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Rainfall erosivity, soil erodibility and natural water erosion potential in the Huambo region, Angola

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Abstract

The use of erosion assessment methods is critical for the sustainability of land use in tropical and subtropical regions, especially in countries lacking national information on soil erosion development, which is the case of Angola. This study aimed to evaluate the rainfall erosivity (R), soil erodibility (K), soil loss tolerance (T) and natural erosion potential (NEP) in Huambo (Angola). The R value estimated for a 25-year period was 7463 MJ mm ha^{-1} h^{-1} y^{-1}. K values estimated from 25 soil profiles, described in the Soil Map of Angola, varied from 0.021 to 0.247 t ha h ha^{-1} MJ^{-1} mm^{-1}, respectively, in yellow ferralitic and paraferralitic soils (Ferralsols) and brown psamitic soils (Arenosols). A two-principal component (PC) model for soil erodibility variables explained 61.7 % of total variance. PC1 was related to particle size distribution and soil erodibility, pointing to a positive correlation between sand content in the soil superficial horizons and K. PC2 expressed soil loss vulnerability, with negative factor loading for soil loss tolerance. The cluster analysis (CA) grouped Arenosols in a significant cluster located in the positive quadrant of PC1, therefore, more erosion prone. The NEP average value found was of 605 t $ha^{-1}y^{-1}$. The obtained results raise awareness concerning soil degradation by water erosion and can be of value for decision-makers and for farmers and land users, contributing to the sustainability of agriculture in Huambo.

Keywords: Arenosols, Ferralsols, multivariate statistical analysis, soil degradation, soil erosion, tropical and subtropical regions

1 Introduction

Soil erosion is one of the greatest environmental threats to the productive capacity and sustainability of agriculture. The most common process is erosion by water, which causes about 55 % of total global erosion (Bridges & Oldeman, 1999). Soil erosion impacts involve the relocation and loss of soil within/from a field, a decline in organic matter, in soil structure, in nutrients content, and in soil fertility (Ketema & Dwarakish, 2019). Furthermore, sediment transport to water bodies also affects the water quality due to adsorbed chemicals, which can result in eutrophication and pollution impacts (Kothyari, 2008). Thereby, soil erosion decreases the overall ability of the soil to provide ecosystem services and, consequently, food security, as it is related with the carbon cycle, soil fertility, crop production and water quality (Labrière *et al.*, 2015; Adhikari & Hartemink, 2016; FAO 2019;). In tropical areas, soil erosion is one of the most destructive and insidious processes of soil degradation, steadily increasing as a result of anthropogenic activities, and raising many concerns regarding the potentially damaging impacts of land use in relation to the often fragile or non-existent land management initiatives (Millward & Mersey, 1999). Current research on soil erosion assessment should focus on prioritizing countries lacking national information on soil erosion and using global datasets with focus on areas where data is missing (FAO, 2019).

In Angola, approximately 40 percent of the population lives in rural areas and these inhabitants depend directly on agriculture and agricultural related activities to sustain their livelihood (Carranza & Treakle, 2014). The independence of

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Angola in 1975 was followed by nearly 30 years of civil war that devastated the commercial and academic infrastructure and destroyed agricultural productivity and scientific progress in the country (Asanzi *et al.*, 2006). After the end of the war, in 2002, the recovery of the agricultural sector has been hindered by multiple factors, including the collapse of internal trade and distribution structures, insignificant levels of domestic credit for agriculture and livestock, poor institutional support, climate change, poor agricultural productivity, or degradation of agricultural land (ACDI-IFAD, 2016). This situation makes it difficult to assess the land use potentials and vulnerabilities, such as the potential areas of soil degradation by erosion. The use of suitable assessment methods is urgently needed since it is crucial for the sustainability of land use.

