

Forecasting Soil Erosion under Climate and Land Use Change Scenarios with Mixed Cell Cellular Automata in Bandama Coastal Watershed, Côte D'Ivoire

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Abstract

For policymakers involved in land use decision-making, improving knowledge about the expected future soil erosion risk, accelerated by human activities and climate change, is critical. However, the mixed structure of land use and land cover (LULC) has been largely ignored in previous studies, leading to a less accurate estimation of soil erosion risk. This study improves the RUSLE2 model by using the mixed-cell Cellular Automata (MCCA) model to simulate the subpixel dynamics of LULC and obtain a finer simulation of C factor under climate change scenarios. The results in Bandama coastal watershed, Côte d'Ivoire, showed that the vegetation area will be reduced, which will strongly affect cover management values, and the bare land area will increase. With the possible rises in precipitation and temperature caused by climate change, these landscape changes pose a significant risk to soil conservation. The findings suggest that projections of vegetation cover and climate together, commonly disregarded in previous studies, could have a significant impact on future soil erosion. Soil erosion in Bandama coastal watershed will continue to increase, especially in January, February, April, May, August, and September in all scenarios, if conservation planning doesn't adopt proper land use management during the next decades. The average annual soil loss was 0.1432, 0.1487, 0.1580 t/ha/year in 2020, Scenario 1 and Scenario 2 respectively. From 2000 to 2020, vegetation and wetlands decreased by 7.05% and 3.33% respectively, while cultivated land, built-up, bare land increased by 13.02%, 65.70% and

72.98% respectively. From 2020 to 2040, bare land will increase by 3%. Significant changes of bare land will be located in the northern part, areas around Korhogo city. Vegetation will decrease up to 3.96%. Government needs to adjust land development rules and plans to include land use change monitoring using remote sensing to protect the ecological environment.

Keywords

RUSLE2 Model, MCCA Model, Silting, Coastal Pollution, Disaster Risk Mitigation, Desertification

1. Introduction

Soil erosion might be significantly impacted by global changes in temperature and land use, which would have an effect on ecosystems and food security [1] [2]. Soil erosion is a major cause of soil degradation, and is affected both directly and indirectly as a result of climate change [3] [4]. Studies demonstrate that changes in rainfall intensity, rainfall amount and patterns of spatiotemporal distribution of rainfall are the cause of the direct effects [5]-[7]. The impact of temperature on soil erosion is not well understood. Indeed, some researchers considered temperature as a direct impact [8]. Other researchers consider temperature as an indirect effect [4]. In all cases, temperature will impact soil loss [9]-[11]. Recently, researchers investigated the impact of temperature on soil erodibility during the thawing and freezing cycles. In the months when the temperature is below 0°C, freezing the soil dramatically reduces its erodibility; nevertheless, following thawing, the erodibility of the soil increases significantly [12] [13]. According to some studies, soil erosion rates do not correlate significantly with precipitation but do correlate with temperature [14] [15]. However, temperature variation is sometimes neglected in future soil erosion studies. Therefore, temperature should be taken into account when forecasting future soil erosion [16]. The indirect impact is linked to human and socio-economic factors [17]. These indirect effects can be more significant than direct effects [18] and are more complex due to different types of cultivation and changes in land use. The relationship between climate change and soil erosion has been observed and studied around the world [4] [9] [19] [20]. Furthermore, the link between vegetation and soil erosion deserves consideration due to its scientific significance and practical applications [21]. Deforestation, uncontrolled land use and climate change are at the heart of the issue of soil loss and land degradation [19] [22]. Recent studies show that land use change models can be combined with the erosion model to forecast soil loss over future climate change to investigate the impact of land-use changes on soil erosion and the associated sediment delivery [23]-[27]. Land-use change modeling is critical to the prediction of soil erosion risk because the land use effect on soil loss can be more significant than other factors [7] [28].

Previous studies in future soil erosion estimation used Cellular Automata (CA) method by assuming that, at each time step, there is only one land use category per cell and used to assign cover management factor (C factor) value to different projected land use patterns [25] [26] [29]. More Previous methods forecasting soil loss used RUSLE that is different from RUSLE2 [29] and did not consider temperature [25] [26]. However, in reality, every pixel is found to have a mixed land cover structure with multiple types. Therefore, in this study, C factor was estimated by projecting the different land use in a pixel using mixed-cell cellular automata (MCCA) to improve the estimation of the projected C factor and integrate temperature variation in RUSLE2 estimation [30]. Our novel approach used MCCA model, which can simulate the subpixel dynamics of LULC and obtain a finer simulation result, which can be used to simulate the future C factor based on the fractional land use. Moreover, this advantage can also improve the RUSLE2 model, for the estimation of C factor in 2040. We used coarse resolution of LULC data with subpixel information, which is finer than previous pure cell LULC data and it allows us to avoid large data amount and achieve finer simulation.

Estimating the combined direct and indirect impacts of changes in precipitation patterns and temperature on soil erosion is challenging as both factors can have both positive and negative impacts [31] [32]. However, researchers attempted to model future influencing factors by using a GIS based soil erosion induced by water model. It will be difficult to separate the direct and indirect impact and obtain realistic results. Therefore, research on forecasting should focus on the combined effect of change in erosion on factors to estimate future soil erosion. Thus, the present study analyzes the combined effect of vegetation cover change and climate change, including the effect of temperature change on soil erodibility by combining MCCA and RUSLE2.

Studying climate change in West Africa is challenging as the region is vulnerable to low adaptive capacity to observe climate change [33]-[35]. According to FAO [19], the poorest regions of the world will be the most vulnerable to climate change for two reasons, firstly, land is not well managed and water resources are likely to become even more scarce. Secondly, insufficient technical and financial resources will make it difficult to adapt to the new climate. Côte d'Ivoire is among the most vulnerable countries to climate change (147th out of 178 countries) because of its geographic position [34]. Côte d'Ivoire's high vulnerability is partly explained by global climate change but also by the country's lack of preparation [34]. Côte d'Ivoire should be confronted by 2050 with the combined effects of the rise in temperatures (+2 degrees Celsius), the variation in precipitation (−9% in May and +9% in October), and the rise in ocean waters (30 cm) [34]. Côte d'Ivoire must not ignore the importance of climate change as it can go so far as to question its quest for economic emergence [34]. In Côte d'Ivoire, the forest heritage has decreased considerably due to agricultural activities. The choice to build the country's economy based on agriculture has hurt the forest resources [36]. Bandama coastal watershed is characterized by climatic, geomorphological and geological conditions favorable to the manifestation of geological hazard risks, including

floods, soil erosion, and landslides. In addition, the development of intensive crops in the watershed has led to an important increase in fertilizing and pesticide intakes. The sediment movement to the coastal area may carry fertilizer and may cause water pollution and degradation of the coastal area. These characteristics expose this area to an important erosive activity which causes considerable damage including the reduction of crop yields, and water pollution. Soil erosion needs to be addressed in Bandama because it is a significant factor of loss of productivity and disturbs fish migration and life in the lagoon on the outlet of Bandama coastal watershed [37]-[39]. More previous research on large watersheds in Africa found that soil erosion is an important issue [40]. Therefore, forecasting soil loss and risk evaluation for potential future soil erosion is of primary importance for land managers to protect the ecosystem and economic activities.

The main aim of this study is to evaluate the effect of climate change and vegetation cover change on soil erosion in Bandama Watershed in 2040. The specific objectives are:

- Projections of future vegetation cover changes in 2040
- estimate future monthly erosivity density and temporal K factor
- Improvement of the future soil erosion estimation

2. Study Area

Bandama coastal watershed is a large coastal watershed vulnerable to soil loss and located in the Côte d'Ivoire, between latitudes 5°14N and 10°21N and the longitudes 3°50W and 7°W. The area is approximately 98883.93 km². The basin's lowest and highest elevations are 16 and 838 meters, respectively (**Figure 1**). The watershed is oriented north-south and covers most of the climatic regions of the country [41]. The Short Rainy Season runs from September to October, while the Great Rainy Season lasts from March to June. The long dry season occurs from November to February, while the short dry season occurs from July to August. The average annual rainfall is 1200 to 1600 mm (north to south), with a temperature of 26°C [42]. The average slope is 6.61%. The soils of the region are dominated by hydromorphic soil, eutrophic ferruginous brown tropical soils. The Bandama has been the subject of partial or limited studies in hydrology and hydrogeology [41] [43] [44]. Recently, human impact in this region has increased, with the building of two substantial hydropower dams (Kossou and Taabo) and many other small dams and hydroagricultural use in the upstream part. The Bandama is of national interest because of its economic, energy, and major environmental importance [41]. From 2000 to 2020 vegetation decreased by 7.05% in the study area (**Table 1**).

