Mapping potential soil erosion in East Africa using the Universal Soil Loss Equation and secondary data

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Abstract Soil erosion is a serious threat of increasing dimensions and tends to blunt efforts to counter global population growth with increased and sustainable agricultural production. The tropics are especially vulnerable because of the circumstantial convergence of intense climatic regimes, frequently fragile soils, low levels of fertilizer use and conservation practices and strong dependence on soil quality for livelihoods. In addition, climate change is expected to aggravate the already existing vulnerabilities of the poorest people, who depend on semi-subsistence agriculture for their survival. Tools for assessing spatially explicit erosion patterns would be a great help for planning soil conservation measures, or targeting agricultural technology or policy interventions that mitigate the adverse effects of soil erosion and could help farmers to adapt. Because extensive measurement of soil erosion is expensive and time consuming, erosion models that make use of secondary data available in a Geographic Information System can offer a useful alternative. In this paper, an attempt is made to analyse and map current soil erosion potential on the sub-continental scale. We use principles of the Universal Soil Loss Equation (USLE) and its reformulations to make a qualitative assessment of soil erosion in East Africa. Data on climate, soils, topography, hydrology and land cover are derived from existing secondary data sources that are spatially explicit and have an adequate resolution to be linked, at least as proxies, to important drivers of soil erosion as represented in the USLE. Obvious limitations of methodology and data, as well as the lack of validation possibilities are discussed. The results have value in reflecting broad patterns of soil erosion across East Africa. The methodology also permits the highlighting of hotspots of soil erosion risk where agricultural research can focus efforts of developing or applying soil conservation measures and target agricultural technology, and policy interventions that can mitigate the adverse effects of soil erosion on poor people's livelihoods.

Key words USLE; erosion; erosion risk; East Africa

INTRODUCTION

Soil erosion, a major factor for decreases in soil fertility and land value, is widely recognized as a threat to farm livelihoods and ecosystem integrity worldwide. The mechanisms involved in soil erosion by water vary over time and space and depend on several factors including ground cover, soil texture, -structure, -porosity/permeability, and topography (Moore & Burch, 1986; Mitasova *et al*., 1996). In addition, human activities, and especially improper land management and use can influence the dynamics of each of these factors (Wischmeier & Smith, 1978). Especially in the tropics, erosion can be particularly threatening because of intense climatic inputs, low levels of fertilizer use and conservation activities, frequently fragile soils, and strong dependence on soil quality for livelihood (Cohen *et al*., 2005; Claessens *et al*., 2007). With the increase in human population and related land-use changes, mapping and quantifying soil erosion becomes more important for the planning of soil conservation measures and sustainable use strategies. Due to the complexity of the processes and variables involved, and the large scale at which they operate, simplicity of data management and the ability to transfer from data-rich to data-poor areas and the use of models and Geographic Information Systems (GIS) is becoming very important (Jha Raghunath, 2002). Two of the most widespread erosion models, especially at larger scale levels, are the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE). The USLE was developed by Wischmeier & Smith (1978). It is an empirical model which has been exhaustively calibrated for the USA and other areas, e.g. China (Baoyuan *et al*., 2002), Kenya (Angima *et al*., 2003), Rhodesia (Stocking & Elwell, 1976), and Japan (Shiono *et al*., 2002).

METHODS

Potential erosion map: (R)USLE approach

The USLE quantifies soil erosion as the product of rainfall erosivity (*R*), soil erodibility (*K*), slope length (*L*), slope steepness (*S*), cover and management practices (*C*), and supporting conservation practices (*P*). The USLE was later modified into the RUSLE by including improved computation of soil erosion factors, such as monthly factors, incorporation of the influence of profile convexity/concavity and improved empirical equations for the *L* and *S* factors (Renard *et al*., 1991; Breiby, 2006). Note that both the USLE and RUSLE only include soil erosion by surface runoff/overland flow, i.e. no gully, wind and landslide erosion. Both models also exclude (re)sedimentation processes. Both the USLE and RUSLE use empirical relationships and therefore can only be considered valid within the range of experimental conditions from which they are derived (Renard & Freimund, 1994). At a larger scale, resource and data limitations on the one hand, and large regional variability in factors on the other, make a quantitative assessment of soil erosion in most cases impossible and results rather reflect broad patterns of relative erosion potential.