One of the most well-known models for the estimation of soil erosion is the Universal Soil Loss Equation (USLE) developed by Wischmeier & Smith, (1978), later updated to RUSLE – the revised USLE (Renard *et al.*, 1997). The RUSLE is based on five factors to predict an average annual soil loss from splash, sheet and rill erosion (A; $t\,ha^{-1}\,y^{-1}$): $A = R \times K \times LS \times C \times P$, where R is rainfall erosivity factor ($MJ\,mm\,ha^{-1}\,h^{-1}\,y^{-1}$), K is the soil erodibility factor ($t\,ha\,h\,ha^{-1}\,MJ^{-1}\,mm^{-1}$), LS is the slope-length and steepness factor, C is the cover management factor, and P is the conservation practice factor. While the C and P factors represent the influence of the anthropogenic activities, mainly agriculture, the remaining are physical factors. In fact, the knowledge of the rainfall intensity and energy, of the soil properties and hydrological characteristics and of the topographic conditions, represented by the factors R, K and LS, respectively, allows to make inferences about the natural erosion potential (NEP) at regional scales, without the influence of the spatial variability of the cover management and conservation practice factors. Several studies have been made using this approach at different scales, from basin level (Correa, 2012; Morais & Sales, 2017) to sub-regional level (Mello *et al.*, 2006). These studies have shown the importance of the assessment of potential risks of soil degradation for land use planning by policymakers and for on-farm management decisions by farmers, contributing to the sustainability of the agricultural sector.

Taking the above in consideration, the objectives of this study were: (i) to evaluate the erosivity of the climate and the erodibility of the soils in the province of Huambo, in Angola; (ii) to assess the natural erosion potential and the tolerance of soil loss associated with different types of soils in the province of Huambo. With our results we aim to contribute for the implementation of decision-making tools for soil erosion control in Angola and in tropical regions, in general.

2 Materials and Methods

2.1 Study region

Huambo is a province of Angola with an area of 29827 km^2 located in Central Angola, specifically in the *Planalto* midland plateau region, at 1,500 to 2,000 m asl of altitude, with a dry-winter subtropical highland climate (Cwb, according to Klöppen classification). The Huambo climate presents a bimodally distributed rainfall which begins in October and extends until April, declining sharply during the dry season from May to August (Asanzi *et al.*, 2006). In the absence of recent time series, records of climatic variables at the Meteorological Station of Nova Lisboa (pre-independence name of the provincial capital, currently named Huambo), were used in this study. The average annual precipitation for a 25-year period (1951-1975) was 1,259 mm and the average mean monthly temperature was 18.9 °C. For the same period, the average annual reference evapotranspiration computed with the Hargreaves equation, as described in Allen *et al.*, (1998), was 1,269 mm.

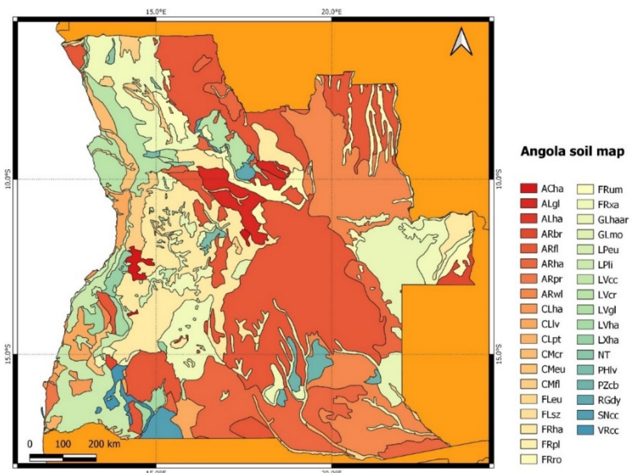

Fig. 1: *Reference Soil Groups of the WRB in Angola (built after Dewitte et al., (2013)). Legend of the soil groups and qualifiers in supplementary file Appendix 1.*

Although there has not been any significant research since independence, a survey of soils of the region was carried out by Missão Pedológica de Angola (1961) and a Soil Map of Angola was published with the description of a large number of soil profiles, containing useful information, such as soil organic content (% SOM), particle size distribution (% sand, silt and clay), or free iron oxide content (% $FeH_2\ OH_3$). Recently, a data set of the soil map of Africa was developed by Dewitte *et al.* (2013) from which the soil map of Angola presented in Fig. 1 was made (Angola Soil Map Legend in the supplementary file Appendix 1). The predominant soil types in Huambo are Ferralitic, belonging to the

Reference Soil Group of Ferralsols in the World Reference Base (WRB) for soil resources (IUSS Working Group WRB, 2015). Ferralsols are widespread in Central, Eastern and Southern Africa (Jones *et al.*, 2013). In Angola, they are the predominant soil type across the western and central plateaus (Fig. 1).

