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# Regional erosion risk mapping for decision support: A case study from West Africa

Farris A.Y. Okou[a,*], Brice Tente[b], Yvonne Bachmann[c], Brice Sinsin[a]

[a] Laboratory of Applied Ecology, Faculty of Agronomic Sciences, University of Abomey-Calavi, 01 BP 526, Cotonou, Republic of Benin
[b] Laboratory of Biogeography and Environmental Science, Department of Geography and Planning, Faculty of Letters, Arts and Humanities, BP 677 Abomey-Calavi, Republic of Benin
[c] Institute of Ecology, Evolution and Diversity, J.W. Goethe-University, Max-von-Laue-Straße 13, 60438 Frankfurt/Main, Germany

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ABSTRACT

Effective soil and water management strategies require regional-scale assessment of erosion risk in order to locate prioritized area of intervention. Our study focuses on the Atacora mountain and surrounding areas (covering more than 18% of the total land area of Republic of Benin) which face a serious erosion threat despite their ecological and economic importance. To appraise the level of soil erosion risk of large area, we rely on the Instituto Nacional para la Conservación de la Naturaleza (ICONA) erosion model and use data from geographic information system (GIS). The erosion risk model requires four main inputs, namely, information on slope, lithofacies, land use and vegetation cover. The slope layer computed from ASTER digital elevation model (DEM) and the lithofacies layer inferred from digital pedogeological map are combined to draw soil erodibility map. To build soil protection map, we use land use/land cover layer extracted from LANDSAT 7 ETM + images in addition to vegetation cover layer derived from MODIS NDVI product. The final erosion risk map (with a resolution of 1 arc second) is obtained by overlapping erodibility and soil protection maps. We find that 21.8%, 58.5%, and 19.5% of the study area presents very low to low, medium, and high to very high level of erosion risk, respectively. Moreover, our findings are aggregated at the district-level (administrative unit). We observe that erosion risk is more acute in Boukoumbe district. Kerou, Kobli and Natitingou districts are mildly affected by erosion risk, while Kouande, Materi, Pehunco, Tanguieta and Toucountouna districts face a low risk. Ultimately, the proposed erosion risk map can help researchers and decision makers design and implement effective soil and water management interventions in the study area.



## 1. Introduction

Land degradation is one of the most serious global environmental issues of our time (Dregne, 1998; Reynolds and Stafford Smith, 2002). Land use activities are among the key drivers of land degradation worldwide. These activities shape the land surface and can induce substantial changes to natural phenomena (Steffen et al., 2007). Human activities are at the heart of several environmental challenges. Actually, Humans dominate, transform and modify ecosystems (Zika and Erb, 2009) to their own benefit, yet often at the expense of the global ecological patterns and processes.

Sound soil and water conservation measures (Bou Kheir et al., 2006) are needed to mitigate the pervasive and disruptive impact of land degradation on sustainable natural resource management. Moussa et al. (2002) and Souchère et al. (2005) argue that a spatially distributed assessment of erosion risk is mandatory and must be performed before implementing any effective soil conservation measure. Other authors advocate for the use of geo-indicators, which are aggregate and efficient proxies of surface processes in the assessment of land degradation (Berger, 1996; Berger, 1997; Dumanski and Pieri, 2000; Gupta, 2002; Hammond et al., 1995; Morton, 2002; Zaz and Romshoo, 2012; Zuquette et al., 2004). Moreover, recent advances in scientific computing, remote sensing, and GIS technologies enable cheap and fast processing of large and complex datasets. This may help alleviate a major practical challenge inherent in implementing erosion models (Merritt et al., 2003), as they are data-intensive and time consuming (Vrieling et al., 2006). However, accessing clean data is a pivotal issue in Sub-Saharan African countries that often lack of well-functioning data collection systems. Interestingly, Van Rompaey and Govers (2002) show that when data are scare and/or unreliable, simple erosion models provide a more accurate assessment than complex ones. Complex erosion models are often adequate for small scale applications, but loose tractability for large scale

* Corresponding author at: 01 Po Box: 357 Porto-Novo, Republic of Benin.
*E-mail addresses:* farrisokou@gmail.com, farrisy@yahoo.fr (F.A.Y. Okou).