Table 1. Land use change in the Bandama coastal watershed.

		2000		2020	
		ha	%	ha	%
1	Cultivated land	1101787.432	11.142	1245283.625	12.593

Continued

2	Forest	6539553.409	66.134	6078551.002	61.472
3	Shrubland	2118651.179	21.426	2396438.128	24.235
4	Grassland	6719.63536	0.068	11919.00908	0.121
5	Wetland	18662.25279	0.189	18041.45865	0.182
6	Built up	40903.8703	0.414	67777.541	0.685
7	Bare land	801.031059	0.008	1385.605577	0.014
8	Water bodies	61314.11783	0.620	68996.55685	0.698
	TOTAL	9888392.93	100	9888392.93	100

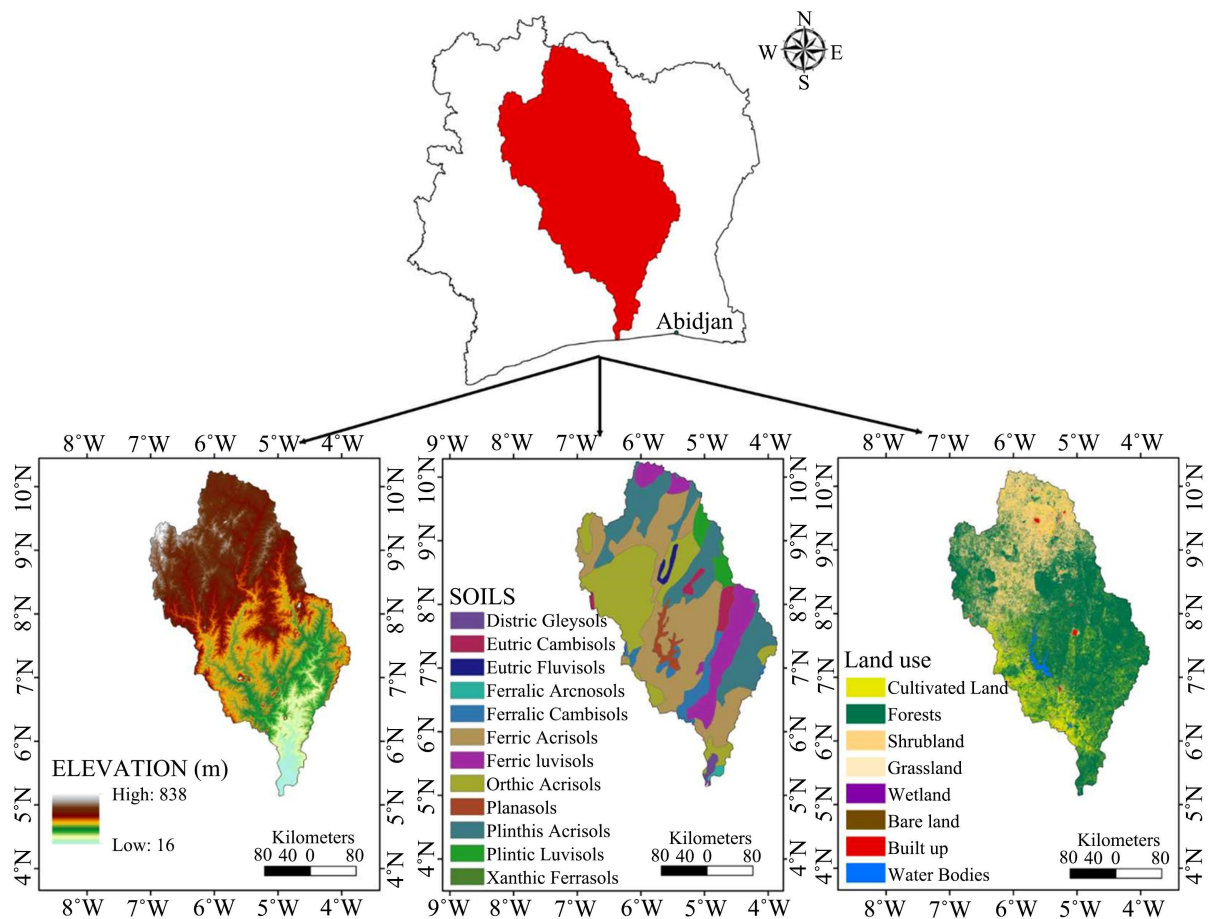


Figure 1. Location, land use, soils and topography of the Bandama watershed.

3. Datasets and Method

The present study constructed a soil erosion forecasting scenario for 2040 using the RUSLE2 model coupled with MCCA model. Precipitation further affects climate change by changing rainfall runoff erosivity density of each month (α_m), temperature change is included in the new equation and affects soil erodibility K factor [45], and vegetation cover change affects the cover management (C factor). In this study, temperature was incorporated as an environmental variable influ-

encing soil erodibility within the model. The inclusion of temperature is justified by its significant role in regulating soil physical conditions that determine susceptibility to erosion. Specifically, temperature affects soil erodibility through two primary mechanisms: soil moisture variation and freeze–thaw cycles. Elevated temperatures enhance evaporation and desiccation, reducing soil moisture and thereby weakening the cohesive forces among soil particles, which increases their vulnerability to detachment by runoff. In contrast, under lower temperature regimes, repeated freeze–thaw processes can disrupt soil aggregates by expanding and contracting pore spaces, leading to surface loosening and reduced structural stability. Within the model framework, these temperature-driven effects are parameterized to represent the dynamic response of soil erodibility to changing climatic conditions over time. The process for forecasting and analyzing climate change and vegetation cover fractions is explained in the following subsections. The complete study flowchart is schematically represented in **Figure 2**.

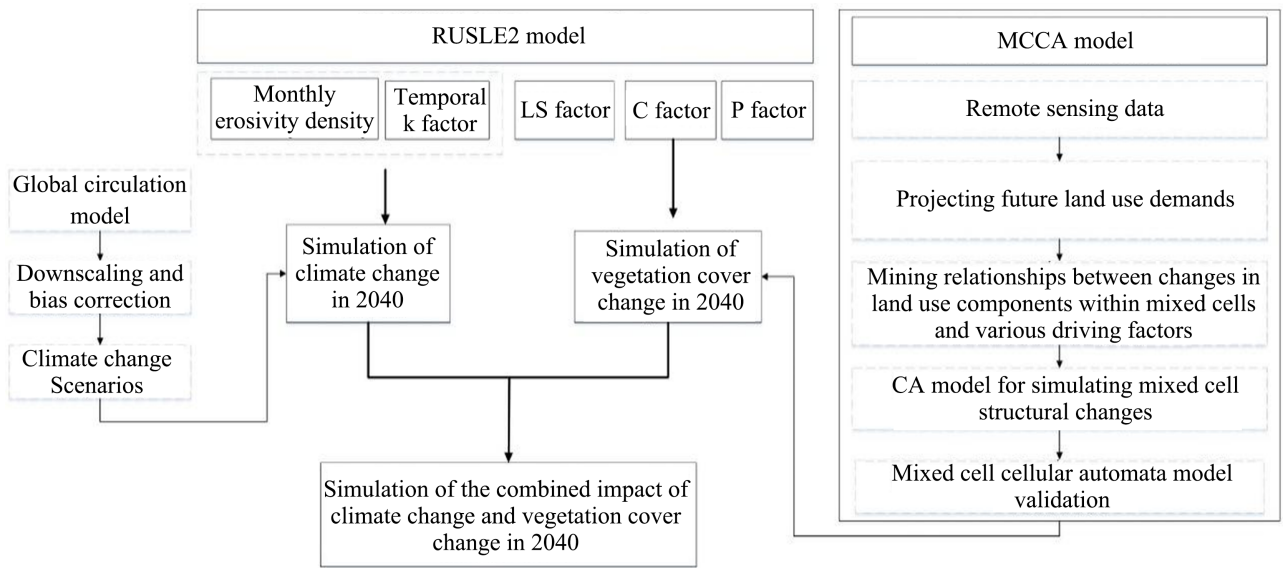


Figure 2. Framework of the overall methodology used in this study.