Rainfall erosivity factor (*R*)

The rainfall erosivity (*R*) index represents the energy that initiates the sheet and rill erosion (Wischmeier & Smith, 1978). Originally, it is computed as total storm energy (MJ m^{-2}) times the maximum 30 minute intensity (El30 in mm h^{-1}), being expressed as e.g. MJ mm ha^{-1} $year^{-1}$ (Renard & Freimund, 1994). The computation of *R* calls for detailed long-term information on number and depth of storm events; information which is only available for very few stations. We used Fournier's (1960) index (*F*), which has the merits of being based on readily available monthly rainfall data. The maximum *R* factor for the period 1901–2002 was calculated using the historical rainfall data from the CRU TS 2.1 Climate Database (Mitchell & Jones, 2005), at 0.5 degrees resolution. For the mean *R* factor for the same period, we used the average monthly and annual rainfall data from the WorldClim v 1.4 database, which is a set of global climate grid layers with a spatial resolution of one square kilometre (Hijmans *et al*., 2005).

Soil erodibility (*K*)

Soil erodibility is determined by the proportions of sand, silt and clay in the soil, the organic matter content, soil structure and -permeability. For some countries in the study area information on soil structure and profile permeability was not available. Therefore, these soil characteristics were excluded from the calculations. Soil data were derived from databases on soils, terrain and other land characteristics of eastern and southern Africa: Soil Map of East Africa (SEA) (FAO, 1997); Soil and Terrain Database (SOTER) for Central Africa (CAF) (ISRIC, 2006); and the SOTER for Southern Africa (SAF) (FAO, 2006). All these data sets were compiled following the digital soil and terrain database (SOTER) methodology (Van Engelen & Wen, 1995). Information on soil characteristics was derived by linking soil type to the World Inventory of Soil Emission Potentials (WISE) soil profiles database, which provides a homogenized set of primary soil data (Batjes, 1995).

Slope and accumulation area factors (*L* & *S*)

Slope (*S*) and slope length (*L*) information was derived separately, rather than combining the two, in order to independently assess erosion distribution associated with each factor. The original standardized measurement of slope steepness and slope length were substituted by slope steepness and slope accumulation area based on a digital elevation model (DEM). We used the 90 m SRTM digital elevation data version 3 from CGIAR-CSI (CGIAR-CSI, 2004). The r.terraflow module (Duke University, 2004) in GRASS GIS (GRASS Development Team, 2007) was used to compute flow routing, slope and upslope contributing area. The multiple-flow direction algorithm (MDF), which is especially suitable for more accentuated terrain (Wolock & McCabe, 1995), was used to assign flow directions to the cells. The USLE was designed for slopes not exceeding 10° (Wischmeier & Smith, 1978), while the equations in RUSLE are valid for slopes up to approx. 12° (Nearing, 1997). In the study area agriculture and livestock keeping is found on slopes that exceed this limit by far, with slopes over 60° in the mountains of Ethiopia and the highlands of Kenya. The best alternative we are aware of is the method described by Nearing (1997), which has been validated for slopes up to 26.6° (Cohen *et al*., 2005). The slope length used in the original USLE is substituted by the upslope contributing or flow accumulation area A to incorporate the impact of flow convergence (Moore & Burch, 1986; Mitasova *et al*., 1996).

Cover and management (*C* factor)

The C factor is very important as it measures the effects of all the interrelated cover and management variables, which are easily influenced by man (Renard *et al*., 1991). In the original USLE equation, the factor C is defined as the ratio of soil loss from land cropped under specific conditions to the corresponding loss from clean-tilled, continuous fallow (Wischmeier & Smith, 1978). Often fixed erosion risk values are assigned to different land-use and cover classes. This requires expert knowledge on the type and intensity of land-use management systems in the area. As an alternative, we looked at vegetation cover using remotely sensed data. The observed vegetation cover is affected by both environmental conditions and land use/management (Mati & Veihe, 2001). Monthly Leaf Area Index (LAI) data layers were derived from the GlobCarbon project (ESA, 2005) for the period 1999–2003. These data layers have a spatial resolution of 1 km^2 and are based on a general cover-type dependent SR–LAI relationship, with SR being the ratio between Near infra-red (NIR) and RED reflectance (VITO, 2005). We calculated the average monthly LAI and subsequently selected per pixel the lowest monthly LAI to include in the C factor (equation (1)).

$$Cfactor = \frac{1}{min(LAI_i)} \tag{1}$$

where LAI_i is the average LAI for month i.

