reflecting cemeteries, grass, other grasses etc., occupied 175,222.2741 ha between [1982–1992]. They reached 175,367.3126 ha between [1992–2002]. A trend that was marked by decreases in the intervals [2002–2012] and [2012–2021], with respective areas covered of 174,707.5823 ha and 150,550.5038 ha. These transitions mark respectively: a drop of 145,0385 ha in 2002; a drop of 659,7303 ha in 2012 and 24,157,0785 ha in 2021.

A better view of these different variations is provided in Fig. 3(a–i) below. It allows one to analyze each of the nine (9) entities, understand their evolution (positive and negative) and situate their proportions in time and space. It is the logic that offers the possibility of effectively projecting the shared responsibilities of each of them and understanding their place once placed in the overall context that covers all the classes.

The general trend in vegetation cover in a region should not be confused with the local trend in a project itself. In the previous paragraphs, it was illustrated that each vegetation class (grasses, trees, fallow, mangroves, crops etc.) has undergone huge fluctuations (sometimes positive and sometimes negative) between 1982 and 2021, while in reality, taken as a whole, the vegetation cover shows a positive trend (Fig. 4(a–c)).

Over the six (6) boreholes, the 10 samples show a different lithology according to the depth profiles, and specific physical characteristics and mechanical behavior. On the same borehole, depending on the slope to be interpreted, the density, cohesion, limit pressures, friction angles and bearing capacities are not the same. This can be explained by the fact that the facies:

– do not have the same chemical and mineralogical elements from which atomic, structural and textural arrangements remain which have different sensitivities;
– are not necessarily subject to the same constraints over time and with the same intensity;
– are not subject to the same factors;
– do not withstand the same degradation factors for the same periods of time;
– do not have the same structural features and/or are not at the same topographic levels.

The different trends of the nine (9) classes between 1982 and 2021 show a gain for some (positive trend) and a loss for others (negative trend). The overall visibility of all units is summarized in Table 3 below.

All these criteria allow, each in its own way, to play a primordial role in the destruction of the initial state of formation of the soils (its degree and its fate).

The different foundations (slab/concrete/grating) are chosen considering all these parameters, all possible factors (anthropogenic and meteorological), the sensitivity of the soil to the stresses at each depth, as well as all the future projections that should ensure a better durability of the electricity pylons. The problems affecting the social and economic situation of people on the Mali-Labé-Linsan route (Fig. 5 (a,b)), which were observed and experienced during the field mission in 2022, are numerous.

Among the most relevant is the degradation of the land, which causes certain activities to slow down considerably or to be held

**Table 3**
Monitoring of trends in the different classes of the land use study on the Mali Labé Linsan axis.

| Class | Height (ha) | Tendancies | Verdict |
|---|---|---|---|
| V1 | 109,247.0502 | Positive | Encouraging. Dynamics to be reinforced. |
| FBC2 | 55,661.6146 | Positive | Encouraging. Dynamics to be reinforced. |
| V3 | 40,419.5979 | Negative | Destructive. Review its management policy. |
| VS4 | 13,730.0539 | Negative | Encouraging. Dynamics to be reinforced. |
| H5 | 31,321.4371 | Positive | Dynamics to be converted into a useful social factor. |
| V6 | 17,305.0716 | Positive | Encouraging. Dynamics to be reinforced. |
| SSM7 | 39,998.6063 | Negative | Attributable to V1, V3, V6 et H3. |
| SS8 | 32,077.1634 | Negative | Destructive. Enhance for social use. |
| HCG9 | 24,961.8473 | Negative | To be followed closely. |

back for long periods. This's the case of the impassability of certain roads and the collapse of certain bridges. Several factors are cited as being responsible. Among the most recurrent, there is the destruction of the vegetation cover which is indexed as a fundamental cause. However, before the present study, no other study had taken the trouble to address the problem in depth, from the multiple causes to the evaluation of the consequences.

## 4. Conclusion

The present study shows that the destruction of vegetation cover can be a basis for reinforcing the impact of wind and water factors on the degradation of the soil and/or some of the structures it supports, but that its positive variation does not necessarily mean that it is a driving force that can reduce the damage. If damage is recorded, it takes longer to restore it. Therefore, this paper highlights the need for geoscientific analysis and geotechnical provisions to deal with all such issues, especially in a world where structures are built on marine coasts, supported by shifting sand. The idea of dealing with the issue at its source is better than making provision after the damage has been done.