3.1. Datasets and Data Processing

This study’s land use data were obtained by classification of Landsat satellite images into eight classes, including cultivated land, forests, shrub land, grassland, wetland, settlement, bare land, water bodies. By applying primary preprocessing operations, land cover fractions for the study region were obtained for the years 2000 and 2020. We gathered spatial variables to represent the driving forces of land use structural change. These variables have been widely used in previous research on soil erosion and land cover simulation [7] [30]. The data used in this study are listed in **Table 2**. The working resolution of this study is 1 kilometer (km). Bandama watershed has been divided to 1 km * 1 km spatial resolution for the simulation. The components for each pixel were derived based on the 30 m resolution of the land use data.

Table 2. Datasets used.

Dataset	Source	Variables	Spatial resolution
Land use Land cover	https://data.casearth.cn	Vegetation fraction, Bare soil fraction, Non photosynthetic fraction	30 m
Climate	https://www.worldclim.org	Precipitation and temperature	2.5 minutes
DEM	https://www.asf.alaska.edu	Elevation	12.5 m
Soil	http://www.fao.org	Sand, silt, and clay fractions; organic matter %	1:5,000,000
Socio economic data	https://www.openstreetmap.org/export	Proximity to primary road, Proximity to secondary road, Proximity to tertiary road, Proximity to railway	
	https://datadryad.org/stash/dataset/doi:10.5061/dryad.dk1j0	GDP	5 arcmin
	https://www.worldpop.org/	Population	100 m

3.2. Simulation of Future Cover Management Factor

The cover management factor denotes the influence of surface cover in soil loss studies and, is known to be more pronounced than the effect of other factors. The innovation in the proposed model is the use of MCCA model, which can simulate the subpixel dynamics of LULC, and obtain a finer simulation result. This simulation result when couples with pixel by pixel equation of C factor can improve the RUSLE2 model. We used the MCCA model to project a future land cover map [30]. The land-cover fraction maps were created by classifying satellite images from the years 2000 and 2020. The Markov chain was used to project future land use demands based on historical data. The Markov model was selected because it is a robust scientific approach among the different methods that can be used to determine future land use demands [30]. The Markov model is particularly well-suited for modeling land use transition probabilities, as it systematically utilizes empirical historical data to represent temporal dependencies in land cover dynamics, thereby providing a statistically rigorous and interpretable framework for predicting and managing future landscape transformations. The selected factors and parameters have been utilized in previous research [30] [46]. MCCA method is composed of three major components that are presented in **Figure 3**.

Land use changes were restricted during the simulation so that some conversions were not permitted, which is a common step in land use modeling [30] [46]. For example, bare land (F_{bs}) is not able to be changed to vegetation land type, whilst vegetation (F_{veg}) can be converted to any other land use type. For this study, based on expert knowledge, allowable conversions were specified in a conversion matrix (**Table A1** in Appendix).

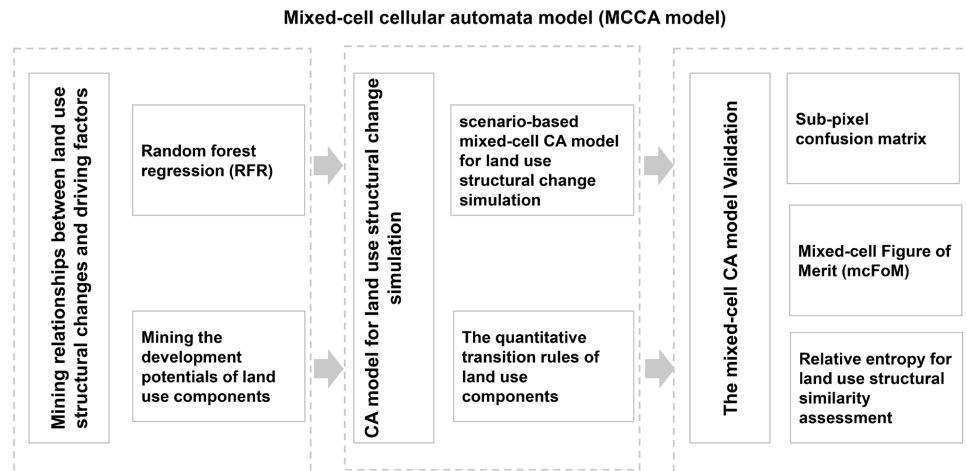


Figure 3. The MCCA model scheme.

3.3. RUSLE2 Model

The present study used the updated hybrid empirical/process-based model RUSLE2 [45]. In investigations on soil erosion and land degradation, this family model has received widespread utilization and validation. It should be noted that RUSLE2 differs from traditional USLE and RUSLE-derived models in that it considers temperature when estimating soil erodibility, runoff, and sediment yield. More previous models yearly estimate soil loss while RUSLE2 calculates the long term average soil loss of the t^{th} day by using the following equation [47]:

$$A = \left(\sum_{i=1}^{365N} r_i k_i l_i S c_i p_i \right) / n \quad (1)$$

where: A = annual soil loss, P_i = support practice, n = number of years, c_i = cover management, S = slope steepness, l_i = slope length, k_i = soil erodibility, r_i = erosivity density. Phinzi and Ngetar [48] summarized various existing equations for deriving different RUSLE parameters. **Table A2** in Appendix shows adapted equations used to derive RUSLE2 factors in this study. We selected empirical equations according to the location of the research, the objectives of the study, and the availability of the data. These equations (**Table A2** in Appendix) were chosen not only because of their utilization worldwide including Africa [38] but also based on their good results compared to other equations tested out in this analysis.

In the present study, we consider Downscaled monthly future climate data from Coupled Model Intercomparison Project 6 (CMIP6) predicted by the General Circulation Models (GCMs) GFDL-ESM4 and MIROC6 under new ssp370 projection in 2040. The monthly and annual precipitation and temperature estimates under the new climatic projection were downscaled, and calibration (bias correction) was done with WorldClim v2.1. Simulated precipitation and temperature for calculations of the monthly rainfall erosivity density and soil erodibility K factor were obtained from worldclim website. MCCA can be used to simulate future land use fractions of bare soil, vegetation cover, water, non-photosynthetic materials, and we can estimate C factor using the pixel-by-pixel equation [49]. Once we es-

timated the monthly erosivity density, and C factor we forecasted soil erosion using Equation (1).

To analyze soil erosion risk in 2040, we developed 2 Scenarios:

Scenario 1: what will happen in 2040 if all other RUSLE2 parameters were held constant to soil erosion in 2020, except vegetation cover, precipitation, and temperature? The monthly erosivity density and temporal K factor estimation is based on the global circulation model GFDL-ESM4 under ssp370 projection;

Scenario 2: what will happen in 2040 if all other RUSLE2 parameters were held constant to soil erosion in 2020, except vegetation cover and climate parameters? The monthly erosivity density and temporal K factor estimation is based on the global circulation model MIROC6 under ssp370 projection.

4. Results

4.1. Projections of Future Vegetation Changes

In the present study, we simulate vegetation cover change and then estimate the C factor value for the year 2040. In this research, bare land denotes land use 1, vegetation represents land use 2, non-photosynthetic material (NPM) land use 3, and water denotes land use 4.

4.1.1. MCCA Calibration and Validation

Calibration of the model and accuracy evaluation

The random forest (RFR) for each land cover type was trained using specimen from the mixed data of 2000-2020 in Bandama coastal watershed. The sampling rate was set as 10% and 100 regression trees were used to construct each RFR model. The Out of Bag root-mean-square error (OOB RMSE) of all land use components was 0.0211432, 0.010141, 0.0269727, and 0.00610531, respectively for bare land, vegetation, NPM, and water. The low OOB RMSE indicates that the RFRs were well trained and able to grasp the relationships between structural changes in land use and driving factors. Once the model had been trained, we simulated the changes of the different mixed pixels. **Figure 4** shows the differences between the simulated and true land use fractions.