Their occurrence is mostly associated with high rainfall areas and very old (Tertiary) land surfaces. Jones *et al.* (2013) identified the maintenance of soil fertility and the prevention of surface soil erosion as the most important management requirements in these soils. For the purpose of this study, we used the data of particle size distribution, SOM and $Fe_2 O_3$ of 25 soil profiles of the Huambo province described in Missão Pedológica de Angola (1961) (Table 1). In Ferrasols soil profiles, surface horizon textures vary from loamy sand to sandy clay loam; in the case of Arenosols, sand and loamy sand textures prevail. The surface horizons SOM vary from low (14.0 $g\,kg^{-1}$ in Brown psamitic soils with lateritic materials) to very high (81.5 $g\,kg^{-1}$ in Humic psamo soils with lateritic materials).

According to the Coppernicus Global Land Service (Buchhorn *et al.*, 2020), the main types of land cover in Huambo in 2019 were forests (44.8 %) and cropland (25.0 %) (supplementary file Fig. S1). Data reported by CountrySTAT Angola (2014) indicate that the most important crops in Huambo in 2014 were: maize (*Zea mays* L.) with an area of 424054 ha; beans (*Phaseolus vulgaris L.*), with 139783 ha; peanuts (*Arachis hypogaea L.*), 24988 ha; potato (*Solanum tuberosum* L.), 21969 ha; sweet potato (*Ipomoea batatas* (L.) Lam), 14772 ha; cassava (*Manihot esculenta* Crantz), 14241 ha; soybean (*Glycine max* (L.) Merrill), 10236 ha. Maize is normally intercropped with beans, peanuts, sweet potato and/or cassava. Most of this land is managed by smallholder subsistence farmers that practice rainfed agriculture, thereby, dependent on the rainy season (ACDI-IFAD, 2016).

2.2 Natural erosion potential

The natural erosive potential (NEP; t $ha^{-1}y^{-1}$) is the product of the non-anthropogenic factors in the USLE model (Mello *et al.*, 2006) given by:

$$NEP = R \times K \times LS \tag{1}$$

The R factor is the average of annual EI30 values, that is, the total kinetic energy (E) multiplied by the maximum 30-minute intensity (I30) of every single storm, over long-time intervals (over 20 years) (Wischmeier & Smith, 1978). Thus, its calculation is dependent on continuous recording rain gauges with time resolution of at least 15 minutes which makes it difficult to determine the R factor in many regions where good spatial and temporal data coverage is scarce (Hernando & Romana, 2015). To overcome these difficulties, several methods have been proposed to estimate R based on easily available rainfall data. Arnoldus (1980) proposed a modification of the Fournier index, known as the modified Fournier index (MFI), as presented in equation 2:

$$MFI = \sum_{i=l}^{12} \frac{P_i^2}{P} \tag{2}$$

where Pi is the monthly rainfall (mm) and P is the annual rainfall (mm).

The estimation of rainfall erosivity from the MFI has been used in several erosion studies, e.g. Lombardi Neto & Moldenhauer (1992), Men *et al.* (2008), Olivares *et al.* (2011), Demirci & Karaburun (2012), or Prasannakumar *et al.* (2012). Recently, Morais & Sales (2017) applied the methodology developed by Lombardi Neto & Moldenhauer (1992) to estimate the value of R, in regions with tropical and subtropical climates, from the monthly values of the Erosion Index (EI; MJ mm ha^{-1} h^{-1}) using equation 3:

$$EI = 67.355 \left(\frac{Pi^2}{P} \right)^{0.85} \tag{3}$$

with R (MJ mm^{-1} h^{-1} y^{-1}) calculated from the sum of EI through the year:

$$R = \sum_{i=l}^{12} EI \tag{4}$$

According to Renard *et al.* (1997), soil erodibility should be viewed as the change in the soil per unit of applied external force or energy. The soil erodibility factor (K) represents the ease with which soil is detached due to the impact of raindrop and the rate and amount of runoff produced, depending upon geological and soil features like structure, texture, inherent material, porosity, and organic content (Ghosal & Das, 2020). Since the direct measurement of K requires the establishment and maintenance of natural runoff plots over lengthy, expensive observation periods at various locations, numerous attempts have been made to establish estimators for soil erodibility from readily available soil property data (Wang *et al.*, 2016). Given the lack of data, in this study we adopted the methodology presented by Mannigel *et al.* (2002) for calculating the K factor, which is based on the Bouyocos formula, as presented in equation 5 (Bertoni & Lombardi Neto, 2005):

$$K = \left(\frac{S + Si}{C} \right) / 100 \tag{5}$$

Table 1: *Soil types found in Huambo province according to the Soil Map of Angola (Missão Pedológica de Angola, 1961) and suggested Reference Soil Groups of the WRB (IUSS Working Group WRB, 2015) (based on Dewitte et al. (2013) and Jones et al. (2013))*

Soil type from the Soil Map of Angola	Code	Number of profiles	Reference Soil Group (WRB)
Red ferralitic-type soils (eruptive rocks)	FR	1	Ferralsols, Lixisols
Yellow ferralitic-type soils (eruptive rocks)	FY	4	
Yellow or orange weakly ferralitic soils (eruptive rocks)	WFY	9	
Yellow or orange paraferralitic soils (clayey rocks)	PFY	1	
Brown to white paraferralitic soils (clayey rocks)	PFB	2	
Diverse soils with lateritic material near the surface	DS	2	Arenosols, Leptosols
Psamoferralitic soils	PSF	2	Arenosols
Brown psamitic soils with lateritic materials	PSB	2	
Humic psamo soils with lateritic materials	PSH	2	

where S, Si and C are the sand, silt and clay content (%), respectively. Considering that the textural gradient of the clay fraction between the superficial and subsurface horizons affects the permeability, drainage and erodibility of the profile, the K factor in the various soil profiles was obtained by the sum of the average values of erodibility, weighted by the depths of the surface and subsurface horizons (Demarchi & Zimback, 2014). In the absence of *in situ* data of slope and length, for the purpose of this study we considered a unit value for the LS factor, representative of a basic slope length and slope gradient of, respectively, 22.13 m and 9 %, as defined by Wischmeier & Smith (1978).

2.3 Tolerance of soil loss

The tolerance of soil loss through erosion refers to the limit of loss that still maintains a high level of crop productivity, economically and indefinitely (Bertol & Almeida, 2000). It can be obtained from variables such as the effective depth of the soil and the textural ratio between subsuperficial and superficial horizons (Lombardi Neto & Bertoni, 1975; Bertol & Almeida, 2000; Mannigel *et al.*, 2002), using:

$$T = \frac{h \times f}{1000} \tag{6}$$

where T is the tolerance of soil loss (mm y^{-1}), h is the depth of the soil profile (mm), limited to a 1 m depth, f is a correction factor that expresses the effect of the clay textural ratio (RT) between the subsurface and surface horizons on weighting soil losses, and 1000 is a constant that expresses the period of time (years) necessary to erode a 1 m depth soil layer, disregarding the ratio of soil formation during that period, an assumption that explains the procedure of limiting the effective soil depth to one meter in calculating the soil loss tolerance (Bertol & Almeida, 2000). The clay textural ratio was computed using:

$$RT = \frac{C_{Hor.B}}{C_{Hor.A}} \tag{7}$$

where $C_{Hor.B}$ is the average clay content (%) in the subsuperficial horizons, and $C_{Hor.A}$ is the average clay content (%) in the superficial horizons, weighted by their respective depths. A high RT indicates a lower infiltration capacity in subsuperficial horizons, thereby accelerating the erosion intensity of the soil surface. Therefore, Bertoni & Lombardi Neto (2005), proposed the correction factor f, in (Eq. 9), for the conversion to a definitive soil loss tolerance, to assume the following values: f = 1.0, if RT < 1.5; f = 0.75, if 1.5 ≤ RT ≤ 2.5, and f = 0.50, if RT > 2.5.