On this basis, it is important to protect the vegetation cover of the soil and to accompany all projects where local environmental degradation is unavoidable with a lateral restoration program. This has direct and positive impacts on both the sustainability of the structures and the fertility of the land (for agricultural use). Two hypotheses that can be understood by the scenario according to which, by photosynthesis, achlorophyllous plants absorb $CO_2$ and $H_2O$, then produce organic matter by releasing $O_2$ according to the equation: $6CO_2 + 12\ H_2O > C_6H_{12}O_6 + 6O_2 + 6H_2O$. The water comes from the soil and is transported by the root bean. Some of the carbohydrates formed provide the environment with the energy it needs to grow and some are stored in the soil grains (oxygen is released into the environment) which contains other chemical elements that are largely present in the micro-organisms. This's the case for nitrogen, which allows vegetative growth, produces succulence and the (green) color of the leaves; phosphorus allows plants to develop rapidly, improves their resistance to low temperatures and diseases (for some), and increases the efficiency of water use; potassium contributes to the growth of the plant, its fruiting, ripening and the quality of its fruits. In addition to playing a considerable role in the plant's resistance to pests and diseases, drought, hail, etc., it's also an important element in enzyme activation, protein synthesis, carbohydrate synthesis, water balance, photosynthesis and meristematic growth. Protecting this biodiversity is of great help in maintaining the stable (formative) state of the soil.

A positive change in the trend of vegetation cover does not mean that the soil is not degraded, let alone that it's stable over time. The geotechnical contributions sufficiently illustrate the approach to be taken to guarantee durable structures over time. The results of the analyses carried out on the boreholes show vertical levels with different lithologies and mechanical realities, as well as net critical bearing capacities that range from [250 Kpa-450 Kpa]. A perfect match of these magnitudes with some physical and mechanical data for the same samples (such as angle of uplift, weight by volume etc.) allows to suggest slab and concrete/grating foundations. The embedment depths of the latter, on all 11 samples, are distributed as follows: E1S1 and E2S1 (at least 5 m), E1S2 and E2S2 (at least 4 m), ES3 (at least 3.5 m), E1S4 and E2S4 (at least 4 m), ES5 (at least 5 m), E1S6 and E2S6 (at least 4 m).

A better way to explore remote sensing would have been to acquire images using drones that could be manipulated in the field. This would have provided more precise data, with possible combinations in the infrared. This study is limited to satellite data. The mapping of vegetation cover in time and space, coupled with the geotechnical sounding campaign, removes any ambiguity about the indexation made on soil degradation in relation to the destruction of green spaces. It's an effective way of qualifying soil quality. However, on closer inspection, this combination does not allow us to visualize the resulting discontinuities in three dimensions.

The fieldwork revealed several underground cavities. This phenomenon could spread over larger areas. The best way to observe it goes beyond any surface investigation, remote sensing, GIS or vertical soil analysis. A tomographic approach coupled with micro-structural analysis is recommended. The former will highlight any deep depressions. The second will pinpoint the real reasons for any degradation, which could be chemical. Identifying degradation factors, knowing the physical and mechanical parameters of the soil, is a set of operations that are all necessary. But more important is to take precautions so that the damage is limited. In the same vein, it is very difficult to say today how much erosion (hydric and wind erosion: classifying them and quantifying their actions) has caused on the lands of the axis studied. This is a dynamic to be encouraged in future projects.

## CRediT authorship contribution statement

**Ibrahima Diogo Diallo:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Amine Tilioua:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Chakib Darraz:** Writing – review & editing, Visualization, Investigation. **Amar Alali:** Writing – review & editing, Investigation. **Diaka Sidibe:** Writing – review & editing, Investigation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


**Fig. 5.** Some heavily degraded structures (a: Mali-Labe and b: Labé).

## References


[1] J. Quense, Changement climatique et dynamique de la végétation dans les Andes du Chili central, depuis le milieu du XXème siècle : l'exemple de la vallée de Yerba Loca. Hal (2011), Thèse de doctorat, Université de Grenoble, 2011. Français. NNT: 2011GRENV036. tel-00639115, https://theses.hal.science/tel-00639115/file/Jquense.pdf.

[2] Nations unies, changements climatiques, un. https://www.un.org/fr/global-issues/climate-change.

[3] FJO et R. Defrance, L'ilet du Gosier victime de l'erosion, Guadeloupe 1 (2023). https://la1ere.francetvinfo.fr/guadeloupe/l-ilet-du-gosier-victime-de-l-erosion-1396986.html.

