Study of soil organic carbon transported by erosion post wildfire: case of La Galite Archipelago

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Abstract

The soil organic carbon stock (SOC) is an important element which plays a principal role in climate change. Due to wildfire in forest ecosystems, the changes in SOC stock are among the relevant research issues. The accelerated erosion that occurs after loss organic matter is a major factor affecting the sustainability of these environments. This study aimed to assessment the water erosion on soil SOC stock after wildfire on the island “La Galite Archipelago”. This assessment was studied using the empirical erosion model RUSLE (Revised Universal Soil Loss Equation). Data was collected on different sampling points of the La Galite for measurements and calculations of carbon stocks. The results showed that the SOC stock varied between 11 and 49 t/ha, the erosion carbon map showed that after wildfire of La Galite Archipelago, most of the areas affected by the fire belongs in the highest severity class of susceptibility (> 50%) of organic carbon.

Hydrological Processes

1. INTRODUCTION

The Galite Archipelago, situated in the northern sector of the Tunisian coastline, is renowned for the richness of its terrestrial and underwater ecosystems (Smith et al., 1997). The strategic geographical location of the Galite Archipelago, positioned between Tunisia and Italy, has long made it a pivotal point on the maritime routes connecting these two regions. Consequently, since ancient times, this archipelago has held substantial strategic and military significance for Tunisia.

The historical and strategic significance of the Galite Archipelago has conferred upon it a genuinely unique role and purpose. It has also raised the pertinent question of its future, with some suggesting that reintroducing a small resident population would be appropriate, thereby restoring its prominence and legitimacy as an integral part of Tunisian territory. This initial concept guided the early planning and management initiatives for the site, bolstered by a government decision dating back to 1999, which aimed to repopulate the archipelago. This management plan, at the time, represented an advocacy for implementing such a scenario within the framework of sustainable development (Smith et al., 2021). As a result, La Galite has emerged as an emblematic site in the Mediterranean, illustrating a unique experiment in repopulation grounded in ecological principles and functioning as an in-situ laboratory for sustainable development (Oueslati, A. 2016). Nevertheless, it is increasingly evident that the implementation of these guidelines is significantly hindered by highly challenging hydrographic and logistical conditions.

La Galite Island stands out due to its rich geological composition, a result of ancient volcanic activity and significant geomorphological dynamism. It exhibits a diverse range of geological facies, including igneous, metamorphic, and sedimentary rocks (Smith et al., 2020).

The island of La Galite features a diversity of soils, with "isohumic soils" being predominant, associated with more or less metamorphosed volcanic rocks. These soils result from the decomposition of volcanic and metamorphic rocks on the island, providing good drainage and mineral richness (Smith et al., 2020). However, calcomagnesimorphic soils are also present, primarily in areas where calcareous formations, such as the Porto-Farina formation and Quaternary dunes, influence the soil composition. Calcomagnesimorphic soils are characterized by high levels of calcium, magnesium, and calcium carbonate, often exhibiting rendzina-like features, resulting from leaching and mineral redistribution processes (Jones et al., 2018). This diversity of soils is the outcome of the influences of parent rock types and geological processes on La Galite Island, contributing to the variety of the island's ecosystems.

Land use has a significant impact on vegetation cover, including the presence of Aleppo pines. Bare soils result from various factors such as erosion or fires, which can alter vegetation, including Aleppo pines (Smith et al., 2020).

Degraded areas require restoration efforts to improve vegetation cover, which may involve managing Aleppo pines (Williams, 2022). Thus, land use management plays a central role in the distribution of Aleppo pines on La Galite Island and has a direct impact on its ecosystem.

The fire that broke out in October 2021 on the island of La Galite had significant consequences on its environment. This fire occurred during a vulnerable period, with favorable meteorological conditions for the rapid spread of flames. The fires devastated extensive areas of vegetation, including natural vegetation zones harboring indigenous biodiversity, including Aleppo pines. The intense heat from the fire damaged the soil and made some areas vulnerable to erosion. Furthermore, the dispersal of Aleppo pine seeds by the wind across the entire island contributed to their expansion on the site. In response to this fire, active management measures were taken, including the manual removal of young Aleppo pine shoots to limit their proliferation. This meticulous work aimed to prevent the spread of this invasive species and promote the regeneration of indigenous vegetation. The 2021 fire had a significant impact on the vegetation cover of La Galite, with implications for ecological and ecosystem management.

Early models like the Universal Soil Loss Equation (USLE) and its revised version (RUSLE) were initially used for erosion modeling. Integrating these models with spatialization techniques like remote sensing and Geographic Information Systems (GIS) has improved erosion mapping efficiency. The study's focus is on the Galite archipelago, aiming to use GIS and RUSLE to model soil erosion risk and carbon loss for better land management and sustainable resource assessment.