Combining the layers

The original (R)USLE simply multiplies the different erosion factors. The different range and magnitude of values of each of the components implicitly introduces a relative weight. However, when parameterization is not based on empirical evidence and proxies are used, this renders the standard multiplicative estimate of soil erosion inappropriate (Cohen *et al*., 2005). To maintain for each factor the relative value between pixels, but remove the weighting between layers, there are various options including standardization, ranging, scaling or normalization. Some methods eliminate size differences, while others reduce both the size and variability to a common scale. Translation and standardization (Legendre & Legendre, 1998) are not suitable as they centre the data on zero, thus creating negative values. Another option, which we adapted, is to standardize the raw factors by each factor's study area mean (as in Cohen *et al*., 2005). This approach maintains the relative weighting of each factor, making it functionally more similar to the standard USLE implementation with respect to relative factor importance.

Hotspots of potential erosion: land use and human population

As argued before, land use/management can be an important factor influencing the rate and degree of erosion. Especially in areas with high population pressure there will be a tendency to land-use intensification. This could ultimately lead to less sustainable land-use practices, thus increasing the likelihood for erosion. Conversely, some land-use systems may be more common in erosion-prone areas than others, thus being more vulnerable to such changes. Combining potential erosion estimates with information on the type and/or intensity of land use will help to identify hotspots were land-use management is more likely to have an impact on soil conditions and/or soil erosion is more likely to affect land-use potential. Moreover, land use change is often linked to human population dynamics, which thus need to be considered as a driver of change. In addition, in areas with high population density, erosion is more likely to have a more direct negative impact. Overlays of the potential erosion map with human population densities were created to identify high erosion potential areas where high human population densities could exacerbate the erosion risk. For human population, we used the 30" raster data layers from the Global Rural-Urban Mapping Project (GRUMP) (CIESIN & CIAT, 2005).

RESULTS AND DISCUSSION

USLE potential erosion map

The final potential erosion map is shown in Fig. 1 (the Nile basin is highlighted). Comparing Fig. 1 with maps for the different USLE factors (not shown) reveals that the *S* factor and to a