[4] H. Xiong, C. Ma, Minghong Li, J. Tan, Y. Wang, Landslide susceptibility prediction considering land use change and human activity, A case study under rapid urban expansion and afforestation in China, Science of The Total Environment journal 866 (2023), 161430, https://doi.org/10.1016/j.scitotenv.2023.161430.

[5] R.P. Quevedo, A. Velastegui-Montoya, N. Montalván-Burbano, F. Morante-Carballo, O. Korup, C. Daleles Rennó, Land use and land cover as a conditioning factor in landslide susceptibility: a literature review, Landslides 20 (2023) (2023) 967–982, https://doi.org/10.1007/s10346-022-02020-4.

[6] Y. Gao, Z. Li, W. Cui, D. Sun, H. Yu, Effect of initial void ratio on the tensile strength of unsaturated silty soils, Acta Geotech journal (2023), https://doi.org/10.1007/s11440-023-01800-z.

[7] W. Hassan, M.F. Raza, B. Alshameri, A. Shahzad, M.H. Khalid, M.N. Nawaz, Statistical Interpolation and Spatial Mapping of Geotechnical Soil Parameters of District Sargodha, Pakistan, Bulletin of Engineering Geology and the Environment, 2023, p. 37, https://doi.org/10.1007/s10064-022-03059-2, 82.

[8] P. Tarolli, A. Pijl, S. Cucchiaro, W. Wei, Slope instabilities in steep cultivation systems, Process classification and opportunities from remote sensing, Land Degrad. Dev. 32 (3) (2020) 1368–1388, https://doi.org/10.1002/ldr.3798.

[9] J. Il, I. Barton, Hyperspectral remote sensing for detecting geotechnical problems at Ray mine, Engineering Geology Journal 292 (2021), 106261, https://doi.org/10.1016/j.enggeo.2021.106261.

[10] N. Efthimiou, E. Psomiadis, P. Panagos, Fire severity and soil erosion susceptibility mapping using multi-temporal Earth Observation data: the case of Mati fatal wildfire in Eastern Attica, Greece, CATENA journal 187 (2020), 104320, https://doi.org/10.1016/j.catena.2019.104320.

[11] A. Abuelgasim, R. Ammad, Mapping soil salinity in arid and semi-arid regions using Landsat 8 OLI satellite data, Remote Sens. Appl.: Society and Environment journal 13 (2019) 415–425, https://doi.org/10.1016/j.rsase.2018.12.010.

[12] Fidelis A. Abija, Joseph I. Nwosu, Abimbola I. Ifedotun, C.C. Osadebe, Landslide susceptibility assessment of calabar, Nigeria using geotechnical, remote sensing and multi-criteria decision analysis: implications for urban planning and development, Journal of Earth Sciences & Environmental Studies 4 (6) (2019) 774–778, https://doi.org/10.25177/JESES.4.6.RA.617.

[13] G. Sreenivasulu, N. Jayaraju, T. Lakshmi Prasad, Land use and land cover change detection study at pennar river estuary, nellore district, Andhra Pradesh, southeast coast of India, Journal of Geotechnical Engineering 1 (2014) 1, https://doi.org/10.37591/joge.v1i1.4024.

[14] B. Lakshmanna, N. Jayaraju, G. Sreenivasulu, T. Lakshmi Prasad, K. Nagalakshmi, M. Pramod Kumar, B. Praveena, A study on dynamics of Krishna River mouth, east coast of India, A geospatial approach, **coasts**, Estuaries and Lakes 17 (2023) 459–469, https://doi.org/10.1007/978-3-031-21644-2_28.

[15] C. Kutir, S. Km Agblorti, B.B. Campion, Migration and estuarine land use/land cover (LULC) change along Ghana's coast, Regional Studies in Marine Science 54 (2022), 102488, https://doi.org/10.1016/j.rsma.2022.102488.

[16] Z. Ijaz, C. Zhao, N. Ijaz, Z. ur Rehman, A. Ija, Statistical evaluation of multiple interpolation techniques for spatial mapping of highly variable geotechnical facets of soil in natural deposition, Earth Sci Inform journal 16 (2023) 105–129, https://doi.org/10.1007/s12145-022-00924-2.