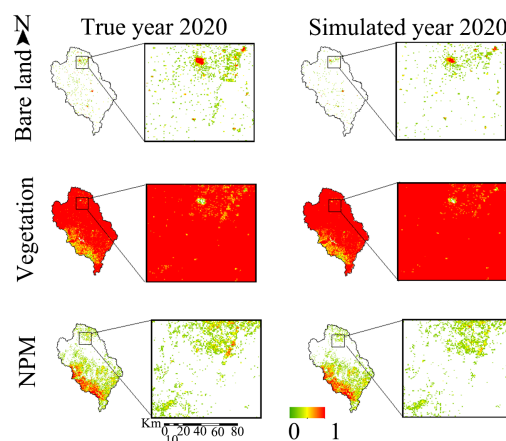


Figure 4. True land use fraction maps and simulated maps in 2020.

We obtained good results of accuracy in the Bandama region for the simulation. The three accuracy indices were acceptable. The relative entropy (RE) to evaluate the simulation process's information loss was mean RE = 0.029534. The overall accuracy was OA = 0.97 and the mixed cell figure of merit was mcFoM = 0.16.

4.1.2. Future Vegetation Cover Management Prediction from 2020 to 2040

The C factor in 2040 was estimated using the fractions of land use obtained in 2040 based on MCCA model and Markov chains. In this study, we used land use data of 2000 and 2020 as historical data. We used the fraction cover of 2000 to 2020 to obtain the conversion probability and land use demand in 2040 using the Markov model. On this basis, we have referred to the multiple land use demands in the Bandama during the study period and used transition rules to restrict the transformation between land units. Finally, the structural land use fractions of bare land, vegetation, NPM and water for 2040 was then predicted in every mixed cells (**Figure 5**). From 2020 to 2040, Bandama will experience an increase of bare land by 3%. Significant changes of bare land will be located in the northern part, areas around Korhogo city. Vegetation will decrease up to 3.96%.

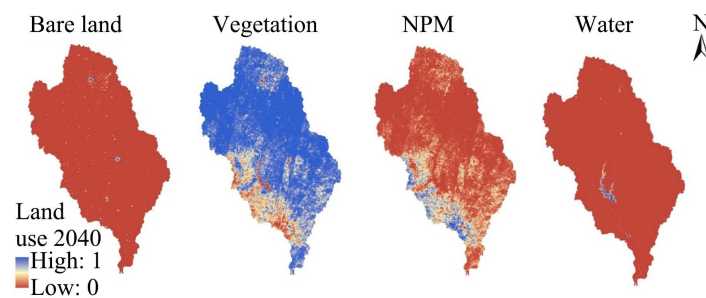


Figure 5. Mixed land use fraction of 2040.

The C-factor values in 2020 and 2040 were compared and results show that land cover changes contributed significantly to the evolution of the C factor thus vegetation land will be reduced by 2040 and bare land will increase (**Figure 6**). Results indicate that the number of pixels with a C value of 1 in 2040 will be more than two times greater than in 2020 and the number of pixels with a C value between 0.001 and 0.1 in 2040 will be more than seven times higher than in 2020.

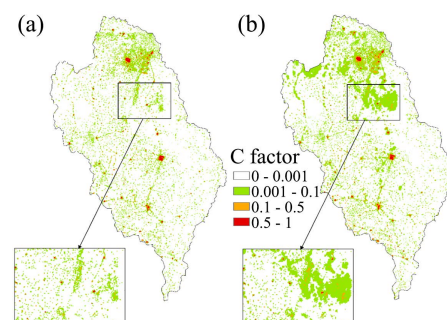


Figure 6. Spatial distribution of the cover management factor. (a) 2020; (b) 2024.

4.2. Projections of Future Monthly Erosivity Density and Temporal K Factor

4.2.1. The Monthly Erosivity Density Factor in 2040

The monthly erosivity density based on GFDL-ESM4 under ssp370

The monthly rainfall erosivity density factor in 2040 in Bandama was estimated using equations in Appendix 1. In the Scenario 1 the value of the monthly erosivity density in Bandama over the years varied between 0.002 in January and 41.77 in June in 2040 (**Figure 7**). In the Scenario 2 the value of the monthly erosivity density in Bandama over different months varied between 0.002 in January and 40.71 in June in 2040 (**Figure 8**).

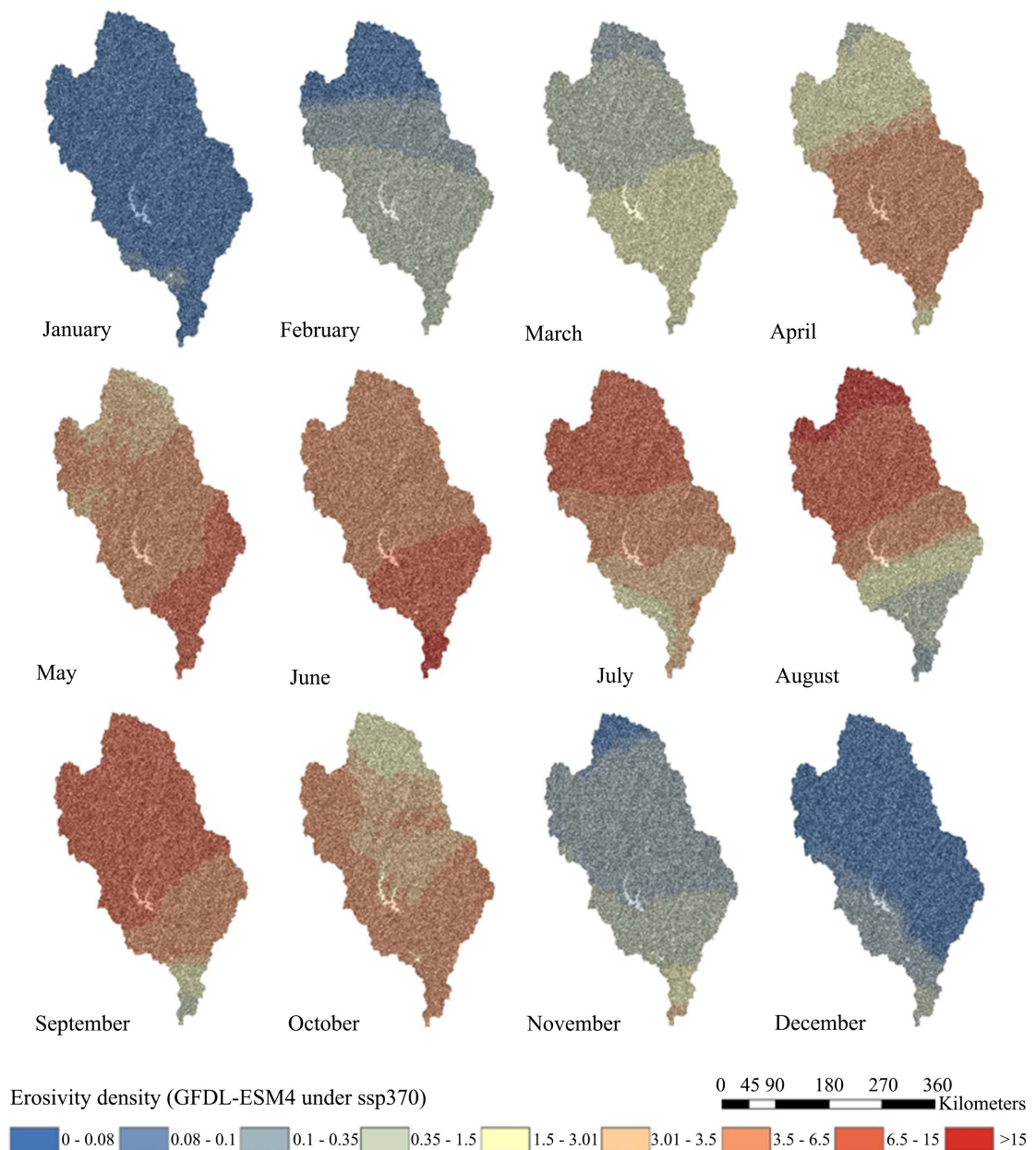


Figure 7. Changes of the erosivity density in the scenario GFDL-ESM4 under ssp370 projection.