2.4 Statistical Analysis

Statistical analyses were made using Statistica 7 (StatSoft, Inc., 2004). A Principal Components Analysis (PCA) was computed with standardized soil data to reduce de number of variables into a small number of independent variables (principal components). The principal components (PC) were retained when presenting eigenvalues > 1 that accounted for a proportion of variance > 10 %. The factor loadings of the first two PC, representing the correlation between the PC and the variables, were plotted accompanied by plots of PC scores of cases (soil profiles). Hierarchical agglomerative cluster analysis (CA) was performed with the factor scores of the first two PC to detect similarity groups between cases. The Euclidean distance for similarity measures was used as linkage distance (dlink), expressed as the percentage of the range from the maximum to the minimum distance (dmax) in the data, dlink/dmax*100. Statistically significant clusters were identified considering Euclidean distances < 40 %.

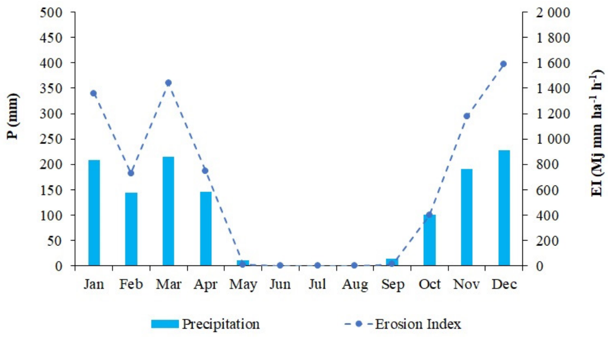

Fig. 2: *Average monthly precipitation (P) and average erosion index (EI) for the period 1951-1975 in Huambo.*

3 Results

3.1 Rainfall erosivity

The monthly erosivity index (EI) followed a bimodal distribution in close relation with the monthly precipitation pattern (Fig. 2). An R factor of 7,463 MJ mm ha^{-1} h^{-1} y^{-1} was estimated for the Huambo region. The highest values of EI occurred from November to March, comprising 84 % of the annual erosivity.

3.2 Soil erodibility and tolerance of soil loss

With the exception of the FY and PFY soils, that presented moderate K values (in the range 0.015 to 0.030, according to the classification proposed by Mannigel *et al.* (2002)), all other soil types had average erodibility from very high (0.045 – 0.060) to extremely high (> 0.060) (Table 2). The RT values varied from 0.89 in Arenosols, PSF and PSH, to 2.19 and 2.51 in the FR and PFB soil types, respectively. It should be expected that tolerance of soil loss presented an inverse relationship with K values, which was not the case. While Yellow or orange paraferralitic soils (PFY) showed the lowest T (0.60 mm y^{-1}), Yellow ferralitic-type (FY) and Psamoferralitic soils (PSF) presented the higher values (0.95 and 1.00 mm y^{-1}, respectively), thus, there is not a clear inverse relationship between erodibility and soil loss tolerance.

The PCA results from soil data can be observed in Fig. 3. The first two principal components (PC1 and PC2) explained, respectively, 43.3 % and 18.4 % of the variance in the model (Fig. 3a). PC1 was a component related to particle size distribution and soil erodibility.