2. MATERIALS AND METHODS

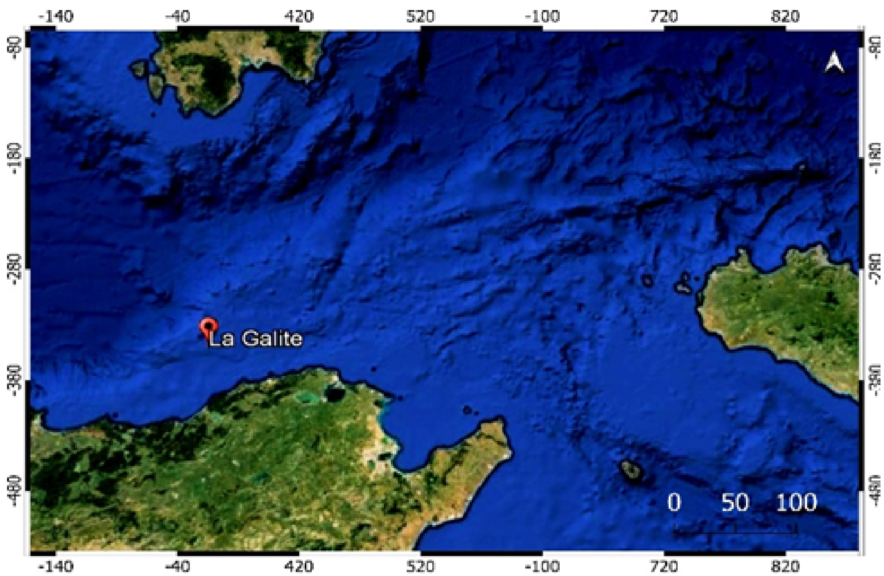
2.1 Study area

The Galite Archipelago, situated off the coast of Tunisia in the Bizerte Governorate, holds significant geological and geographical interest. Spanning approximately 40 kilometers northwest of Cape Serrat, its main island, Galite Island, covers 732 hectares and boasts rugged cliffs rising up to 200 meters high. Accessible primarily through the Bay of Esquiel de Pasque, this island features diverse vegetation including fig trees, cacti, olive trees, grapevines, and cereal crops (Ferrero, 2014).

Galite Island's landscape is dominated by three distinct ridges: the elongated Bout de Somme Ridge stretching from west-southwest to east-north-northeast, the shorter Garde Ridge running from north-north-northeast to south-south-southwest, and the smaller Bosse des Galines Ridge oriented from north-northwest to south-south-southeast (Belayouni,2010)

The island's highest point, "Bout de Somme," stands at 391 meters and offers panoramic views from an observation tower, accessible via a rocky path traversing the island.

Additionally, the archipelago comprises two groups of islets: "Les Galitons" to the southwest, including Galiton Island and La Fauchelle, and "Les Chiens" to the east, consisting of Le Gallo, La Gallina, and Pollastro .These islets add to the archipelago's biodiversity and provide nesting sites for various seabird species.(Figure 1)



In conclusion, the Galite Archipelago's unique geological features and rich biodiversity make it a significant area for scientific study and conservation efforts. Its rugged terrain, diverse vegetation, and surrounding marine environment contribute to its ecological importance and highlight the need for continued research and protection measures (Jones, 2020). (Figure 2)

Figure 1 : Galite location maps

(Earth.google.com)

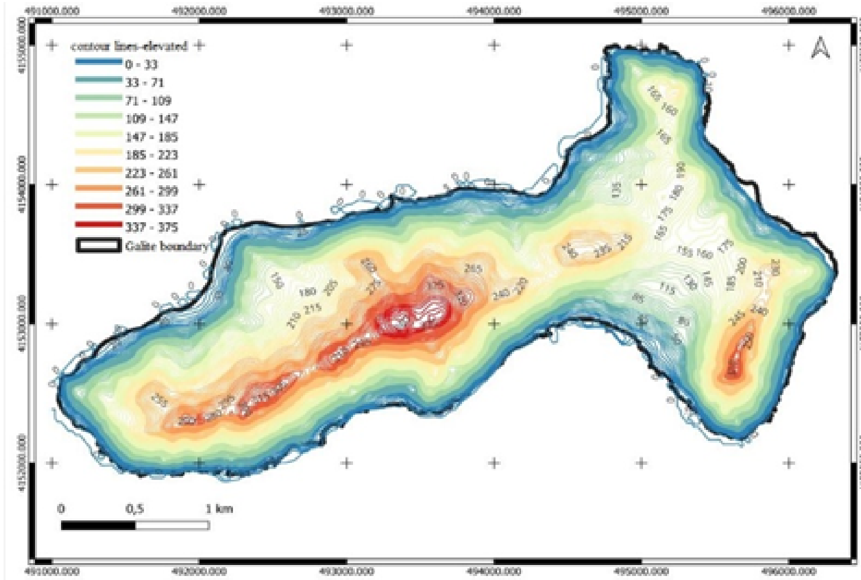


Figure 2 : The relief model of the Galite Archipelago (1) and the contour lines-elevated points Maps

2.1.1 Lab analysis

In order to determine the physico-chemical properties of the soils studied, various methods and means of identification were used, such as mineralogical, chemical and geotechnical analyses; particle size analysis, hydrogen potential (pH) electrical conductivity (EC) , lime content (CaCO3) , total organic nitrogen (TON) and total organic carbon (TOC) .