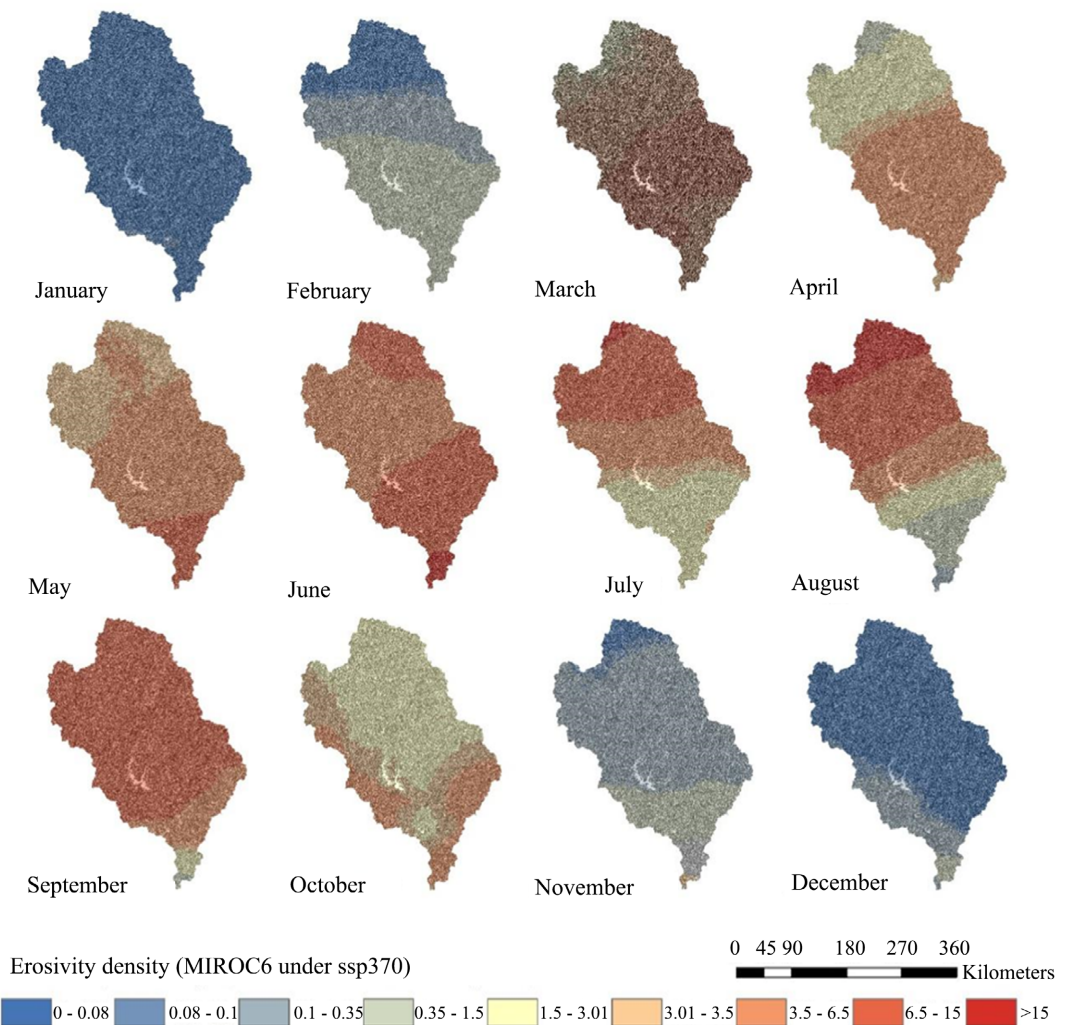


Figure 8. Spatiotemporal variation in the monthly erosivity density for the scenario MIROC6 under ssp370 projection.

4.2.2. The Temporal Soil Erodibility K Factor

Results showed high soil erodibility value during the rainy season. In the Scenario 1, the temporal k factor in 2040 in Bandama was estimated using equation in Appendix 1 to estimate the impact of temperature on soil erodibility. The value of the temporal K factor in Bandama during the year 2040 varied between 0.0013 in January and 0.047 in April, May, June, July, August, and September (**Figure 9**). In the Scenario 2, the temporal K factor in Bandama over different months varied between 0.0013 in January and February, and 0.047 in March, April, May, June, July, August, September and October in 2040 (**Figure 10**).

4.3. Improvement of the Future Soil Erosion Estimation

The combined effect of climate change and vegetation cover change in soil loss in Bandama was developed to improve the forecasting of soil loss by integrating, mixed cell cellular automata and temperature in the estimation. The value of soil loss in Bandama in 2020 varied between 0 in January and 22.94 t/ha/month in

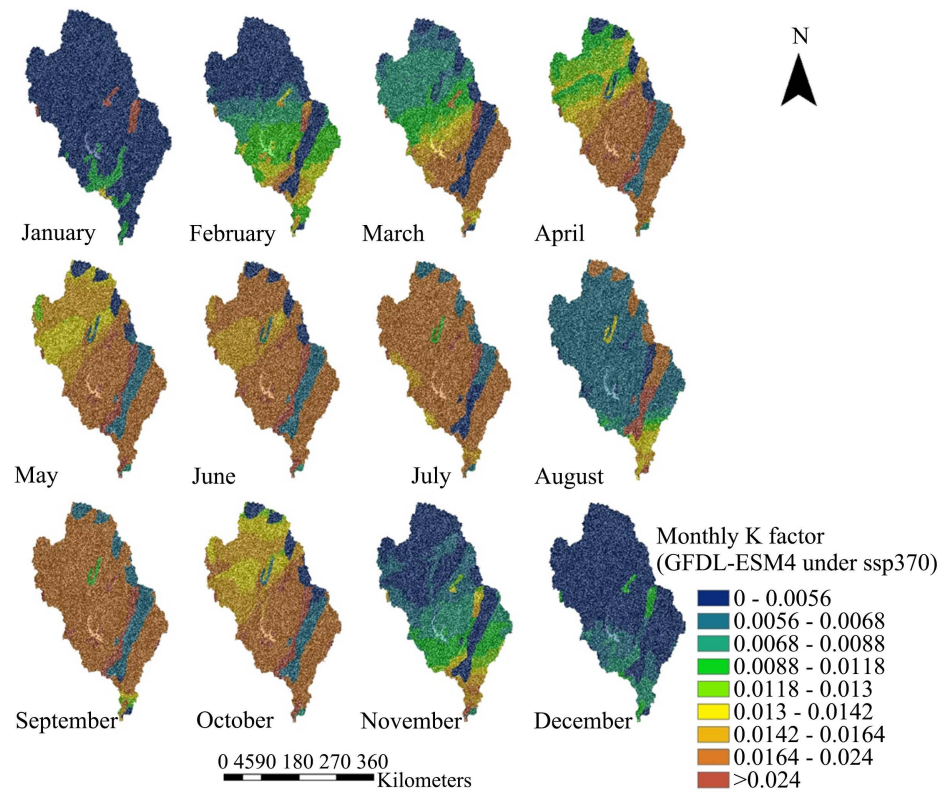


Figure 9. Temperature effect on soil erodibility in 2040 based on the GCM GFDL.