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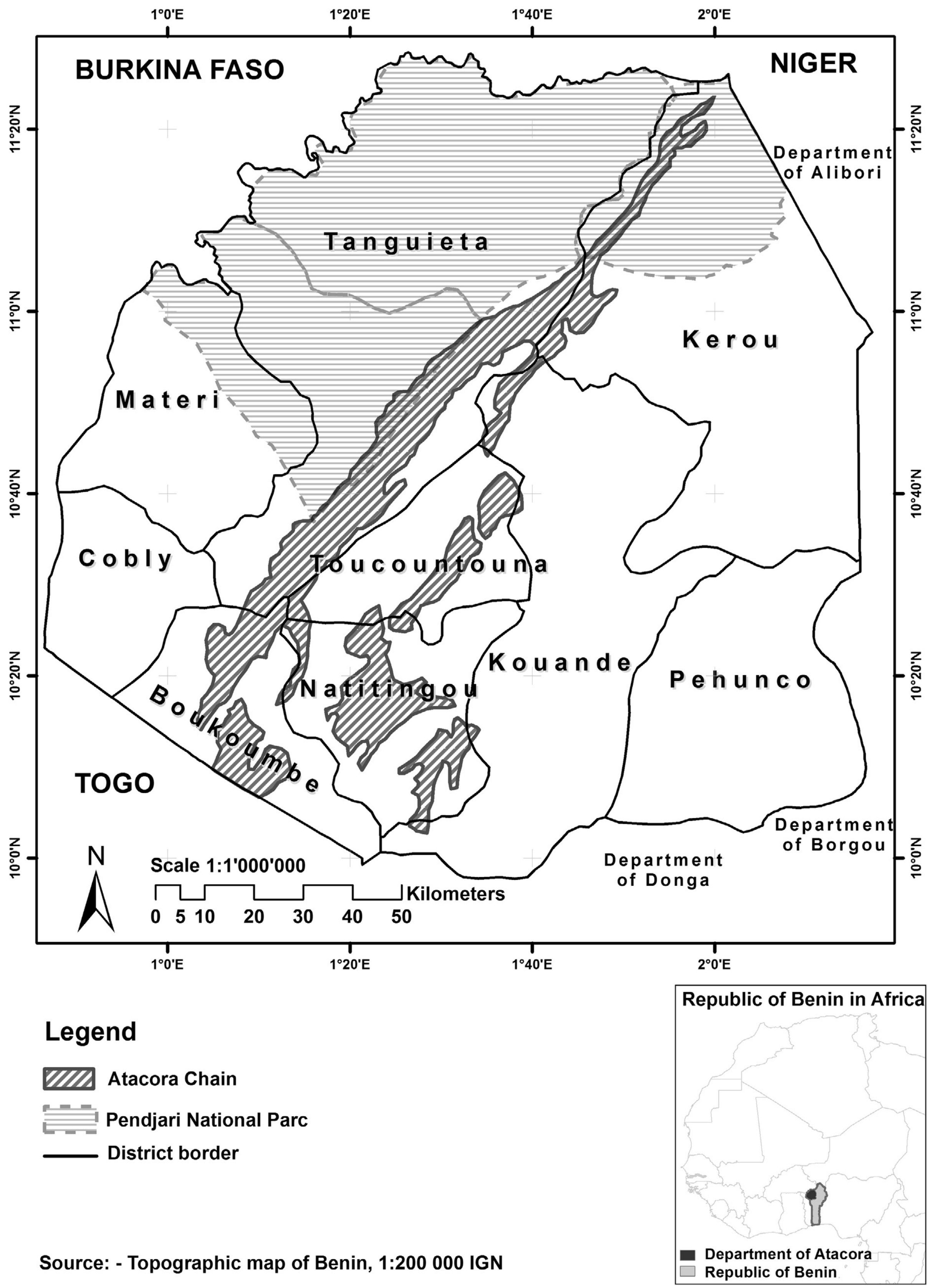


**Fig. 1.** Location of the study area.

implementations, as pointed out by Kirkby et al. (1996), Schoorl et al. (2000), Yair and Raz-Yassif, (2004), among others. Moreover, less data-consuming methods seem more appealing to decision makers (Renschler and Harbor, 2002). According to Bayramin et al. (2003); ICONA (1991, 1997); Zaz and Romshoo (2012), the ICONA model is one of the easiest and flexible qualitative methods for assessing and mapping soil erosion risk. This model has been used by European Union (EU) countries and Mediterranean states (e.g., Turkey, Tunisia, Syria, and Egypt), as documented by Bayramin et al. (2003).

In Benin, Atacora Mountain chain is of high ecological and biological value (Adomou, 2005). It has an exclusive vegetation type (the Synsepalum passargei-Broenadia salicina riparian community) and the two Beninese endemics *Thunbergia atacorensis* and *Ipomoea beninensis* (Akoègninou and Lisowski, 2004). Soil fertility loss, physical and chemical soil degradation are a few threats identified by many authors (Adegbidi et al., 1999; Mulder, 2000; Tente and Sinsin, 2005). Their harmful effects are potentially increased by steep slope, shallow soil, strong demographic pressures, and transborder transhumance from Sahelian countries such as Burkina Faso and Niger (Meurer, 1994). There is a narrow body of literature addressing global and detailed estimation of land alteration in Atacora Mountain. Tente and Sinsin (2005) investigate at the scope of some hills of Atacora Mountain and find that erosion reduces, on average, 8.6 cm/ ha/year of the soil thickness. The 2008 "National Self-assessment of Capacities to Enhance for the Management of Global Environment" report reveals that Atacora Mountain and its surrounding areas are characterized by slight, average and extreme degradation status (ANCR-GEM et al., 2008). This report is the most recent large scale assessment of land degradation in the study area. Nonetheless, this assessment is rough and only relies on expert-folk opinions.

This study aims at evaluating and determining the erosion risk status of Atacora Mountain and its surrounding areas using GIS and ICONA model.

## 2. Study area

The study area covers the department of Atacora, which accounts for more than 18% of the surface area of Republic of Benin. The Atacora Mountain range (Fig. 1) skirts this area located in the West African climatic zone. The region features two seasons: a dry season (November to March) and a rainy season (April to October) with a rainfall ranging between 800 and 1000 mm. Note that the annual rainfall can reach up to 1300 mm due to the orographic influences of the relief. Over the past 35 years, the yearly average temperature varied from 25.3 °C to 30.5 °C, while the monthly relative humidity level lied between 26.8% (dry season) and 80.5% (wet season).

The region's topography is characterized by hillsides with steep slopes (30–60%), hilltops, plateaus, and valleys. In general, hills are oriented east or west. East-facing sides are mostly exposed to the Harmattan, a dry northeast wind that blows from the Sahara Desert during the dry season (Jenik and Hall, 1966). West-facing sides are mostly exposed to the West African moist monsoon, a southwest wind that blows from the Atlantic Ocean (Le Barbe et al., 2002). Rocky and shallow soils are dominant, whereas sandy and clay soils with moderate stone content may be found in seasonally wet or inundated valleys. The combination of ecological factors at these stations explains the diversity of observed vegetation patterns, which consists of shrub, tree, and woodland savannas dominated by *Isoberlinia doka*, *Daniellia oliveri*, *Vitex* spp., *Terminalia glaucescens*, *Parinari polyandra*, etc. (Sieglstetter and Wittig, 2002; Tente and Sinsin, 2002; Wala, 2005).

Four main ethnic groups (Bètamaribè, Wama, Natemba, and Gourmantché) dwell in the Atacora chain (Wala, 2005). These groups interact among themselves and conduct activities that impact Atacora chain ecosystems. Farming and animal breeding are the two main activities of local people who also have fishery, hunt, or small industries as their secondary occupation.