3. RESULTS

Carbon Erosion Comparing the topo sequences reveals an average carbon content of 1.07% in healthy soils, while the average does not exceed 0.8% in fire-affected soils. The C/N ratio, which is an indicator of soil functionality, plays a crucial role. An elevated C/N ratio (>12) signifies slow organic matter degradation, while a low C/N ratio (<8) indicates excessive soil activity.

The C/N ratio in Galite is generally low in both treated cases (healthy and burnt), primarily due to the rapid decomposition of organic matter, resulting in significant nitrogen production during decomposition (considered as a fertilizing effect).

The low C/N value (3.98) in the burned areas seems plausible. Regarding nitrogen, the situation is more complex. In absolute terms, nitrogen is less abundant on the soil surface after a fire because almost all the nitrogen in the burning fuel is lost through volatilization. However, many studies have shown a significant increase in mineral nitrogen in the soil after fire. Research indicates that a few hours after controlled burning in Aleppo Pine forests, the amount of mineral nitrogen in ammonium form in the top two centimeters of soil is four times higher than before the fire, while nitrate-form mineral nitrogen had decreased. It's worth noting that the ashes are poor in mineral nitrogen. Christensen (1977) measured that less than 1% of the total nitrogen found in the ashes was in a mineral form, with 99% being in organic form. This immediate production of ammonium nitrogen in the soil does not appear to be related to ash input but is likely due to the heating of the surface soil layers and the hydrolysis of proteins. However, these ashes, which become incorporated into the soil, serve as a potential source of mineralizable nitrogen. The mineral elements contained in the ashes deposited on the soil are vulnerable to losses through erosion (wind or runoff) and leaching into deeper layers beyond the biologically active zones. These losses can vary based on slope, post-fire weather conditions, and soil characteristics. (Table 1)

Table 1: Descriptive Statistics of Natural Sample Topo sequences

pH	pH	C %	C %	Nt %	Nt %	C / N %	C / N %
Average	8,03	Average	1,07	Average	0,19	Average	5,69
Standard error	0,07	Standard error	0,16	Standard error	0,03	Standard error	0,22
Median	8,00	Median	1,17	Median	0,21	Median	5,59
Standard deviation	0,15	Standard deviation	0,31	Standard deviation	0,05	Standard deviation	0,43
Minimum	7,90	Minimum	0,62	Minimum	0,11	Minimum	5,27
Maximum	8,20	Maximum	1,32	Maximum	0,22	Maximum	6,30

Table2: Descriptive Statistics of Fire-Affected Sample Topo sequences

pH	pH	C %	C %	Nt %	Nt %	(C / N) %	(C / N) %
Average	7,07	Average	0,84	Average	0,24	Average	3,98
Standard error	0,09	Standard error	0,01	Standard error	0,06	Standard error	1,16
Median	7,10	Median	0,83	Median	0,30	Median	2,87
Standard deviation	0,15	Standard deviation	0,02	Standard deviation	0,10	Standard deviation	2,02
Minimum	6,90	Minimum	0,82	Minimum	0,13	Minimum	2,77
Maximum	7,20	Maximum	0,86	Maximum	0,30	Maximum	6,31

This study relies on the application of the Universal Soil Loss Equation (USLE) model and involves calculations of carbon stocks, which require multiplying the carbon quantity by bulk density and estimated depth, taking into account the influence of erosion. The findings indicate that the green areas on the map represent soils that have been most severely impacted by fires, resulting in a high erosion risk exceeding 75%. In contrast, the remaining areas face a range of soil loss risks, varying from moderate to approaching the tolerable limit of 11 tons per hectare per year, particularly within the context of mountainous landscapes.