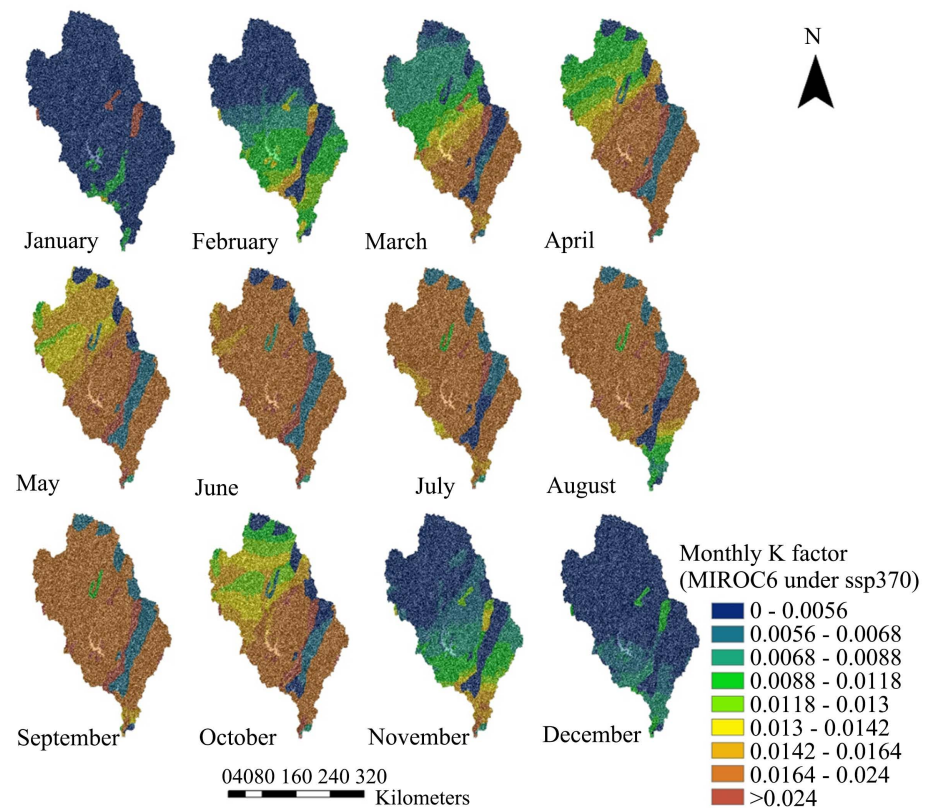


Figure 10. Temperature effect on soil erodibility in 2040 based on the GCM MIROC6.

July 2020. During July 2020, Bandama was the most vulnerable around the city of Korhogo, and on steep slope soil erosion sometimes can reach 22.94 t/ha/month (Appendixes 1-3). The ranges of erosion values were selected according to the availability of data in the region. In the region soil loss range varies from slight (0 - 0.03), moderate (0.03 - 0.2), high (0.2 - 12), very high (12.1 - 15), severe (15 - 20), very severe (>20).

4.3.1. Soil Erosion Based on Scenario 1

The combined direct and indirect impact of climate change of soil loss in 2040 based on the Scenario 1 is illustrated in **Figure 11**. The monthly soil loss was estimated using Equation (1). The soil erosion risk map in the in Bandama over different months varied between 0 t/ha/month in January and 24.54 t/ha/month in June in 2040 in the Scenario 1.

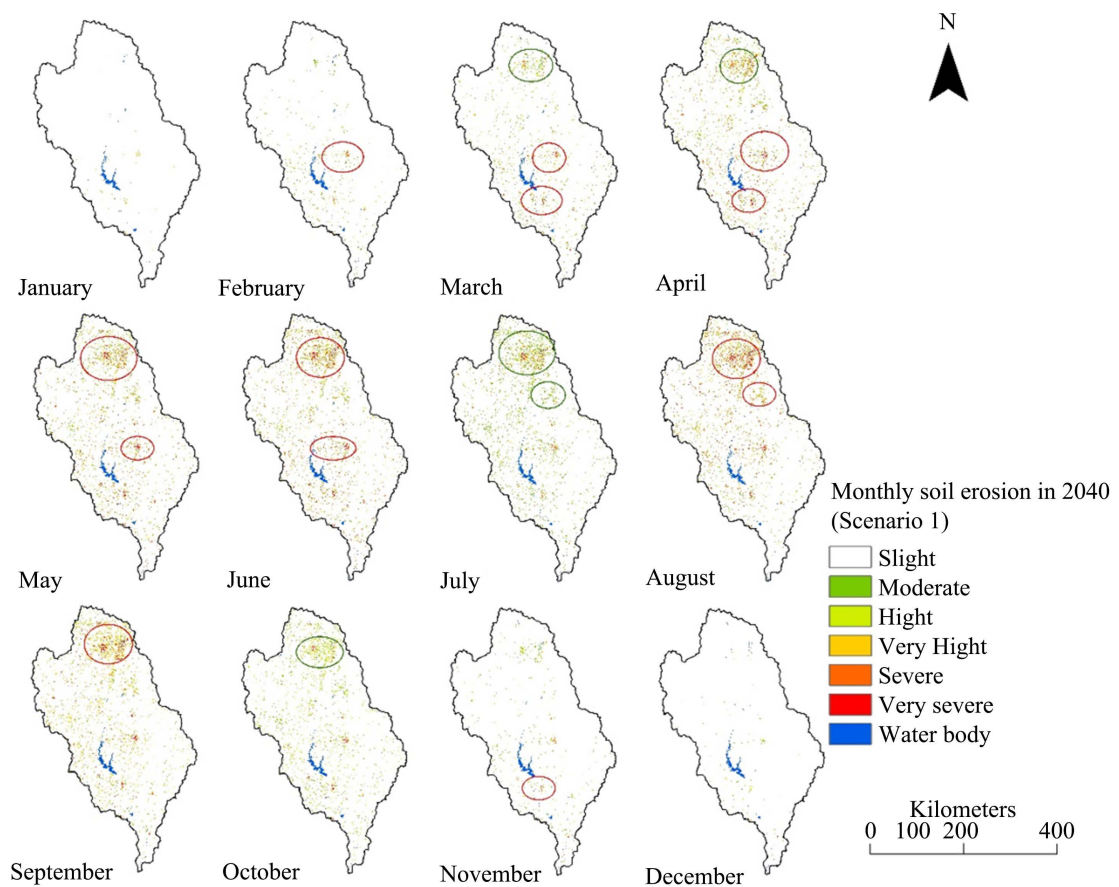


Figure 11. Spatial distribution of soil loss risk based on Scenario 1 (GFDL-ESM4 under ssp370 projection).

4.3.2. Soil Erosion Based on Scenario 2

The combined effect of climate change and vegetation cover change in Bandama in 2040 based on the global circulation MIROC6 under SSP 370 projection is depicted in **Figure 12**. The monthly soil erosion based on Scenario 2 was estimated using Equation (1). The value of soil erosion in the Bandama over different months varied between 0 in January and 92.97 t/ha/month in March in 2040.

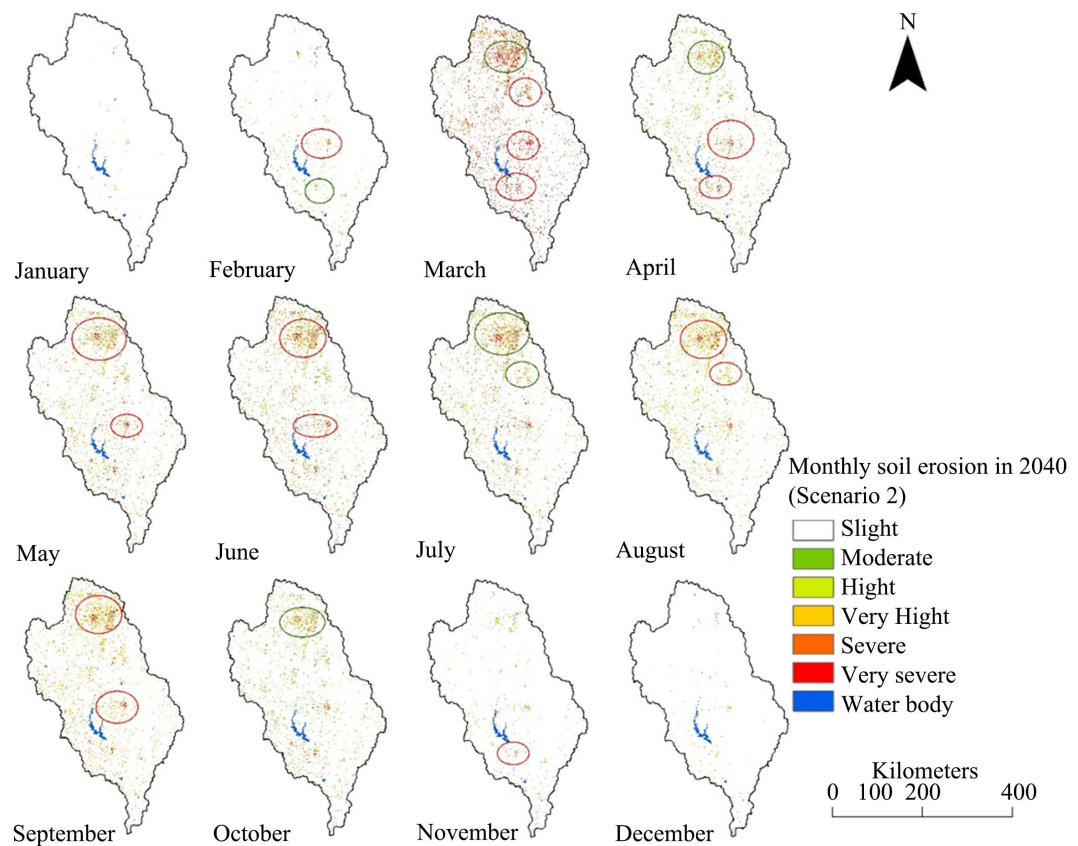


Figure 12. Spatial distribution of soil loss risk based on Scenario 2 (MIROC6 under ssp370 projection).