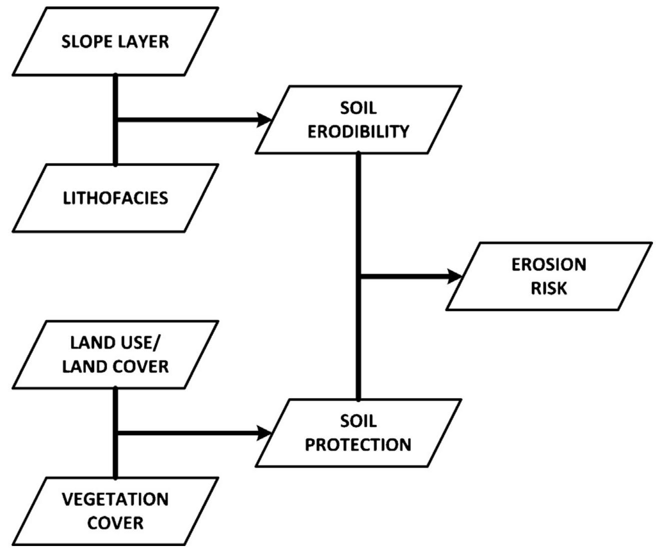


**Fig. 2.** Steps of the ICONA.
model source: Bayramin et al. (2003)

## 3. Methodology

### 3.1. Modelling approach

The ICONA model is an erosion risk assessment method, which uses qualitative decision rules and hierarchical organisation of four main inputs. The mapping of erosion risk follows a multi-step procedure (Fig. 2) where base maps are used to construct four factorial maps, namely, a slope map, a lithofacies map, a land use/land cover map, and a vegetation cover map. These four factorial maps are then combined to produce two thematic maps, i.e., soil erodibility and soil protection maps. Finally, merging soil erodibility and protection maps yields the erosion risk map. It worthy to point out that the ICONA model is a flexible analytical framework that can be easily adapted to account for specific features of the study area (ICONA, 1997).

### 3.2. Maps construction

#### 3.2.1. Slope map

The slope layer is generated from ASTER GDEM Version 2 (METI and NASA, 2011). In addition, five different classes of slope theme expressed in percentages are constructed in ArcGis 10.2. These classes are defined as flat and gentle 0–3%, medium 3–12%, steep 12–20%, very steep 20–35%, and extreme >35%.

#### 3.2.2. Lithofacies map

The lithofacies map identifies the different types of rock or sediment/soil surface on the basis of chemical and physical resistance of different formations to weathering process (ICONA, 1997). Many authors base their classification strategy on geological units of the study area (Bayramin et al., 2003; Zaz and Romshoo, 2012). In this work, we mainly rely on the different type of soils. Actually, soils are surface material often involved in erosion processes. Soils also constitute highly valuable resources and pivotal production factors for the local population. Our classification is based on the cohesive soil characteristics of the study area clustered by the K erodibility factor from the RUSLE equation (Azontonde, 1991; Youssouf et al., 2002). The pedogeological map (Dubroeucq and Faure, 1977) is used to generate the lithofacies map. Table 1 reports the correspondence between the model-implied classes and the soil types found in the study area.

**Table 1**
Correspondence between soil types and lithofacies classes.

| Lithofacies classes (type of material) | Soil types | K Factor |
|---|---|---|
| (1a) Non-weathered compact rock, strongly cemented conglomerates or soils, crusts, hard pans (massif, limestone, highly stony soils, igneous or eruptive rocks) | Water bodies & Settlement | – |
| (2b) Fractured and/or medium weathered cohesive rocks or soils | Ferralitic soil<br>Eutrophic brown soils | 0.05 < K < 0.07 |
| (3c) Slightly to medium compacted sedimentary rocks (slate, schists, compacted marls etc.) and soils | Verti soil<br>Hydromorphic soil | 0.1 < K < 0.2 |
| (4d) Soft, low-resistant or strongly/deeply weathered rock (marl, gypsum, clayey slates, etc.) or soils | Ferruginous soil | K ∼ 0.2 |
| (5e) Loose, non-cohesive sediment/soils and detritic material | undeveloped mineral soils | K > 0.6 |

### 3.2.3. Land use/land cover map

The land use/land cover map drawn in 2006 by the project "BOIS DE FEU – PHASE II" (National Forest Inventory) is a key input of the model. Four LANDSAT 7 ETM+ images acquired in December and January (2006) cover the study area. The images are submitted to a supervised classification using maximum likelihood classification technique implemented in ERDAS IMAGINE (Orekan, 2007). In the context of image classification, the maximum likelihood method is a simple and powerful approach that requires precise inputs (Tehrany et al., 2013; Tehrany et al., 2014). The images are classified by selecting accurate polygons as training areas based on field survey. At least 20 training areas are selected for each land use class. Next, classification results are imported into ArcGIS ESRI for enhancement. For instance, one can increase the image's smoothness by reducing the "salt and pepper" effect. Six Land use classes including barren land, field and fallow, plantation, savanna, woodland, and forest are retained for the ICONA model analysis.

### 3.2.4. Vegetation cover map

The Normalized Difference Vegetation Index (NDVI) provides information about the spatial and temporal distribution of vegetation "greenness" (or photosynthetic activity) and productivity (Reed et al., 1994; Tucker et al., 1985), vegetation biomass (Reed et al., 1994), and the extent of land degradation in various ecosystems (Holm et al., 2003; Thiam, 2003). In the study, we use the NDVI as a proxy for the vegetation cover. The vegetation cover represents the fraction of ground covered by green vegetation or the average percent cover of existing vegetation for a 30-m grid cell. NDVI is retrieved from the MODIS Terra Vegetation Indices available at https://lpdaac.usgs.gov/products/modis_products_table. The MODIS product is a monthly cloud free, 16-day vegetation composite product with a resolution of 5600 m. The NDVI information is extracted with ERDAS IMAGINE and processed in ESRI Arc GIS 10.2. A total of 22 images are obtained covering the entire year of 2006. The raster calculator module in ESRI Arc GIS 10.2 is then used to build an image corresponding to the 2006 average NDVI value. Four intervals of NDVI values are considered for the analysis: (1) <25%; (2) 25%–50%; (3) 50%–75%; (4) >75% (ICONA, 1997).