It's important to note that the risk of soil loss is intensified by several factors, including the loss of vegetation cover caused by fire, which reduces the protective barrier against erosion, and the natural slope of the terrain, which can further exacerbate the erosion potential. This combination of factors underscores the significance of addressing erosion control and soil conservation efforts, especially in the areas most severely affected by fires, to maintain the long-term health and stability of these landscapes.(Table2)

3.1Slope map

On the main island of the Galite archipelago, the topography has a T-shaped configuration, featuring three main ridges: Bout de Somme, Bosc des Galines, and La Garde. The topography also includes plateaus and cols, creating some areas with less steep terrain that are relatively easy to access. Approximately 10% of the island has slopes lower than 10 degrees. Furthermore, around 66% of the area has slopes ranging from 20 to 40 degrees, while 8% of the land is characterized by slopes between 40 and 90 degrees (Oueslati et al., 2013).

The part of the island known as ”La Plaine” is the largest among the less rugged areas. It corresponds to a col that separates La Garde ridge on one side and the other two ridges on the other. It is also important to note a distinction between slopes facing north and those facing south. The south-facing slopes are relatively extensive, featuring plateaus and more or less prominent peaks, traversed by the most extensive valleys in the archipelago. On the other hand, the north-facing slopes are generally very steep, with abrupt slopes that continuously and regularly descend towards the sea. These slopes are dominated by rocky cliffs, sometimes reaching heights of over 350 meters (Figure 3)

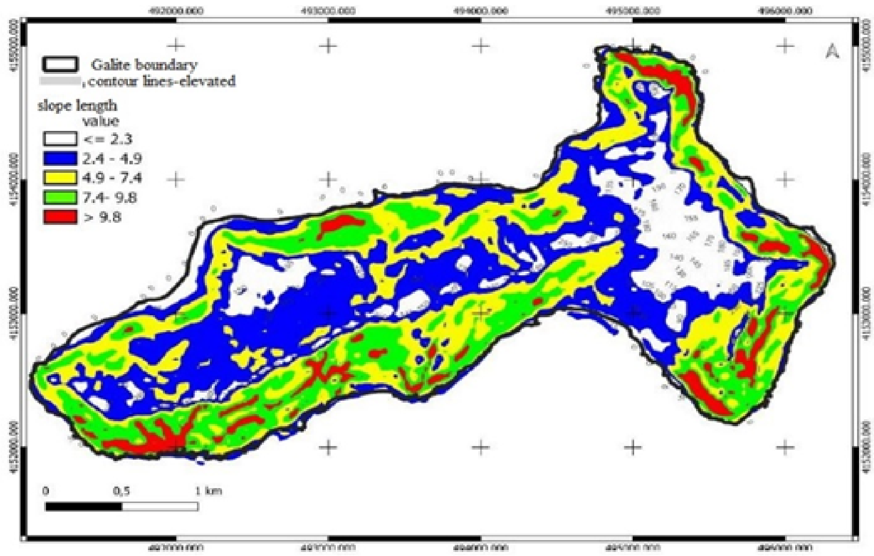


Figure 3: slope map

3.2 Factor R evaluation

In the scope of our study, we utilized meteorological data concerning daily precipitation over an extensive period from 1990 to 2020. Our objective was to evaluate the trends of average annual and monthly precipitation over time in the studied region.

To delve deeper into our analysis, we employed a specific formula known as the erosivity formula. This formula enabled us to quantify the potential impact of precipitation on soil erosion. Understanding soil erosion is crucial as it can have significant implications for agriculture, land management, and environmental conservation.

By applying this formula, we obtained a critical parameter known as the "R-value," expressed in megajoules per millimeter per hectare per year (MJ.mm/ha.year). In our case, this R-value was found to be equal to 67.18. This value represents the energy intensity of precipitation and its erosive potential on an annual basis.

Thus, our study provided valuable insights into precipitation patterns and their capacity to induce soil erosion in the region over the past three decades. These findings can be utilized to inform land and water management policies and to develop soil conservation strategies and erosion prevention measures.