The largest contributor to PC1 was the sand content (S), with a factor loading of 0.966, followed by the clay content (C), and silt content (Si), which present negative loadings of, respectively, -0.893 and -0.736. Moreover, K contributed to this PC with a loading of 0.666. Hence, it can be deducted

Table 2: *Descriptive statistics (Mean ± standard error, when applicable) of textural ratio (RT), tolerance of soil loss (T), and soil erodibility (K) for the studied soil types of Huambo.*

Soil type*	K (t·ha·h·ha^{-1}·MJ^{-1}·mm^{-1})	RT (%)	T (mm·y^{-1})
DS	0.095 ± 0.047	1.44 ± 0.42	0.81 ± 0.06
FR	0.077	2.19	0.75
FY	0.025 ± 0.009	1.19 ± 0.04	0.95 ± 0.03
PFB	0.067 ± 0.003	2.51 ± 0.78	0.63 ± 0.13
PFY	0.021	1.34	0.60
PSB	0.247 ± 0.139	1.36 ± 0.19	0.75 ± 0.00
PSF	0.191 ± 0.048	0.89 ± 1.14	1.00 ± 0.00
PSH	0.096 ± 0.001	0.89 ± 0.08	0.73 ± 0.28
WFY	0.049 ± 0.011	1.61 ± 0.14	0.89 ± 0.04

* Legend for the types of soils can be found in Table 1.

that K is positively correlated with S and negatively correlated with C and Si, which is in accordance with Miguel *et al*. (2021) that found a relationship between erodibility and sandy loam textures in soils of Rio Grande do Sul (Brazil). The PC2 was positively loaded with RT (0.885) and negatively with T (-0.547), thus expressing a factor of soil loss vulnerability. Furthermore, it was observed that SOM locates in the same quadrant of T, thereby, a relation between SOM content and soil resilience regarding erosion was evidenced.

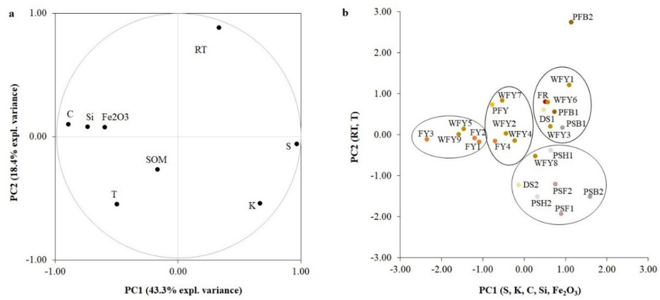

Fig. 3: *PCA results: a) Loading plot of variables of the first two components (PC1 and PC2). b) Score plot of cases of the first two components. Ellipses represent significant clusters with dlink/dmax*100 < 40 %. RT – textural ratio; T – tolerance of soil loss; K – erodibility factor; S – Sand content; Si – Silt content; C – Clay content; SOM – Soil organic matter content; Fe_2O_3 – Free Iron oxide content. Legend for the types of soils can be found in Table 1. Numbers next to soil codes correspond to the profile in each type of soil.*

In the biplot representing the factor scores of cases, four significant clusters can be observed (Fig. 3b). The clustering pattern was mainly soil type-controlled, with Ferralsols grouped in three clusters and Arenosols in the remaining. In fact, with the exception of the DS1 soil profile, all Arenosols profiles were grouped in a cluster located in the quadrant of positive loadings in PC1, thus positively correlated with S, and more importantly, with K. No cluster is clearly related with T, pointing to the vulnerability of the studied profiles of the Huambo region to soil loss.

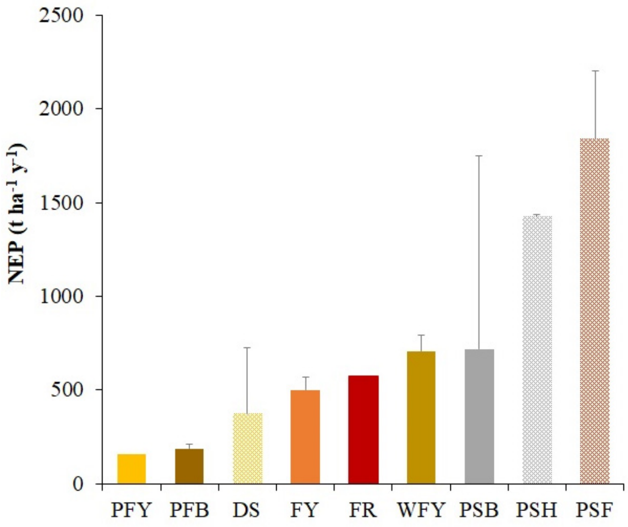

Fig. 4: *Average natural erosion potential (NEP) of soils in Huambo. Whiskers represent the standard error. Legend for the types of soils can be found in Table 1.*