### 3.2.5. Thematic and erosion risk maps

The erodibility map is generated by overlapping the slope layer and the lithofacies layer. To this end, we use the erodibility matrix (slope vs. lithofacies) reported in the first panel (I) of Table 2. Five (5) classes are selected i.e.: (a) Extreme erosion (EX), (b) high erosion (EA), (c) medium erosion (EM), (d) low erosion (EB), and (e) very low erosion (EN). Thus, the following classification rule is applied: a given area has a low level of erodibility when the slope is low and soils are slowly weathered. By contrast, soil erodibility is considered as extreme when the slope is markedly steep and soils are quickly weathered.

The second panel (II) in Table 2 contains the soil protection matrix constructed by overlapping the land use/land cover and the vegetation cover. In this case, five clusters are retained: very high protection (MA), high protection (A), medium protection (M), low protection (B), and very low protection (MB). The spectrum of land use/land cover (except for barren land) ranges from predominantly open anthropogenic land use type such as field and fallow to closed natural land cover type such as forest. Accordingly, the soil protection is classified as low when land use is of open anthropogenic type and vegetation cover is low. On the contrary, soil protection is high when land cover is of natural closed type and vegetation cover is high. Finally, the erosion risk map is obtained by overlaying the soil erodibility map and the soil protection map. The ICONA erosion risk matrix given in last panel (III) of Table 2 drives our codification rule. A low soil erodibility combined with a high soil protection entails a low erosion risk, while a high soil erodibility combined with a low soil protection induce a high erosion risk.

## 4. Results

### 4.1. Slope map

The map in Fig. 3a illustrates the aerial distribution of the various slope classes. It is immediately clear that the bulk of the studied area (70.2%) has a medium slope, whereas 17.1% of the region features a flat to gentle slope. Nearly 12.7% of the study area located on (or close to) the Atacora mountain hills is characterized by a steep to extreme slope.

### 4.2. Lithofacies map

The lithofacies map (Fig. 3b) reveals that 78.3% of the study area exhibits soft, low-resistant, or strongly/deeply weathered (ferruginous) soils. Moreover, 20.8% of the area has loose, non-cohesive soils including shallow and undeveloped mineral soils. Overall, 95.3% of the study area presents soil characteristics that are more or less highly vulnerable to erosion.

### 4.3. Erodibility map

The erodibility map (Fig. 3c) shows that 12.4% of the study area faces high to extreme level of soil erodibility. For comparison, 20.6% (respectively 67%) of the study area is affected by low (respectively medium) erodibility risk. These findings underscore the importance of the slope in the determination of soil erodibility. The steeper the slope, the higher the soil erodibility risk.

### 4.4. Land use/land cover map

Looking at the land use/land cover map (Fig. 4a), we see that savannas cover the largest portion of the study area (70.9%), followed by fields and fallows (16.3%), woodlands (10.8%), and forests (2%). Plantations, barren lands, settlements, and waters cover 0.3%, 0.3%, and 0.2%, respectively. Note that the land use/land cover map

**Table 2**
Decision rule matrices for map overlapping.

I

| Slope classes | Litho-facies | | | | |
|---|---|---|---|---|---|
| | 1(a) | 2(b) | 3(c) | 4(d) | 5(e) |
| Flat and gentle 0–3% | 1(EN) | 1(EN) | 1(EN) | 1(EN) | 2(EB) |
| Medium 3–12% | 1(EN) | 1(EN) | 2(EB) | 3(EM) | 3(EM) |
| Steep 12–20% | 2(EB) | 2(EB) | 3(EM) | 4(EA) | 4(EA) |
| Very steep 20–35% | 3(EM) | 3(EM) | 4(EA) | 5(EX) | 5(EX) |
| Extreme >35% | 4(EA) | 4(EA) | 5(EX) | 5(EX) | 5(EX) |

II

| Land use types | Vegetation cover | | | |
|---|---|---|---|---|
| | <25% | 25–50% | 25–50% | >75% |
| Barren land | 5(MB) | 5(MB) | 5(MB) | 4(B) |
| Fields & fallows | 5(MB) | 5(MB) | 4(B) | 4(B) |
| Plantation | 5(MB) | 5(MB) | 4(B) | 3(M) |
| Savannas | 5(MB) | 4(B) | 3(M) | 2(A) |
| Woodlands | 4(B) | 3(M) | 2(A) | 1(MA) |
| Forest | 3(M) | 2(A) | 1(MA) | 1(MA) |

III

| Soil protection | Soil erodibility | | | | |
|---|---|---|---|---|---|
| | 1(EN) | 2(EB) | 3(EM) | 4(EA) | 5(EX) |
| 1(MA) | 1 | 1 | 1 | 2 | 2 |
| 2(A) | 1 | 1 | 2 | 3 | 4 |
| 3(M) | 1 | 2 | 3 | 4 | 4 |
| 4(B) | 2 | 3 | 3 | 5 | 5 |
| 5(MB) | 2 | 3 | 4 | 5 | 5 |

I—(1a) Non-weathered compact rock, strongly cemented conglomerates or soils, crusts, hard pans (massif, limestone, highly stony soils, igneous or eruptive rocks); (2b) Fractured and/or medium weathered cohesive rocks or soils; (3c) Slightly to medium compacted sedimentary rocks (slate, schists, compacted marls etc.) and soils; (4d) Soft, low-resistant or strongly/deeply weathered rock (marl, gypsum, clayey slates, etc.) or soils; (5e) Loose, non-cohesive sediment/soils and detritic material.
Extreme erosion (EX), high erosion (EA), medium erosion (EM), low erosion (EB) and very low erosion (EN).
II—Very high protection (MA), high protection (A), medium protection (M), low protection (B) and very low protection (MB).
III—Very high risk (5), high risk (4), medium risk (3), low risk (2), very low risk (1).

reveals seven (7) distinct classes, but only six classes are considered for the subsequent analysis. The settlement and water class is discarded in the construction of soil protection map.

### 4.5. *Vegetation cover map*

The vegetation cover map (Fig. 4b) shows that 66.7% of the study area has a vegetation cover ranging between 25%-50%. A higher vegetation cover level (50%-75%) is observed for 33% of the study area.