We compared all the mean soil loss values obtained in the two scenarios in 2040 and the results in 2020. The impact of climate change on soil loss that caused changes between scenarios in 2040 and the baseline period 2020 were analyzed and significant variation of the mean soil loss was observed in January based on the different scenarios. From 2020 to 2040, soil erosion increased by 1900% and 2600% in January in Scenario 1 and Scenario 2 respectively. In fact, increases are from a very low baseline value, which can amplify the relative change. The research shows that the rainfall erosivity density highlighted soil erosion patterns. During January, March, August, and September soil erosion will increase from 2020 to 2040. The mean soil erosion is predicted to decrease from 2020 to 2040 in October by 25.91% and 74.83% and in December by 3.64% and 90.94% in Scenario 1 and Scenario 2 respectively.

Spatially we observed a great difference of the monthly erosivity density between the two scenarios (**Figure 7**, **Figure 8**). This difference can be attributed to the impact of rainfall during the rainy season and vegetation change. The red circle represents the areas with high soil erosion risk mainly located in the northern and center part of the watershed, indicating that this part is vulnerable and prioritization measures should be strengthened (**Figure 11**, **Figure 12**). Conservation planning should include the protection of areas around the cities of Yamoussoukro and Korhogo

5. Discussion

The present study is the first conducted on forecasting soil loss in Bandama coastal watershed and combining future direct and indirect effects of climate change on soil erosion. In order to analyze the effects of climate change and vegetation cover changes on soil erosion based on 2 scenarios, this study combined MCCA model, the RUSLE2, and synthetic precipitation and temperature.

The direct field measurements of climate variables and soil loss in Bandama are scarce. Thus, the results of our research are based on model estimation without possibility of field verification. Therefore, the quantitative results from this research should be interpreted with caution. However, this estimation of soil erosion risk map gives suggestions to conservation planning. The budget for soil conservation could be adjusted and strengthened between different months in vulnerable areas. Bandama is a large watershed with potential economics activities like mining, agriculture. Recording and vulgarization of climatic data and collection of soil loss by implementing many stations could help to better analyze the simulation of natural hazards that affect human life, ecosystems, and economic activities. Similar studies pointed out that the high vulnerability of some areas is due to neglecting the problem of soil erosion induced by water and a lack of long-term data collection [7] [34] [50] [51].

Previous research on large watersheds in Africa found that soil erosion is an important issue [40]. The ranges of erosion values were selected according to the availability of data in the region [38] [52]-[54]. It was challenging to compare and select range values since the new RUSLE2 model uses monthly rainfall density factor instead of the rainfall factor used in previous model RUSLE and USLE. The new RUSLE2 model also integrates temperature and precipitations in the K factor equation. The comparison of our results with previous studies that didn't consider these factors should be done with caution. Previous research didn't propose a monthly range of soil loss tolerance in the study area. Cote d'Ivoire should reinforce the capacity of conservation planning to investigate this hazard in the Bandama coastal watershed.

Figure 10 shows that future changes in vegetation cover will impact the cover management in Bandama. Bare land will increase and will lead to increasing soil erosion. Similarly, previous studies show that the *c* factor and its resulting soil erosion can be impacted by vegetation cover change [23] [24] [26] [55]. Thus, the decreasing vegetation cover and expansion of bare land from 2020 to 2040 will lead to increased soil erosion during the year 2040. Vegetation cover change has significantly affected soil loss. This change represents the effect caused by human activities. Results demonstrate that if vegetation cover is not well managed increasing soil erosion is expected in all months in 2040. Similarly, the importance of managing the cover management was noticed by previous research and it can reduce soil erosion by 20% to 60% [52]. As shown in **Figure 1**, the majority of Bandama was covered by vegetation, following by cropland and urban areas. In combination with this land use, due to the specific topographic conditions and

slope of the region, soil erosion was high because of the steep slope and rainfall even if most of the area is covered by vegetation. Our study shows that areas with high erosion rates correspond to steeper slopes and high rainfall erosivity density in Bandama. This implies that steeper slopes contribute to the amplification of soil loss risk by increasing runoff. Indeed, increasing the slope length will induce increasing water flow power and transmission of erosional force. Our result is consistent with others' studies revealing the role of rainfall and a steep slope on increasing soil erosion rate [25] [38]. Moreover, our future estimation of change in vegetation cover compared to previous study considers socio economic factors among driving factors of land use change [26].

Future soil loss rate might increase significantly especially in January, February, April, May, August, September in all scenarios. The possible reasons could be the reduction of vegetation cover which will happen because of human activities, more dryness of savannas during the great dry season. More during the great rainy season runoff will increase and affect soil loss. In this research we notice that temperature plays a role in soil loss even if it is not at the same level like in alpine regions. The dry season in the region is characterized by a long period of dryness and short torrential rain. The combined effect of temperature that makes trees lose their leaves and the reduction of vegetation cover combining to the torrential rainfall increases soil loss. Conservation planning could reinforce capacities of stakeholders involved in the mitigation of soil loss. Afforestation in the region could help to reduce soil loss during the different seasons.

The problem of soil erosion is an urgent problem to be addressed in recent decades because soil is important for ecological landscape management. Our results demonstrate that both climate and vegetation changes impact future soil erosion rates. Thus Bandama will be more vulnerable because Côte d'Ivoire is not prepared to tackle global climate change effects. Results show that climate scenarios may help to simulate the occurrence of the future monthly precipitation and rainfall erosivity density. Studying future soil erosion is complex because of the multiple interactions between factors. Similarly researches indicated that the combined direct and indirect impacts of climate changes on soil erosion might cause positive and negative impacts [31] [32]. There will be more potential of soil erosion induced by water in 2040 around some areas including, cities, roads and steeper slope.

Many models have been developed for soil erosion estimation, and some of them required complex data that is difficult to find in the study area (G2 model, EPM model). Many scholars at home and abroad have continuously improved the RUSLE model, using the predicted C, P factors and K, LS, and R factors to estimate future soil erosion. However, when linking to GIS for the regional analysis, previous research on the estimation of future soil erosion did not consider the mixture of land use in pixels. Also few studies consider together the effect of precipitation, temperature and vegetation change in the future estimation of soil loss. Our study differs from previous studies by improving the delineation of soil erosion risk map

by improving the RUSLE2 equation. RUSLE2 and MCCA used with GIS and remote sensing demonstrate the capability to differentiate the mixing structure of land use units within pixels to improve the delineation of future potential erosion areas. Our model maps the fractional cover of land use and soil erosion pattern within each grid cell, offering more information about erosion risk than discrete classes at the same spatial resolution. Simulation of future land cover fraction in Bandama via MCCA may help to estimate and improve the results of mapping future soil loss risk compared to traditional methods that assume that one land use is one pixel or assign a C factor value to the land use prediction [24]-[26] [56]-[59].

This study broadens the methods to forecast soil erosion. Recent research monthly estimate soil erosion using RUSLE model by predicting the rainfall erosivity factor and the cover management factor but didn't use the monthly rainfall erosivity density factor and didn't integrate precipitation and temperature in the calculation of the soil erodibility factor [60] [61]. Considering the difference between the factors used for the estimation of soil erosion, variation in the results might be remarkable. Field studies are needed to quantitatively evaluate soil erosion in the study area. Future research could integrate, precipitation and temperature in the estimation of K factor, the monthly erosivity density, and the mixture of land use in monthly satellite images to forecast soil erosion for a more realistic estimation.