3.3 Natural erosion potential

The NEP values of the 25 soil profiles of Huambo varied from 38.6 to 2,874.2 t ha^{-1} y^{-1}, with an average value of 605 t ha^{-1} y^{-1}. Within the 25 studied profiles, 8 % presented extremely high NEP, above 1600 t ha^{-1} y^{-1}; a NEP moderate to high, varying from 400 to 1600 t ha^{-1} y^{-1}; was found for 48 % of the profiles; the remaining profiles presented NEP lower than 400 t ha^{-1} y^{-1}.

4 Discussion

Both the high R value encountered for Huambo and the seasonal (bimodal) rainfall erosivity distribution should be a concern regarding crop management practices that leave land exposed to agri-environmental degradation, like soil tillage or sowing along the maximum slope gradient, and cultivation patterns that allow for periods of bare soil during the rainy season. The R value is higher than the ones found by Aquino *et al*. (2006), in the range 3,516 – 6,877, or by Morais & Sales (2017), 5,475 – 7,340, in a dry subhumid climate of Northeast Brazil. In humid subtropical climates in Campinas and Rio Grande do Sul (Brazil), Lombardi Neto & Moldenhauer (1992) and Miguel *et al*. (2021), found average annual R values of 6,738 and 6,556, respectively. There is an influence of the altitude in the region over its rainfall amount and distribution that could explain higher erosivity rates than the ones found for similar subtropical climates by Lombardi Neto & Moldenhauer (1992) and Miguel *et al*. (2021). A similar approach of approximate the R factor from sparce data in a humid subtropical mountainous region was used by Schönbrodt-Stitt *et al*. (2013), that found a mean annual R factor of approximately 5,222 MJ mm ha^{-1}h^{-1}y^{-1}, with increasing values at higher altitudes (a 7,547 MJ mm ha^{-1} h^{-1} y^{-1} maximum at an altitude of 3,078 m). Notwithstanding these relationships, calculations of the R factor using local adjusted or well-established methods with sufficient and current data are needed for Huambo, in order to obtain reliable and current estimates that may also take into account the influence of climate change in the region. Furthermore, the T values were influenced by the assumptions made for depths of soil profiles and the correction factors for RT, indicating that lower amplitude ranges of RT and correspondent f values in equation 6 would lead to differentiated results. Also, the possibility of calculating T using the soil bulk density data, as reported in Mannigel *et al*. (2002) and Demarchi & Zimback (2014), would bring more accuracy to the estimation.

The high RT values denoting higher clay content in the subsoil than in the topsoil, could be a result of pedogenetic processes (clay migration) leading to argic subsoil horizons. Thereby, Red ferralitic- (FR) and Brown to white paraferralitic (PFB) soils could be classified as Lixisols in the WRB classification system (IUSS Working Group WRB, 2015) and not as Ferralsols, as suggested in Table 1. The FY and PFY soils, which presented the lower K values, show RT near 1, denoting similar clay content both in superficial and subsuperficial soil horizons. Equation 5 may have led to an overestimation of K that could be related, on one hand, to a high sand content in the superficial and/or subsuperficial horizons, as is the case of many of the studied soils, and, on the other hand, to the omission of the effects of iron and aluminium oxides, the main particle-aggregating agents in tropical soils (Barthès *et al*., 2008).

Clustering of soil profiles showing positive correlation between sand content and erodibilty indicates that Arenosols are more erodible-prone. Support practices like cross-slope or contour farming, no-till farming, use of vegetative buffer strips, terracing, should be adopted in agricultural areas where these soils predominate (Labrière *et al*., 2015).