### 4.6. *Soil protection map*

The map in Fig. 3c gives the soil protection map obtained by combining the land use/land cover map with the vegetation cover map. The spatial representation indicates that 7% of the study area soil is highly protected, 27.2% is mildly protected, whereas 65.6% has a low level of protection.

### 4.7. *Erosion risk map*

The erosion risk map suggests that 21.8%, 58.5%, and 19.5% of the study area face very low to low, medium, and high to very high erosion risk, respectively (Fig. 5). Three clusters of erosion risk emerge from the spatial aggregation of the risk level measured by district (Table 3):

**Table 3**
Spatial distribution of erosion risk classes at district level.

| Districts | Erosion risk classes | | |
|---|---|---|---|
| | High + Very high | Medium | Very low + Low |
| Boukoumbe (type 1) | 42% | 41% | 17% |
| Kerou (type 2) | 21% | 60% | 19% |
| Kobli (type 2) | 37% | 42% | 21% |
| Natitingou (type 2) | 24% | 56% | 19% |
| Kouande (type 3) | 19% | 61% | 20% |
| Materi (type 3) | 22% | 53% | 25% |
| Pehunco (type 3) | 18% | 58% | 23% |
| Tanguieta (type 3) | 11% | 65% | 24% |
| Toucountouna (type 3) | 14% | 59% | 26% |

(1) Areas in Boukoumbe district face high erosion risk. This observation is driven by the type of land use (fields and fallows cover 30% of the district area) and high slope values (steep, very steep, and extreme slope areas cover 30% of the district surface).
(2) Areas in Kerou, Kobli, and Natitingou districts face high to medium erosion risk. These areas commonly present a large coverage of land uses such as fields, fallows, and settlements but less frequent high slopes.
(3) Areas in Kouande, Materi, Pehunco, Tanguieta, Toucountouna districts face low to medium level of erosion threat.

Moreover, we find that 4.8% of the Pendjari National Park's area (located inside the study area) faces a very high risk of erosion because of the combination of low soil protection and high (64.4% of Pendjari park surface) to extreme (35.6% of Pendjari park surface) erodibility levels. Into the park, the most widespread types are: steep slope, ferruginous soil, woodland land use and

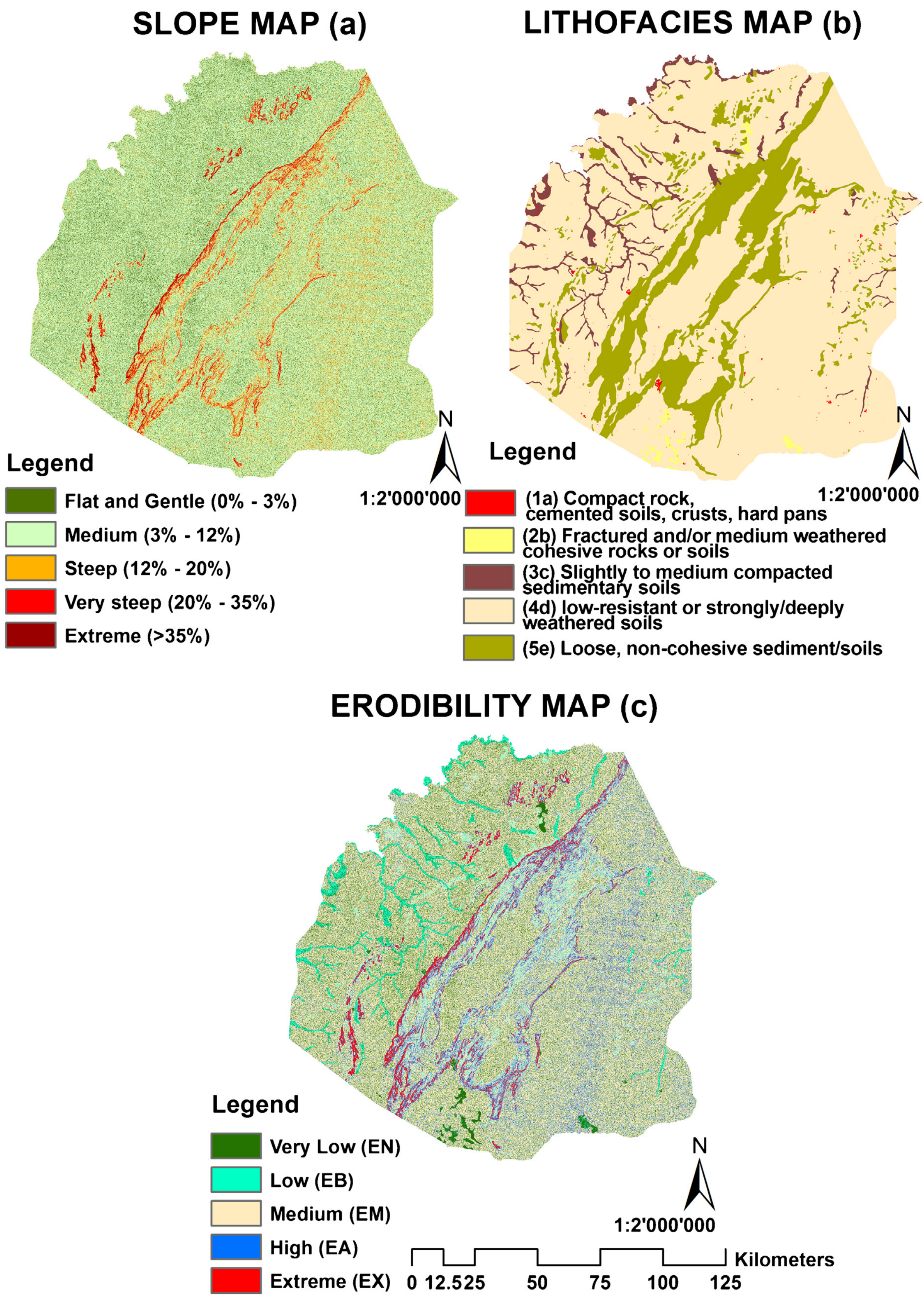


**Fig. 3.** Maps of slope (a), lithofacies (b), erodibility (c).

25% – 50% vegetation cover (44.9%, 55.3% 84.7%, 96.7% of Pendjari park surface respectively).