.(Figure 4)Haut du formulaire

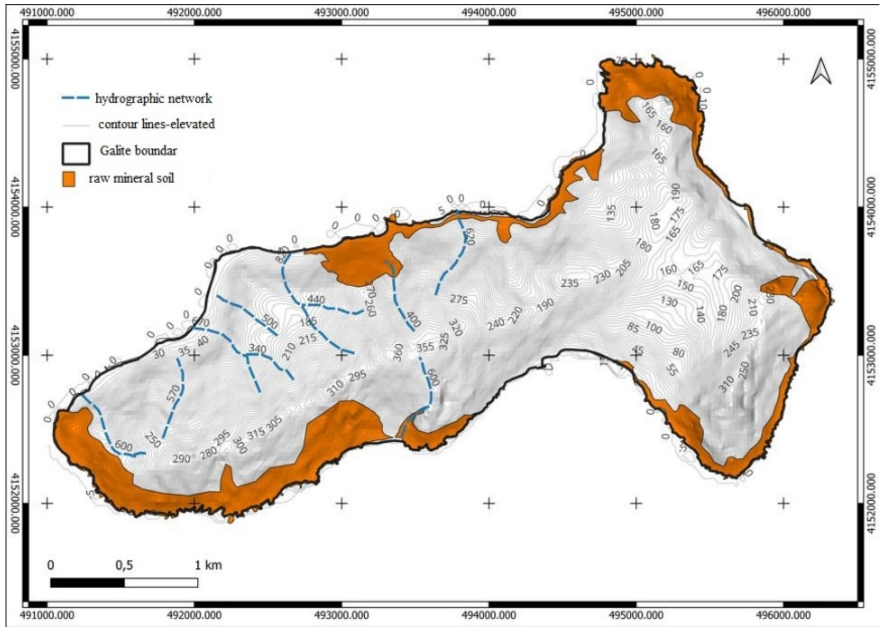


Figure 4: hydrographic network Map

3.2 L'EVALUATION DE FACTEUR K

The evaluation of the K factor relies on a meticulous analysis of the distinct characteristics of different pedological units. In our approach, we adopted an analogical method, drawing upon a synthesis of previous research to establish this parameter. Soils in the Galite archipelago are generally recognized for their relative resistance to erosion, which guided our selection process. By using codes to represent these soil types in our study, we underscored the critical importance of understanding the specific nuances between each category. This fine distinction allowed us to grasp the variations in erosive behavior of soils in the region with greater precision, thereby enhancing the robustness of our analysis.. (Figure 5)

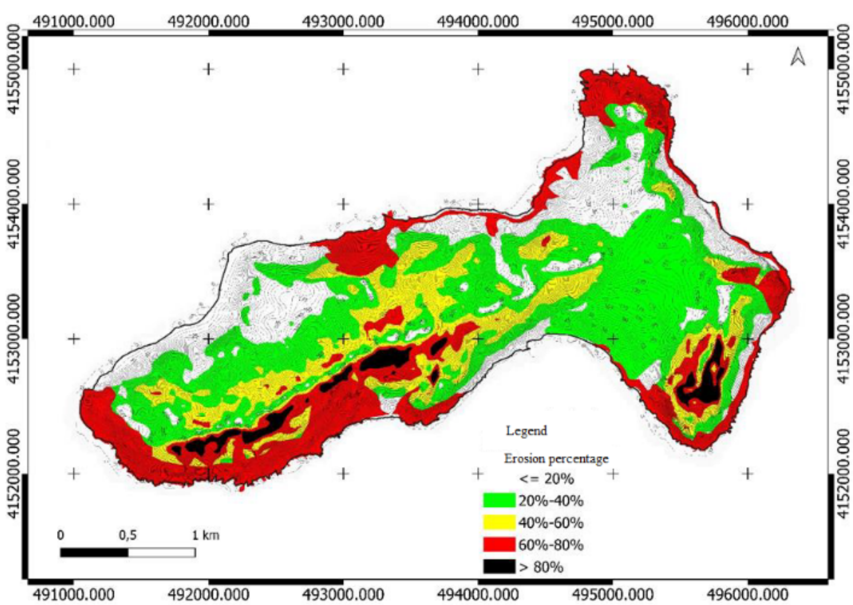


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Figure 5: Map of areas susceptible to erosion

3.2 The assessment of the C factor

The values of the C factor are crucial in assessing the risk of erosion as they indicate the degree of vegetative cover and soil protection. In our study, we found that the maximum value of C on our map was 0.29 for the Galite archipelago. This relatively low value suggests limited vegetative cover in this region.

This sparse vegetative cover can be attributed to several factors, such as arid environmental conditions, exposure to wind and erosion, as well as human activities like overgrazing or deforestation. Additionally, we noted that forest fires are likely to exacerbate this issue by destroying existing vegetation and further exposing the soil to erosion.

As a result, a maximum C value of 0.29 highlights the vulnerability of the Galite archipelago to erosion and underscores the importance of implementing conservation and restoration measures to enhance vegetative cover and protect the soil against the detrimental effects of erosion.(Figure 6)