The high NEP average of 605 t ha^{-1} y^{-1}, reflects both the erosivity rate and erodibility distribution for the studied soil profiles, as well as the assumptions made for the calculation of the R, K and LS factors. Therefore, it should be expected different NEP when applying local adjusted R and rigorous estimations of the erosivity and slope-length factors.

An increase trend of water erosion in Africa has been reported, either due to climate change (Panagos *et al.*, 2017) or driven by changes in land use (Borreli *et al.*, 2017). Sub-Equatorial Africa has been identified as a soil erosion hotspot by Borreli *et al* (2017). Mendelsohn (2019) refers that large volumes of soil and soil nutrients have been lost in the Huambo Central *Planalto* and surrounding higher areas of Ferralsols. In addition to the environmental conditions which favour the erosion process, and the climate change impacts, the main driver of such erosion amounts is the landscape change that has occurred in recent years. This author reports that much of this change has been due to clearing for small-scale crop farming, particularly of dry-land crops, and large-scale commercial agriculture. Other losses resulted from the harvesting of charcoal, wood fuel, timber production, and from mining activities.

To counteract pressure on land and water resources, soil conservation measures must be implemented to improve the productivity of land by controlling or arresting erosion. Such measures include (Grepperud, 1995; Pimentel, 1995; Morgan, 2005; Kambauwa, 2015): (i) crop management techniques, like rotation, leguminous crops, and/or fallowing, the latter still widely practised in tropical agriculture, associated with shifting cultivation; (ii) soil management practices, such as mulching, cover cropping, intercropping, vegetative buffers, and organic matter addition; (iii) conservation tillage, including no-till cultivation, ridge-planting, and minimum tillage; (iv) cross-slope, contour and strip farming; (v) structural measures like terracing, construction of waterways and drainage ditches.

More work needs to be done to demonstrate to decision makers and farmers the benefits that reducing land degradation can have for the protection of soil resources, the maintenance of its productive capacity and the reduction of poverty.

5 Conclusions

The current study provided insights about soil vulnerability to water erosion in the Huambo province of Angola using a methodology based on sparce data of climate and soil, a common limitation in developing countries. The estimated annual erosivity factor was 7,463 MJ mm ha^{-1} h^{-1} y^{-1} with 84 % of the rainfall erosivity occurring from November to March. Soil erodibility values varied from 0.021 t ha h ha^{-1} MJ^{-1} mm^{-1}, in Ferralsols to 0.247 t ha h ha^{-1} MJ^{-1} mm in Arenosols. A two-dimensional principal components model for soil and soil erodibility variables explained 61.7 % of total variance. While the first principal component was related to particle size distribution and soil erodibility, highlighting a positive correlation between sand content in the soil superficial horizons and soil erodibility, the second was related to soil loss vulnerability, with negative factor loading for soil loss tolerance. The clustering pattern of soil profiles was mostly soil type-controlled, with Arenosols grouped in one cluster located in the positive quadrant of PC1, thereby, more erodible-prone. The natural erosion potential of 25 soil profiles varied from 38.6 to 2,874.2 t ha^{-1} y^{-1}, with an average moderate value of 605 t ha^{-1} y^{-1}.

Even though the validation of these results with current climate, soil and topography data or with *in situ* measurements of soil loss was outside the scope of this study, it provides information that raises awareness concerning the natural potential for soil degradation by water erosion and can be useful for decision-makers and for farmers and land users, helping to reduce soil erosion and implement wise management options that contribute to the sustainability of agriculture in Huambo. These set of results indicates that further studies are needed focusing on up to date climate data, detailed soil information, current practices of land use and influence of climate change on the vulnerability of soils to erosion in the Huambo region.

Supplementary material

Supplementary files: Appendix 1. Legend of the soil reference groups and qualifiers in the soil map of Angola (Dewitte *et al.*, 2013; Jones *et al.*, 2013); Fig. S1. Land Cover composition of Huambo province, Angola (Buchhorn *et al.*, 2020).

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Conflict of interest

We certify that there is no conflict of interest with any financial, personal, or other relationships with other people or organisation related to the material discussed in the manuscript.

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