The erosion risk distribution by land use types shows that natural vegetation such as savannas, woodlands and forests have 11.7%, 16.3%, and 0.9% of their corresponding coverage areas facing high

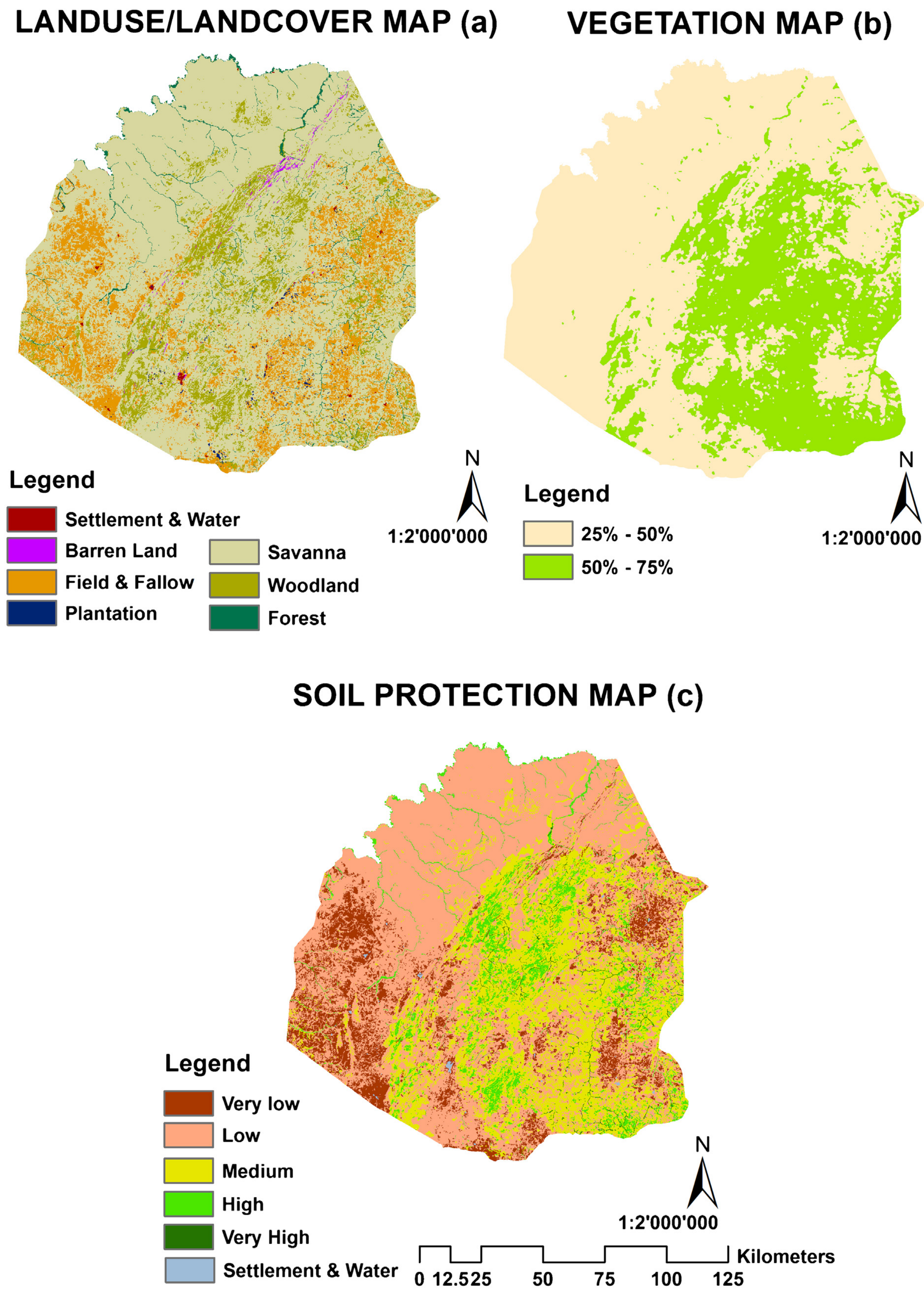


**Fig. 4.** Maps of land use/land cover (a), vegetation cover (b) (% vegetation cover stands for fraction of ground covered by green vegetation), soil protection (c).

to very high erosion risk. At the same time, the anthropogenic land use types reveal that 44.7% of plantations, and 56.4% of fields and fallows are under high to very high erosion risk. When we turn our attention to the erosion risk distribution by slope levels (Fig. 6), we notice that flat (respectively gentle) slope areas have 23% (respectively 73%) of their corresponding surface under very