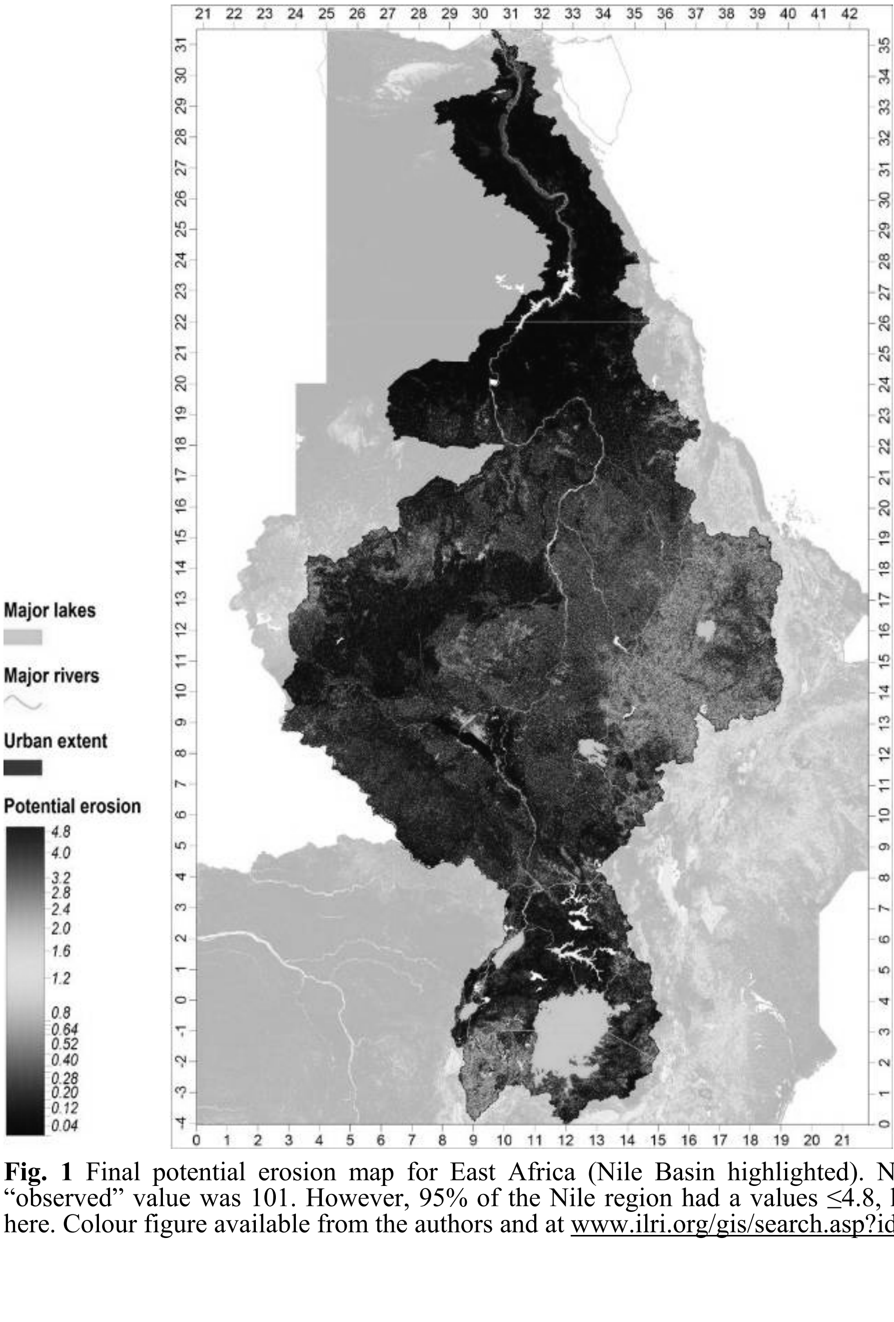

Fig. 1 Final potential erosion map for East Africa (Nile Basin highlighted). Note that the highest "observed" value was 101. However, 95% of the Nile region had a values ≤4.8, hence the scale used here. Colour figure available from the authors and at www.ilri.org/gis/search.asp?id=489.

lesser extent the *R* factor, are the main factors defining the large potential erosion patterns. Both exhibit distribution patterns with a strong spatial autocorrelation, while their relatively large magnitude and strongly skewed frequency distributions ensure this is reflected in the final map. The two main areas that stand out in Fig. 1 are the Ethiopian highlands and Burundi and Rwanda, where a highly accentuated topography and high rainfall make soil erosion more likely, especially where vegetation cover is low. Soil and vegetation cover are determinative factors in e.g. the large area extending west of Khartoum (Sudan), where erosion potential is low because of less susceptible soil types that are prevalent in that area. In the semi-desert and desert areas between roughly (14°–18° latitude) a combination of low rainfall and low to virtually absent vegetation cover results in high potential erosion.

Potential erosion and human population

Figure 2, which combines information from Fig. 1 with human population density, shows that the Ethiopian highlands and Rwanda and Burundi do not only contain the more erosion prone areas,