[17] J.N. Kpoha, H.B. Akokponhoue, V. Orekan, N. Bi Vami Hermann, Contribution of remote sensing and GIS to the mapping of land use units and its changes in the face of the flooding problem on the Allada plateau in Benin between 1986-2020, International Journal of Innovation and Scientific Research 65 (2) (2023) 171–183. http://www.ijisr.issr-journals.org/.

[18] C. Valdivieso-Ros, F. Alonso-Sarria, F. Gomariz-Castilo, Effect of the synergetic use of sentinel-1, sentinel-2, LiDAR and derived data in land cover classification of a semiarid mediterranean area using machine learning algorithms, Remote Sens Journal 15 (2) (2023) 312, https://doi.org/10.3390/rs15020312.

[19] ELD Initiative and UNEP, L'économie de la dégradation des terres en Afrique : les bénéfices de l'action l'emportent sur ses frais, site online de la eld initiative, 2015. https://www.eld-initiative.org/fileadmin/pdf/ELD-unep-report_french_03_screen_72dpi.pdf.

[20] United Nations, World Future Council et Green Cross : Lutte contre la désertification et la degradation des terres, les meilleures politiques au monde, WordFuturCouncil, 2017. https://. www.worldfuturecouncil.org/wp-content/uploads/2017/08/FPA-Brochures, 2017_FRENCH.pdf.

[21] FAO and ITPS, Status of the World's Soil Resources (SWSR)-Main Report, **Online Platform of Food and Agriculture Organization of the United Nations** 978-92-5-109004-6, 2015. https://www.fao.org/documents/card/en/c/c6814873-efc3-41db-b7d3-2081a10ede50/.

[22] L. Montanarella, M. Badraoui, V. Chude, I. Dos Santos Baptista Costa, T. Mamo, M. Yemefack, M.S. Aulang, K. Yagi, S.Y. Hong, P. Vijarnsorn, G.L. Zhang, D. Arrouays, H. Black, P. Krasilnikov, J. Sobocá, J. Alegre, C.R. Henriquez, M. de Lourdes Mendonça-Santos, M. Taboada, D.E. Victoria, A. Alshankiti, S.K. A. Panah, E.A. El Mustafa El Sheikh, J. Hempel, D. Pennock, M.C. Arbestain, N. McKenzie, Team of the International Technical Panel in Soils, **Food and Agriculture Organisation of the United Nations**, Status of the World's Soil Resources 978-92-5-108960-6, 2015. https://www.fao.org/3/i5199e/I5199E.pdf.

[23] P. Brabant, La degradation des terres en Afrique, Menaces sur la flore, Les cahiers d'outre-mer, 172 : 343-362. Schnell (R.) : 1976, Introduction à la phytogéographie des pays tropicaux, II., La flore et la végétation de l'Afrique tropicale, IRD 3 459 (4) (1992) 378. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers14-09/35304.pdf.

[24] E. Roose, Degradation des terres et développement en Afrique de l'Ouest, Bulletin de Recherche Agronomique Gembloux 20 (3/4) (1985) 505–537. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_5/b_fdi_16-17/22640.pdf.

[25] Publications Professionals LLC, Global Environnement Facility : combattre les dégradations des sols dans les zones d'activité économique, **GEF (Global Environment Facility)**. https://www.thegef.org/sites/default/files/publications/GEF_LandDegradation_CRA_FRE_0.pdf, 2014.

[26] Z.A. Tra Bi, Etude de l'impact des activités anthropiques et de la variabilité climatique sur la végétation et les usages des sols, par l'utilisation de la télédétection et des statistiques agricoles, sur le bassin versant du Bouregreg (Maroc), These de doctorat, Université Félix Houphouët Boigny d'Abidjan cotutelle Université d'Artois, 2013. La Secheresse, http://www.secheresse.info/spip.php?article57635.

[27] M. Boughalem Kasmi, Impact du système de gestion sur la vulnérabilité des sols à l'erosion ; cas du bassin versant de l'Isser -Tlemcen, Thèse de doctorat, **Site de l'Université Abou Bekr Belkaid Tlemcen (UABT)**, 2013. Algérie, http://dspace.univ-tlemcen.dz/handle/112/20100.

[28] M. Ouadraogo Hamadou, La degradation du couvert végétal et ses conséquences socio-économiques dans la région de Toussiana (Province de Houet), Mémoire de maitrise, **Université de Ouagadougou, Burkina. Faso**, 1992. https://beep.ird.fr/collect/depgeo/index/assoc/OUEHAM92/OUEHAM92.pdf.