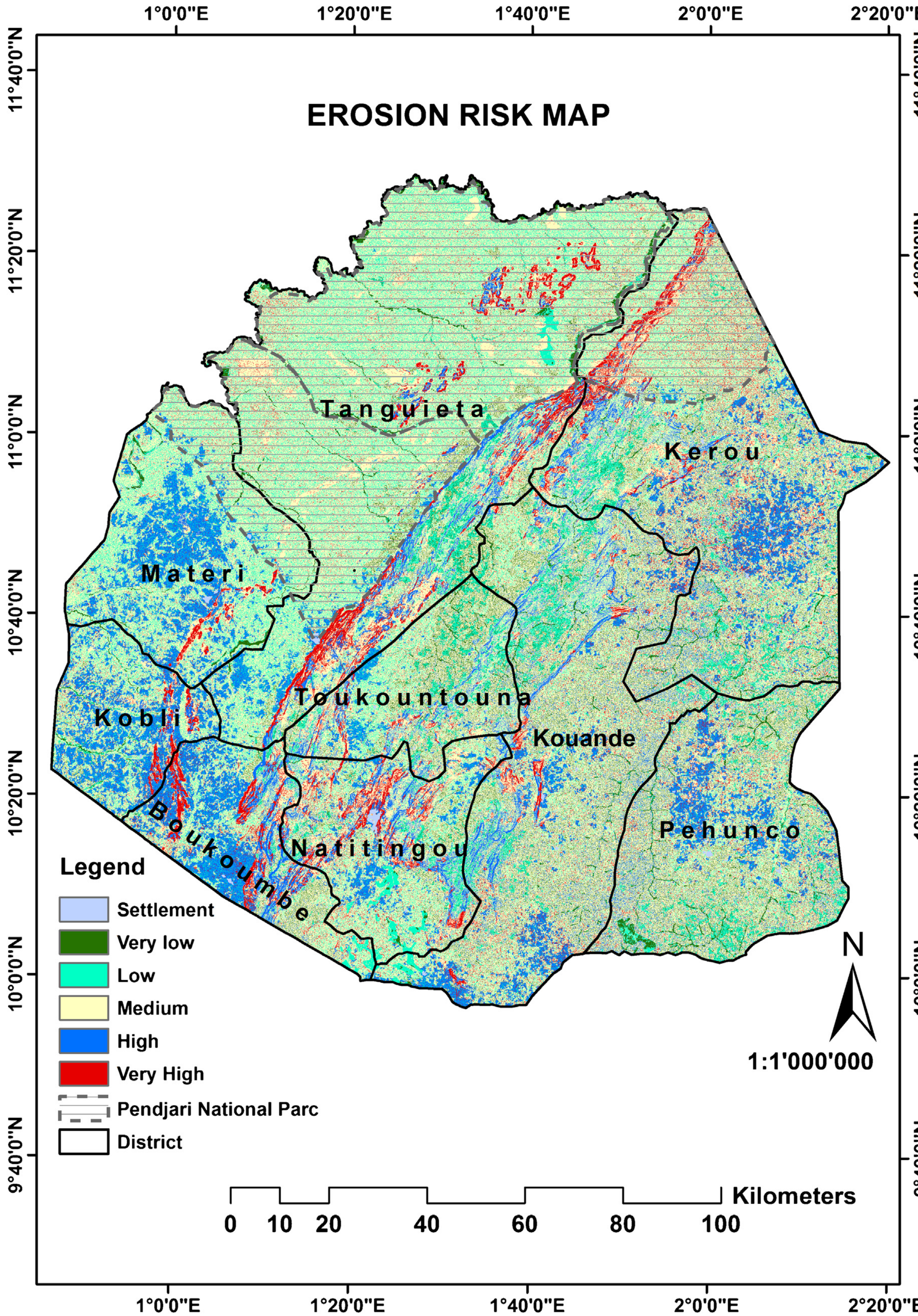


**Fig. 5.** Erosion risk map (two column).

low (respectively low) erosion risk. Moreover, medium slope areas present medium (respectively high) erosion risk on 81% (respectively 12%) of their corresponding surface and steep (respectively very steep and extreme) slope areas present 87%, (respectively 99 and 100%) of corresponding coverage areas under high and very high erosion risk. We also notice that the coverage areas of field

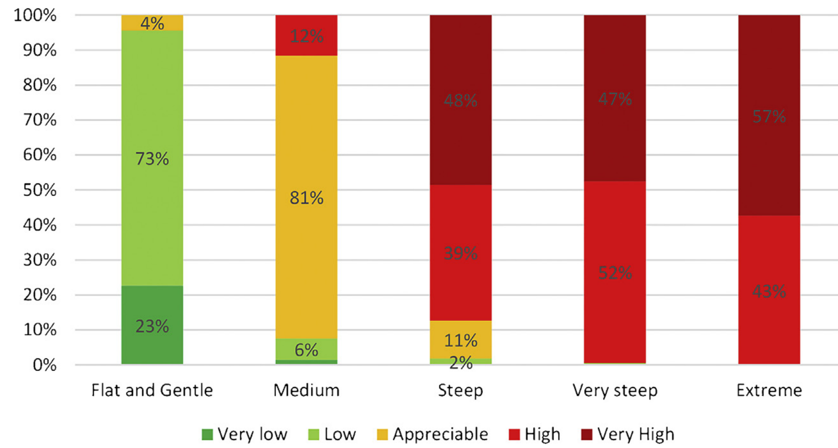


**Fig. 6.** Distribution of the ICONA erosion classes on different slope classes.

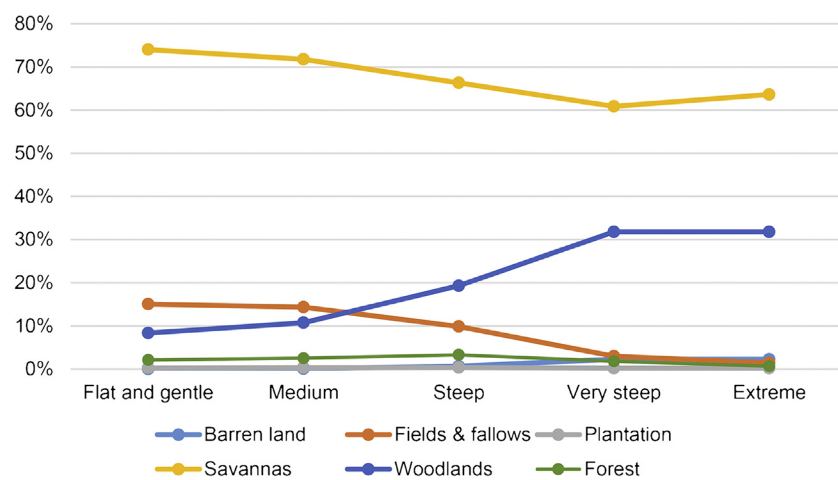


**Fig. 7.** Distribution of the land use types on different slope classes.

and fallows decrease from flat and gentle slope area (15%) to very steep part of the study area (1.4%) and natural vegetation like woodland showed an increase of its cover from 8.3% on flat and gentle area to 31.8% on very steep area (Fig. 7).