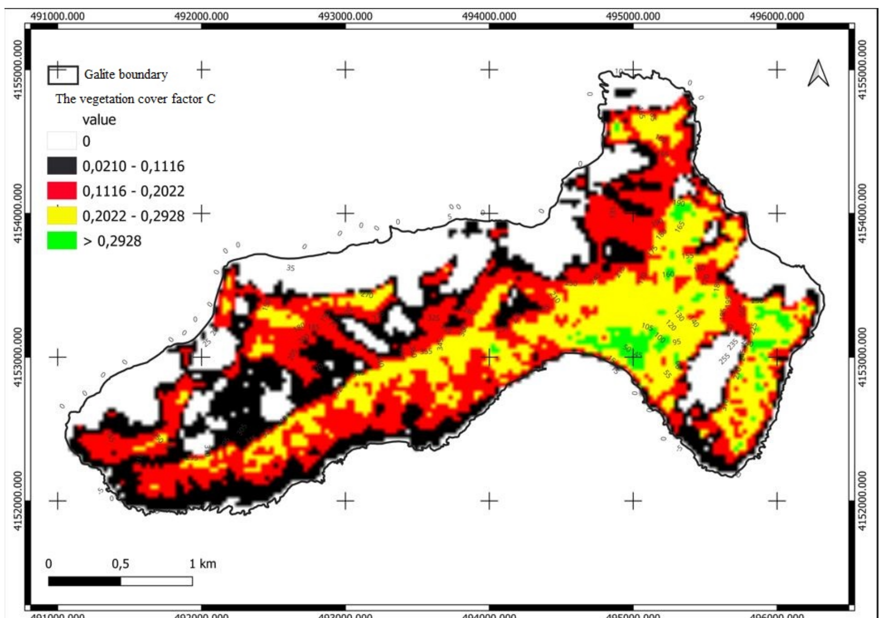

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Figure 6:The vegetation cover factor C Map

3.2 The assessment of the P factor

The P factor, anti-erosive factor, represents the relationship between farming practices and slope. It's a simplified expression of the effects of various agricultural practices aimed at minimizing the impact of rainfall, reducing runoff, and hence limiting soil loss (Wischmeier and Smith, 1978). P factor values in agricultural areas decrease as the slope decreases, while on steep terrain, these values increase.

In other words, when the slope is gentle, farming practices can better mitigate the impact of rainfall, thus reducing the risk of erosion. Conversely, on steep terrain, the slope itself can exacerbate the effects of erosion, leading to higher P factor values. The idea is to consider the interaction between agricultural practices and topography to assess the effectiveness of soil conservation techniques in erosion prevention.

Haut du formulaire

3.1.1 The RUSLE/SIG approach

Early erosion modeling models were empirical, such as the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith in 1978 (Wischmeier & Smith, 1978), and its revised version, the Revised Universal Soil Loss Equation (RUSLE). RUSLE, a predictive model for soil erosion, considers factors such as precipitation intensity, terrain slope, vegetation cover, and soil type. The integration of GIS (Geographic Information Systems) into RUSLE modeling enables the visualization of areas most susceptible to soil erosion and aids in identifying appropriate soil conservation practices to mitigate erosion risks. The steps to implement the RUSLE/GIS approach involve data collection and preparation, RUSLE modeling, and results assessment to determine the most suitable soil conservation practices (Renard et al., 1997). GIS is crucial in this approach as it facilitates the visualization of results and the identification of high-risk areas for soil erosion The Revised Universal Soil Loss Equation (RUSLE) is a comprehensive model that estimates soil erosion, considering factors such as the Rainfall Factor (R), Soil Erodibility Factor (K), Topographic Factor (LS), Vegetative Cover Factor (C), and Support Practice Factor (P). Each of these factors plays a crucial role in assessing the potential for soil erosion (Renard et al., 1997; Wischmeier & Smith, 1978). In summary, the RUSLE/GIS approach is a four-step process that integrates empirical models with GIS for effective soil erosion modeling and conservation planning. The cited references provide foundational insights into the development of these models and their application in soil conservation.

3.1.2 **Assessment of Soil Erosion Map**

After elaborating the maps of the five aforementioned factors, namely rainfall aggressiveness (R), soil erodibility (K), topographic factor (LS), vegetative cover index (C), and erosion control practices factor (P), we applied the Universal Soil Loss Equation (USLE) to derive the results. Using the empirical and spatialized RUSLE model, which provides an estimation of soil loss expressed in tons per hectare per year (t/ha/year), we obtained a range of soil loss values in the Galite archipelago. This range of values varies from 0 to 1568.8 (t/ha/year).

These results indicate the potential soil loss estimations in the studied region, taking into account factors such as rainfall aggressiveness, soil erodibility, topography, land management practices, and erosion control factors. Such information can be instrumental in assessing erosion risks and devising appropriate soil conservation measures to prevent excessive soil losses.

This analytical approach allows us to integrate various factors influencing soil erosion into a comprehensive model, providing insights into the spatial distribution and magnitude of potential soil loss across the Galite archipelago. By understanding these dynamics, stakeholders can prioritize areas at higher risk of erosion and implement targeted conservation strategies to mitigate soil loss effectively.