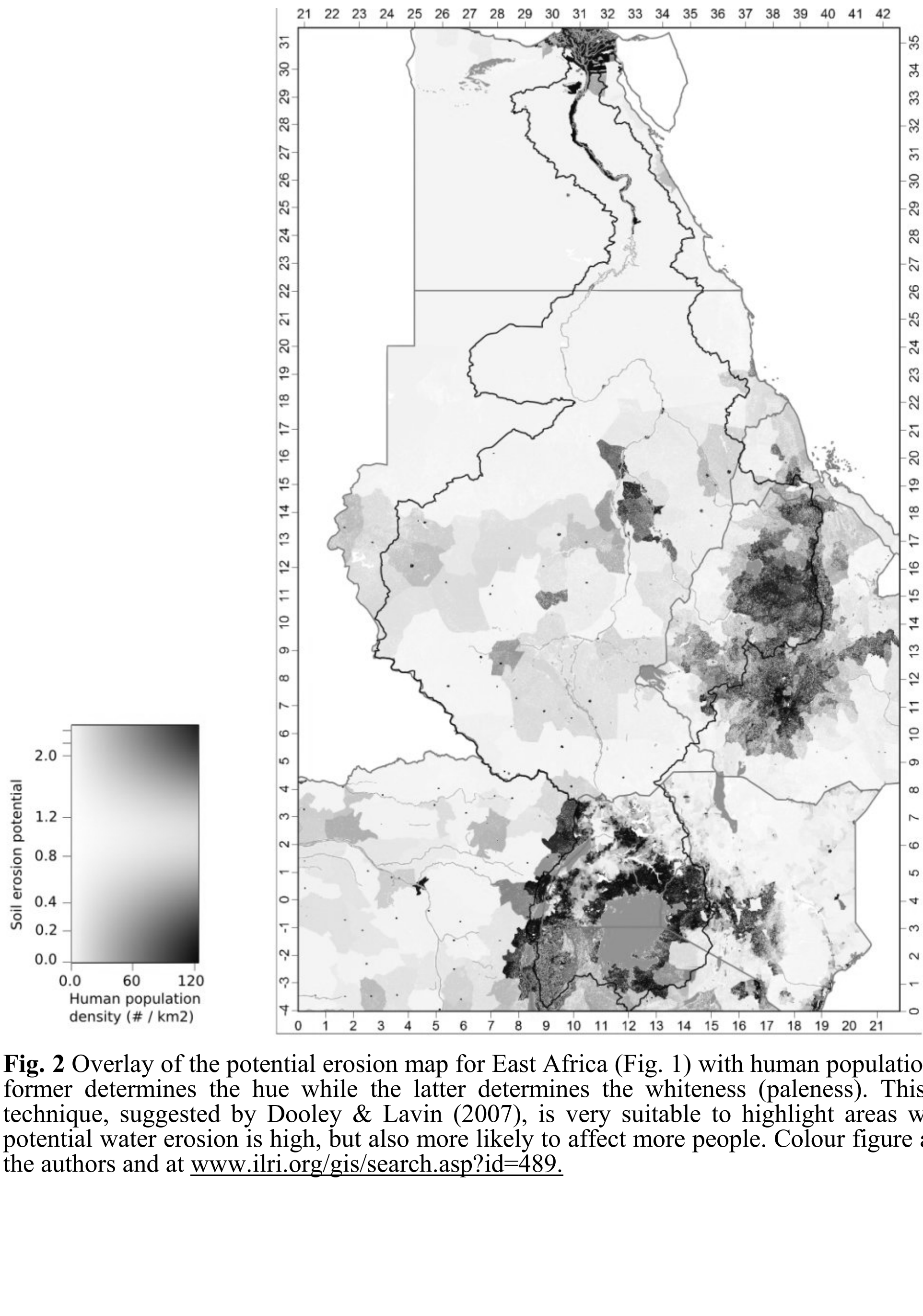

Fig. 2 Overlay of the potential erosion map for East Africa (Fig. 1) with human population density. The former determines the hue while the latter determines the whiteness (paleness). This visualization technique, suggested by Dooley & Lavin (2007), is very suitable to highlight areas where not only potential water erosion is high, but also more likely to affect more people. Colour figure available from the authors and at www.ilri.org/gis/search.asp?id=489.

but are also amongst the most densely populated. Other areas might be less prone to water erosion, but high human population densities could still exacerbate the likelihood of and increase the risks associated with soil erosion. Clear examples are the areas north and south of Lake Victoria, central Uganda, around Khartoum and along the Nile and the Nile delta.

USLE approach

The USLE and RUSLE are empirical models, but for a study at the sub-continental scale, the sheer scale, complexity and diversity of environmental–human factors and interactions make parameterization of the models difficult and validation of the results almost impossible. Only a few studies in the area actually undertook calibration and/or validation of the model, and never beyond the watershed/sub-basin level. (Gachene, 1995; Mati *et al*., 2000; Angima *et al*., 2003; Lufafa *et al*., 2003; Cohen *et al*., 2005). The USLE remains useful in that it lists the basic factors of soil erosion by water, but a number of simplifications are necessary, largely dictated by the availability of data, and their reliability, accuracy and resolution.

C factor

The approach was based on the assumption that the most erosive rains occur close to the onset of the rains, in the period when vegetation cover is low, which might be reasonable for the drier areas (Moore, 1979). However, if in a given area erosive rains occur later in the growing season, erosion vulnerability will be overestimated. An alternative approach in these cases might therefore be to use the LAI of the month with the lowest LAI/precipitation ratio. Another implicit assumption is that a very low LAI in areas with natural vegetation is treated the same as in agricultural areas. Yet, even in the dry season, there might be a substantial amount of dry material as well as developed root systems of perennial plants in areas with natural vegetation, which can provide protection against erosion to some extent. One possible approach could be to assign different weightings to crop land *versus* areas with natural vegetation (e.g. extensive grazing areas). Another option that can be used to assess degradation in the vegetation cover and the long-term influence of land use is to examine trends in annual net biomass production (ANBP) with trends in precipitation. It is well recognized that aboveground net primary production (ANPP) is related to mean annual precipitation (Le Houérou, 1984), denominated as the rain use efficiency (RUE). The RUE is systematically lower in ecosystems subject to drought stress, but also in degraded areas it is expected to be lower compared to similar non-degraded lands (Le Houérou, 1984, 1988; Snyman, 1998; Illius & O'Connor, 1999; O'Connor *et al*., 2001). Therefore, deviations in temporal patterns between rainfall and RUE patterns, with a declining trend in RUE where precipitation does not change or shows an increasing trend, could indicate a degradation in the vegetation cover (Bai & Dent, 2006; Hein & De Ridder, 2006; UNEP-WCMC & IUCN-WCPA, 2007).