## 5. Discussion

We find and document that 17% of the natural vegetative cover (savannas, woodlands, and forests) face high to very high erosion risk. Analogously, more than 40% of the surface cover by various anthropogenic land uses (plantations, fields, and fallows) is under high to very high erosion threat. The distribution of erosion risk classes by land use types confirms the positive impact of existing natural vegetation on erosion risk. This evidence is in line with previous studies carried out in China (Luo et al., 2014) and Nigeria (Oruk et al., 2012), documenting that areas with lower vegetation cover suffer from greater soil erosion. Moreover, in mountainous and hilly regions with fragile ecosystems (Wolka et al., 2015) similar to our study area, soil erosion levels and patterns are very sensitive to the type of in-situ land cover (Cebecauer and Hofierka, 2008; Stanchi et al., 2013). For instance, Schiettecatte et al. (2008) report that land degradation and soil loss increases from forests to cultivated lands.

Our results also imply that areas with flat, gentle or medium slope experience very low to medium erosion risk, consistent with the evidence reported in Morocco by Gaatib and Larabi (2014) and in Ethiopia by Wolka et al. (2015). We further notice that steeper parts (hills of Atacora Mountain chain) of our study area characterized by a high erosion risk, are less disturbed by agricultural activities than lower slope parts. Fields and fallows cover decreases from flat and gentle to steep and very steep parts of the study area, while woodlands cover increases. These findings are in accordance with the work of (Okou et al., 2014) who argue that higher slope constitutes a natural protection against land degradation in this region. A research conducted inside and around Bukit Barisan Selatan National Park located on the Indonesian island of Sumatra leads to a similar conclusion: conversion to arable land of lowland forests often located on gentle slopes is much higher and faster than that of hill forests commonly found on steep slope areas Kinnaird et al. (2003). Nevertheless, increasing demographic pressures and land demand for agricultural activities threaten the conservation of montane ecosystems as well. According to Wolka et al. (2015), the combination of steep slope, low vegetation cover, along with erosive rainfall or extreme weather situations, induces a non-tolerable soil erosion problem. Therefore, erosion risk mitigation strategies in the study area should focus on the protection of steep slope areas. In Pendjari National Park, the combination of steep slope, ferruginous soil (sensitive to erosion) and low vegetation cover appears to be a critical driver of high erosion risk. Thus, planting trees on steep slope areas seems clearly adequate and beneficial, as it will stabilize the land and significantly reduce soil loss.

The validation of the erosion risk map is also an important aspect of the proposed analysis. This can be achieved through a quantitative assessment such as the execution of erosion measurements

(Stroosnijder, 2003). Alternatively, one may rely on quantitative surveys such as repetitive measurements of rill volumes (Bewket and Sterk, 2003). Note that the implementation of these validation techniques in order to get reliable data on erosion processes is labour intensive and time consuming. Thus, it is very difficult in practice to perform a large scale quantitative validation of the erosion risk map. From a practical perspective, an appealing alternative is to conduct a qualitative validation of regional erosion maps, as advocated by (Vrieling et al., 2006). In this work, the validation is done by comparing the erosion risk map to a land degradation status map. A 2008 "National Self-assessment of Capacities to Enhance for the Management of Global Environment" project report contains a qualitative assessment of the study area degradation status based on expert-folk opinions. In that report, each district was classified and mapped according to the most widespread degradation status, i.e., slight, average and extreme degradation (ANCR-GEM et al., 2008). In our erosion risk map, very high and high erosion risk levels are merged into a single class corresponding to extreme degradation status, while very low and low erosion risk levels are merged into a class corresponding to slight degradation status. These two maps are then submitted to cross tabulation analysis into IDRISI Selva software. They show a fair intensity of association (Cramer's V index = 0.6) and a low level of correspondence, as evidenced by an overall kappa index of 0.37. Note that in our study, we use districts as base units for comparing degradation status map, whereas the comparison units for erosion risk map are pixels with a resolution of 1 arc second. This discrepancy could explain the weak correspondence between these two maps. As mentioned earlier, the validation of erosion risk maps for large areas is a challenging task. This may explain why articles on erosion risk tend to skip the validation step (Jürgens and Fander, 1993; Li et al., 2006; Lu et al., 2004; Reusing et al., 2000; Shrimali et al., 2001; Vaidyanathan et al., 2002). In our study, the vegetation cover map is extracted from the NDVI MODIS product that has a low resolution of 5600 m. Recall that vegetation cover is a key driver of erosion patterns, as shown in various studies on regional erosion assessment for mountainous regions (Bou Kheir et al., 2006; Okoth, 2003; Okou et al., 2014; Vrieling et al., 2006). The (low) resolution of the vegetation cover map used in our model seems to be insufficient to accurately estimate the local vegetation cover variation, thus reducing the erosion risk map precision.

The erosion risk map can be updated as new observations become available. In the context of paucity of available data, the ICONA model is a reliable framework for the assessment of erosion risk (Bayramin et al., 2003; ICONA, 1991, 1997; Zaz and Romshoo, 2012). The ICONA model is flexible, as it allows for an effective adjustment of decision rule matrices to meet specific conditions in each country or region (ICONA, 1997). In the same vein, one must view our findings as guidelines for designing efficient soil and water conservation policies. Indeed, each type of area requires the implementation of targeted resource (soil and water) management measures. Type (1) areas, namely the district of Boukoumbe, should be prioritized when implementing compensation and conservation measures. The institutions conducting soil and water conservation strategies should focus their limited financial and human resources and efforts on small areas (Vrieling et al., 2006). The erosion-risk map offers information on the location of problematic areas and suggests where immediate erosion mitigating interventions should be carried out. In that regard, the proposed erosion risk map extends the set of tools that could be used by scientists and decision makers in Benin.

## 6. Conclusion

This study highlights the analytical value of embedding Geographic Information System (GIS) data into the ICONA model to better-assess potential erosion risk in a large region including the Atacora Mountain range. The model includes erosion factors such as slope, soil properties, land use/land cover, and vegetation cover. Decision rules take into account expert knowledge on erosion processes. The resulting erosion risk map allows to identify areas experiencing a high risk of erosion. The bottom-up nature of this study paves the way for future research on small-scale to global erosion risk measurement in the area. Targeted and cost-effective soil conservation policies will also greatly benefit from our findings.

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