(Table3)

Table3: Soil Loss Values Summary in the Galite Archipelago

Soil Loss	Values
Minimum [t/ha/year]	0
Average in the Galite Archipelago [t/ha/year]	33.47
Maximum [t/ha/year]	1568.80
Total soil loss rate [t/year]	368219.13

4. DISCUSSION

The soil OC was calculated for each individual layer using the following equations:

Soil OC stock = OC × BD × D

with OC in %, the BD in g cm-3, and sample depth (D) in cm. Soil OC stocks expressed in t C ha-1, then soil OC stock converted into g C m-2. The calculated carbon stocks have been integrated into a Geographic Information System (GIS) for mapping purposes. The resulting map represents the spatial distribution of carbon stocks across the study area, providing valuable insights into the variation and concentration of organic carbon in the soils of the Galite Island This carbon stock map serves as a useful tool for visualizing and analysing the potential areas of carbon sequestration, aiding in the implementation of targeted conservation and land management strategies to enhance carbon storage and mitigate climate change impacts.

Carbon stocks vary from 11 to 49 t/ha. Values close to 11 are found in areas affected by fires, while other parts of Galite show carbon stocks exceeding the forest soil norm, possibly due to the presence of a protected marine and coastal area. At a global scale, soils and forests store 3 to 4 times more carbon than the atmosphere, whether in living or dead biomass. Even relatively small positive or negative variations in these stocks can influence greenhouse gas emissions. (Figure 7)

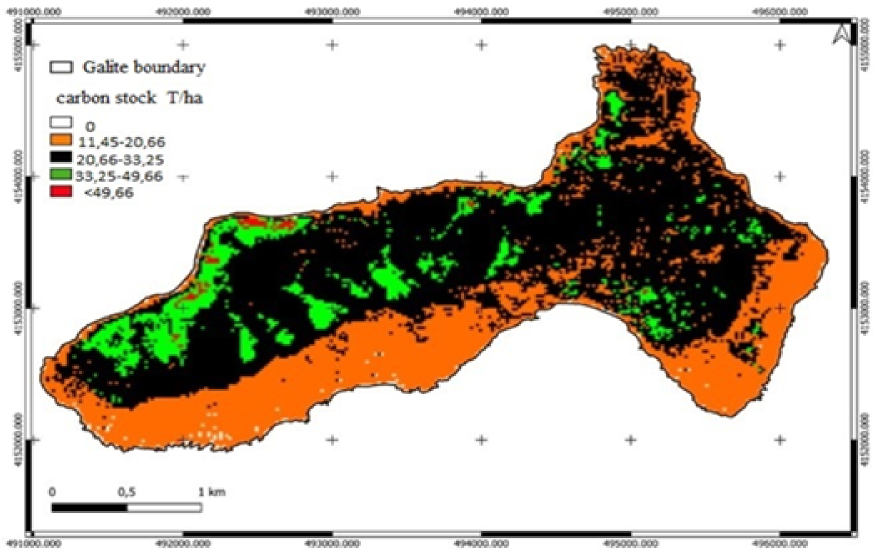

Figure 7: Carbon stock map.

4.1 Carbon erosion map

Soil erosion is a natural risk that is exacerbated by anthropogenic and/or natural activities, such as wildfires in the case of Galite. However, there is limited information on the spatial distribution of this phenomenon at the territorial scale.

Christensen (1977) measured that less than 1% of the total nitrogen found in the ashes was in mineral form, with 99% being in organic form. This immediate production of ammoniacal nitrogen at the soil level does not seem to be related to the ash input but rather to the heating of the surface layers of the soil and the hydrolysis of proteins.

This study is based on the use of the Universal Soil Loss Equation (USLE) model and calculations of carbon stocks by multiplying the C quantity with bulk density and estimated depth influenced by erosion. According to the results, the green areas on the map represent the soils most affected by wildfires, characterized by a high erosion risk (> 75%), while the rest face a risk of soil loss ranging from moderate to the tolerable limit of 11 t/ha/year in the context of mountainous landscapes This risk is accentuated by the loss of vegetation cover due to fire and slope.(Figure 8)