[29] O. Balarabé, Capital Sol et arrangements institutionnels dans les agrosystèmes du Nord-Cameroun, Thèse de doctorat, Sciences économiques, Montpellier SupAgro, 2024 P, France, **CIRAD (La recherche agronomique pour le développement)**, 2012. https://agritrop.cirad.fr/579035/.

[30] B. Tchatchou, D.J. Sonwa, S. Ifo, A.M. Tiani, Déforestation et dégradation des forêts dans le bassin du Congo, vols. 978–602, Center For International Forestry Research (CIFOR), 2015, pp. 1504–1569, https://doi.org/10.17528/cifor/005457, 7.

[31] M.O. Bah, B. Jean, J. Trouvé, Forets, politique forestière et gestion des ressources naturelles en Guinée, **Bibliothèque numérique des Nations Unies**, 1996, pp. 55–60. https://digitallibrary.un.org/record/236114?ln=fr.

[32] Ministère de l'agriculture, de l'élevage et des forêts : Programme d'action nationale de lutte contre la désertification, Prevention Web, 2006. https://www.preventionweb.net/files/61025_ben149187.pdf.

[33] UICN, L'initiative pour la réduction de la pauvreté et la gestion de l'environnement. Restauration et paiement des services environnementaux dans le bassin du Tinkisso (Repase), **UICN-PREMI** (2009), l'Initiative pour la Reduction de la Pauvreté et la gestion de l'Environnement. https://www.iucn.org/sites/default/files/import/downloads/brochure_premi_francais.pdf.

[34] B.R. Evans, H. Brooks, C. Chirol, M.K. Kirkham, I. Möller, K. Royse, K. Spencer, T. Spencer, Vegetation interactions with geotechnical properties and erodibility of salt marsh sediments, Estuarine, Coastal and Shelf Science 265 (2022), 107713, https://doi.org/10.1016/j.ecss.2021.107713.

[35] A.M.d.R.F. Jardim, G.d.N. Araújo Júnior, M.V.d. Silva, A.d. Santos, J.L. B.d. Silva, H. Pandorfi, J.F.d. Oliveira-Júnior, A.H.d.C. Teixeira, P.E. Teodoro, J.L.M. P. de Lima, C.A. d S. Junior, L.S.B. de Souza, E. Araújo Silva, T.G.F. da Silva, Using remote sensing to quantify the joint effects of climate and land use/land cover changes on the Caatinga biome of northeast Brazilian, Rem. Sens. 14 (2022) 1911, https://doi.org/10.3390/rs14081911.

[36] Y.C. Wang, J.J. Ni, Biochar application on heavy metal immobilization in unsaturated soil with vegetation: a review, Int. J. Geotech. Eng. 17 (3) (2023) 260–270, https://doi.org/10.1080/19386362.2023.2227486.

[37] D.C. Refati, J.L. Bezerra da Silva, R.S. Macedo, R. da Cunha Correia Lima, M.V. da Silva, H. Pandorfi, P. Costa Silva, J.F. de Oliveira-Júnior, Influence of drought and anthropogenic pressures on land use and land cover change in the brazilian semiarid region, J. S. Am. Earth Sci. 126 (2023), 104362, https://doi.org/10.1016/j.jsames.2023.104362.

[38] D. Cazzuffi, G. Cardile, D. Gioffrè, Geosynthetic engineering and vegetation growth in soil reinforcement applications, Transportation Infrastructure Geotechnology 1 (2014) 262–300. https://link.springer.com/article/10.1007/s40515-014-0016-1.

[39] J. da Silva Cruz, C.J. Cavalcante Blanco, J.F. de Oliveira Junior, Modeling of land use and land cover change dynamics for future projection of the Amazon number curv, Sci. Total Environ. 811 (2022), 152348, https://doi.org/10.1016/j.scitotenv.2021.152348.

[40] P.M. Crivelari-Costa, M. Lima, N. La Scala Jr., F. Saragosa Rossi, J.L. Della-Silva, R. Dalagnol, P.E. Teodoro, L.P. Ribeiro Teodoro, G. de Oliveira, J.F. de Oliveira Junior, C.A. da Silva Junior, Changes in carbon dioxide balance associated with land use and land cover in Brazilian legal Amazon based on remotely sensed imagery, Rem. Sens. 15 (11) (2023) 2780, https://doi.org/10.3390/rs15112780.