Climate, soil, terrain, vegetation, and agricultural conditions have caused soil and water nutrient losses to varying degrees in most areas around cities of Korhogo, Yamoussoukro, and agricultural land and in the savannah. Soil and water nutrient loss on sloping fields is not only related to agricultural issues, but also to ecological and environmental issues. Severe soil nutrient loss and soil erosion in the northern part of the watershed will cause soil nitrogen, phosphorus, potassium and other losses, degradation of soil quality, and then affect soil productivity, leading to further deterioration of the ecological environment, that is an important form of non-point source pollution.

Our results enable conservation planning to evaluate the extent of land degradation and the application of environmental protection policies.

Bandama watershed environmental and socioeconomic variables must be taken into account while implementing sustainable land management strategies. Land management strategies can be developed in this area by increasing the availability and accessibility of the data.

It is an extremely tall order for the Ivorian government to adapt and mitigate climate change as they simultaneously manage a host of other development priorities. Appropriate policy, institution, and governance system design at all scales can help with land adaptation and mitigation. Climate and land policies that are mutually supportive have the potential to save land resources, aid in ecological restoration, and promotion of collaboration among multiple stakeholders should be encouraged. A combination of policies rather than a single policy solution can

help to address the difficulties of sustainable land management and climate change due to the complexity of the challenges and the range of parties involved in addressing land challenges.

Côte d'Ivoire by adopting an integrated, coordinated and coherent manner could assist climate resilient development to address desertification, land degradation and food security. To this end, recently the Ivorian government hosted the COP15 on the theme: "land, life, and legacy: from scarcity to prosperity". It served as a wake-up call to make sure that land, which is the lifeblood of this planet, continues to benefit both the current and future generations. Despite the commitment of the government, the present research indicated that soil hazard could increase in 2040. Therefore, actions should be strengthening from now to 2040 to tackle this hazard and restore billion hectares of degraded land by promoting agroforestry, constructing terraces on steep slopes. Spatial planning, regulations, and land use zoning can mitigate soil erosion and reinforce ecosystem management. To facilitate the outcomes the government may increase individual and institutional capacity, facilitate and accelerate the knowledge transfer, putting early warning systems in place and addressing implementation gaps.

6. Conclusions

The MCCA model demonstrates the advantage of incorporating sub pixels for a better delineation of the erosion area in 2040. The proposed model takes into account seasonal fluctuations in precipitation and temperature in soil edibility factor in 2040 and helps to better estimate K factor with temperature data rather than data from current graphs. The novel method of combining the MCCA model, RUSLE2 model, and future climate scenario, has improved research on the effect of climate change and vegetation cover change on soil erosion in Bandama Watershed in 2040. Previous studies have not examined future soil erosion induced by water in this area considering the direct and indirect impact together. Few studies have considered the future monthly variation of soil loss. Land restoration and land use policies were discussed because of their importance for human wellbeing, and it is recommended to seriously adopt such kind of solution proposed here to tackle soil erosion and understand future soil loss.

Our research suggested that future soil loss rate might increase significantly, especially in January, February, April, May, August, September in all scenarios. Bandama is more vulnerable in the Scenario 2 than in the Scenario 1. The study's findings reveal the continuous increase of soil loss in 2040 if improper land conservation policies are taken. Thus, the present study indicates that it is not just rainfall and vegetation change that has an impact on soil erosion, but also temperature, which is most of the time neglected in soil erosion research. The mixed cell integrated with RUSLE2 helps to better delineate vulnerable areas. The proposed solution is simple and reproducible. It can help managers to make better decisions.

Limited quantitative soil erosion research within the area was noticeable.

Therefore, this study's quantitative results should be interpreted with caution. However, this work can serve as a theoretical basis for environmental protection, soil conservation and ecological restoration.

Future research requires soft computing tools that couple hydrological, erosion and vegetation models. There is a need for integrated modeling studies. Integrating the future erosion model with GIS should consider the mixture of the land use in a pixel and the combined impact of precipitation, temperature and vegetation for a more realistic estimation of the soil erosion risk map.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix 1

Table A1. Land use conversion matrix (1 = conversion possible; 0 = not possible).

Change to	Bare land	Vegetation	NPM	Water
Bare land (land use 1)	1	0	0	0
Vegetation (land use 2)	1	1	1	1
NPM (land use 3)	1	0	1	1
Water (land use 4)	0	1	0	1

Appendix 2

Table A2. RUSLE2 parameters equations used in this study.

RUSLE2 parameter	Formula	Equation number	Equation number
R	$R = \sum_{i=1}^{12} 1.735 * 10^{\left[1.5 \log_{10} \left(\frac{P_i^2}{P} \right) - 0.08188 \right]}$ where P_i represents the total monthly precipitation (mm), and P is the mean annual precipitation (mm). $= 1.735 * 10^{(1.5 * \text{LOG10}() - 0.08188)}$	(2)	Arnoldus (1980)
α_m	$R_m = \alpha_m P_m$ where R_m = monthly erosivity, α_m = monthly erosivity density, and P_m = monthly precipitation.	(3)	USDA-ARS (2008)
Geographical k factor	$K = \frac{2.1 \times 10^{-4} \cdot M^{1.14} \cdot (12 - OM) + 3.25(2 - b) + 2.5(c - 3)}{759}$ where K is the soil erodibility factor, OM is the soil organic matter content (%), M = (percentage limons + percentage very fine sands) $\times$ (100 – percentage clay), b is a soil structure code, c is a permeability class.	(4)	USDA-ARS (2013))
Temporal k factor	$\frac{K_j}{K_n} = 0.591 + 0.732 \left(\frac{P_j}{P_s} \right) - 0.324 \left(\frac{T_j}{T_s} \right) \quad T_j \geq 40^\circ \text{F}$ if $\frac{K_j}{K_n} > 2$ then $\frac{K_j}{K_n} = 2$ if $\frac{K_j}{K_n} < 0.4$ then $\frac{K_j}{K_n} = 0.4$ where K_j represents the average daily soil erodibility factor for the ith day; K_n denotes soil erodibility value from the RUSLE2 soil erodibility nomograph, T_j denotes average daily temperature for the ith day ($^\circ\text{F}$), T_s represents average temperature for the summer period, P_j denotes average daily precipitation, and P_s represents average precipitation for the summer period.	(5)	USDA-ARS (2013)
LS	$LS = \left(\frac{\lambda}{22.13} \right)^m (0.065 + 0.045S + 0.0065S^2)$ where λ is slope length; S is the slope percent. The value of “m” is 0.5 if the slope is 5% or more, “m” is 0.4 if the slope is 3.5% - 4.5%, “m” is 0.3 if the slope is 1% - 3%, and “m” is 0.2 on uniform where slope is less than 1%.	(6)	Wischmeier and Smith (1978)

Continued

	$C = \frac{F_{bs}}{1 + F_{veg} + F_{NPM}}$		
<i>c</i>	where F_{bs} denotes the fraction of bare soil: the bare soil endmember information was collected from Landsat images; F_{veg} denotes different forest tree species in Bandama, and F_{NPM} represents non-photosynthetic material. The data on endmembers for the NPM were derived from open spaces, abandoned cultivated fields, branches, rocks, dried leaves, or gravel.	(7)	Asis and Omasa (2007)
<i>p</i>	$p = 0.2 + 0.3 * S$ where S is the slope grade in percent (%)	(8)	Wenner (1980)

Appendix 3

Table A3. The Sub-pixel Confusion Matrix for the simulation from 2000 to 2020 (PA represents the producer's accuracy, UA is the user's accuracy).

Category	Bare land	Vegetation	NPM	Water	UA
Bare land (land use 1)	0.004989	0.001601	0.000268	2.00E-05	0.725319
Vegetation (land use 2)	0.00248	0.802096	0.010487	0.000816	0.983107
NPM (land use 3)	0.001165	0.007666	0.157488	0.000603	0.943483
Water	3.31E-05	0.000178	0.000113	0.008903	0.96485
PA	0.575657	0.988362	0.935441	0.860857	
OA = 0.973476					