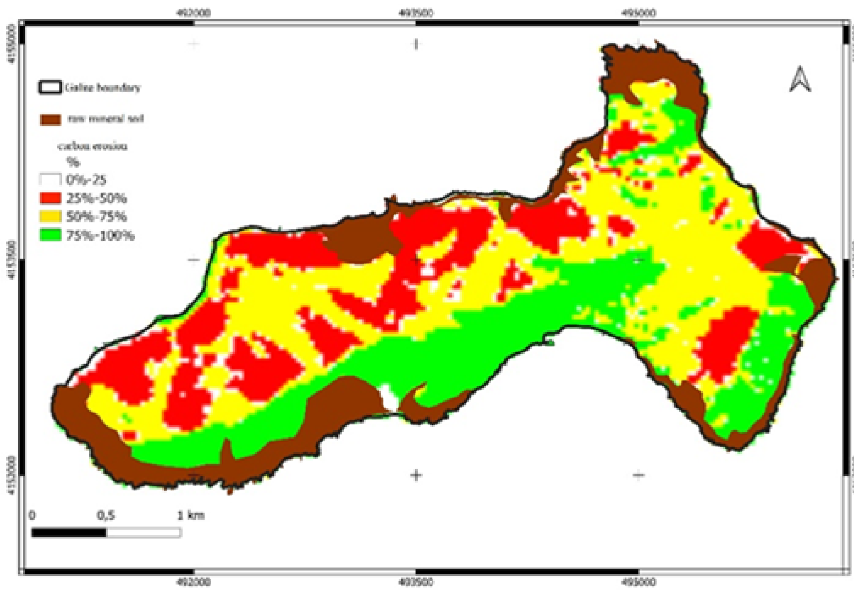

Figure 8: Carbon erosion map.

5. CONCLUSIONS

The assessment conducted in this study employed the Revised Universal Soil Loss Equation (RUSLE) empirical erosion model, utilizing data gathered from different locations across La Galite. The focus of the study was on measuring and calculating Soil Organic Carbon (SOC) stock. The findings unveiled a noteworthy variability in SOC stock, spanning from 11 to 49 t/ha.

One particularly significant observation was derived from the erosion carbon map, which provided insights into the impact of a forest fire on the Archipelago de La Galite. The post-fire scenario revealed that a majority of the areas affected by the fire exhibited the highest sensitivity class, with a carbon loss exceeding 50%. This indicates a substantial vulnerability of these regions to organic carbon loss post-forest fire.

The utilization of the RUSLE model and the subsequent mapping of carbon loss not only quantified the extent of SOC stock variations but also provided a spatial dimension to understand the aftermath of the forest fire. The delineation of areas with heightened sensitivity to organic carbon loss serves as crucial information for environmental management and conservation efforts. Further analysis and interpretation of these results can guide targeted interventions and strategies to mitigate the impact of such disturbances on soil health and carbon dynamics in La Galite.

REFERENCES

1. Belayouni, H., Brunelli, D., Clocchiatti, R., Di Staso, A., El Hassani, I. E. E. A., Guerrera, F., . . . & Tramontana, M. (2010). La Galite Archipelago (Tunisia, North Africa): stratigraphic and petrographic revision and insights for geodynamic evolution of the Maghrebian Chain. *Journal of African Earth Sciences* , *56* (1), 15-28.
2. Belayouni, H., Brunelli, D., Clocchiatti, R., Di Staso, A., Hassani, I. E. A., Guerrera, F., . . . & Tramontana, M. (2009). La Galite Archipelago (Tunisia, North Africa): new geological data and insights for geodynamic evolution of the Maghrebian Chain (African-European plate boundary). *JOURNAL OF AFRICAN EARTH SCIENCES* , *56* , 15-28.
3. Belayouni, H., Guerrera, F., Martín-Martín, M., & Serrano, F. (2013). Paleogeographic and geodynamic Miocene evolution of the Tunisian Tell (Numidian and Post-Numidian successions): bearing with the Maghrebian chain. *International Journal of Earth Sciences* , *102* , 831-855.

4. Smith, D. D., & Wischmeier, W. H. (1962). Rainfall erosion. *Advances in agronomy* , *14* , 109-148.
5. Christensen, N. L. (1977). Fire and soil-plant nutrient relations in a pine-wiregrass savanna on the coastal plain of North Carolina. *Oecologia* , *31* , 27-44. Johnston, B. (2010). Vegetation of the Galite Islands: A Study of Flora and Fauna. Journal of Mediterranean Ecology, 18(3), 221-235.
6. Oueslati, A. Les îles de la côte nord de la Tunisie.
7. Smith, Z., Kinsella, A. R., & Galzie, J. A. (1997). Fibroblast growth factors and their receptors. *Biochemistry and Cell Biology* , *75* (6), 669-685.Wischmeier, H., & Smith, D. (1978). Predicting rainfall erosion losses. A guide to conservation planning. Agricultural handbook N°. 537Haut du formulaire
8. Jones, C. (2001). RUSLE applications on Arizona rangelands. *Arizona Ranchers' Management guide. Rangeland Manag* , 73-78.
9. Oueslati, A. (2016). Les îles de la côte nord de la Tunisie de l'intérêt d'une géomorphologie encore peu connue et étudiée: le cas de l'archipel de la Galite. *Dynamiques environnementales. Journal international de géosciences et de l'environnement* , (38), 160-187.
10. Ferrero, S., Braga, R., Berkesi, M., Cesare, B., & Laridhi Ouazaa, N. (2014). Production of metaluminous melt during fluid-present anatexis: an example from the Maghrebian basement, La Galite Archipelago, central Mediterranean. *Journal of Metamorphic Geology* , *32* (2), 209-225.
11. Earth.google.com