R factor

Preferably, R values are calculated based on data from individual rainstorm events. If these are not available, alternatives using daily rainfall data can be used. Since these data are not available for most regions in the tropics, estimated relations between monthly or annual average rainfall and R values can be used. As noted by Renard & Freimund (1994), any given relation should be considered location specific, especially when comparing locations with distinct environmental conditions. This is illustrated by the results of Roose (1983) who established a relation between R and average annual rainfall that worked well for 20 meteorological stations in various West African countries, but which was not valid for stations in amongst others mountainous and coastal regions. Likewise, Stocking & Elwell (1976) found a good but different linear relationship between mean annual rainfall and the rainfall intensities for the eastern districts of Zimbabwe and the rest of the country, indicating lower erosive storm events in the former, more mountainous districts. Thus, the resulting map of this study should be interpreted with care and only used for a preliminary comparison between sites at (sub-)regional scale. Parameters should be replaced by site-specific estimations or measurements when possible, especially when zooming in to e.g. district or catchment level.

A factor

Since RUSLE is only suitable for estimating erosion due to inter-rill and rill processes, there is an upper bound on the slope accumulation area that should be used. Different threshold values to delineate (and exclude) the stream network result in different total stream lengths, and consequently, different drainage densities (Wang & Ying, 1998). For the work presented in this report, an arbitrary threshold value of 500 grid cells (about 4.2 km^2) was taken. To simulate the catchment areas with their stream patterns as they really exist, one needs to devise some criteria for choosing the value of the threshold area. One possible way, proposed by Jain & Kotyari (2000), is to compare the total stream length generated using a given threshold and the observed total stream length. The two should be the same if the value of the threshold were chosen correctly. As various physiographic regions may have different thresholds for channel initiation, threshold values should be calculated at sub-basin/watershed level. The observed total stream length could be estimated from e.g. high resolution topographic maps. For estimation of the stream length, the most detailed database available is probably AEON's Africa River Database (Stankiewicz & de Wit, 2005), which includes all rivers and lakes (perennial and non-perennial) manually digitized from topographic maps of individual countries on the basis of their own cadastral databases.

L factor

The occurrence of soil erosion by surface runoff/overland flow is dependent on slope gradient (which largely determines the velocity) and the sediment concentration within the flow. If the flow is fully saturated with sediment, any decrease in velocity will result in deposition rather than erosion. Conversely, if the flow is relatively unsaturated, it will take a very significant decrease in slope (possibly to near zero) to result in deposition (van Remortel *et al.*, 2001). Thus, depending on the slope characteristics and sediment concentration, certain areas will have net soil erosion while other areas will experience net sedimentation. For the presented potential erosion map no attempt was made to identify or mask out deposition areas. This would require quantification of a threshold where the change in slope angle from one cell to the next along the flow direction pathway would result in deposition rather than erosion. Appropriate values for this threshold should be set by expert knowledge or experimental data. Where such information is not available, a value closer to 0.5 (slope decreasing by 50% or greater) may be appropriate for slope gradients of 5% or greater based on assumptions made in other studies (Wilson, 1986; Griffin *et al.*, 1988). For slopes of <5%, a 0.7 value is suggested because it is generally easier to initiate deposition on lesser gradient slopes (Van Remortel *et al.*, 2001).

K factor

Due to the composite nature of the soil map, with multiple soils per mapping unit, not all spatial variability in the *K* factor could be captured in one single map. Using the dominant soil type gives potential erosion estimates one is most likely to encounter in any given mapping unit. However, in 70% of the area, soils more erosion prone than the dominant soils are found. As a result, the maximum potential erosion in those areas can be considerably (up to six times) higher. To benefit fully from the information contained in the soil database, one would therefore need to make maps for each of the soil types potentially occurring in a mapping unit. The SOTER data sets were used in the construction of the potential erosion map because they offer one of the most comprehensive regional data sets. Being based on one single methodology, the maps allow for unbiased comparison across the region. A disadvantage is that the WISE database, which links soil characteristics to soil type, is based on global data. Thus, it does not provide directly measured soil characteristics, but best estimates based on 10 000 soil profiles in the database. For some countries, e.g. Kenya, national soil maps offer more detailed information and should be considered when zooming in to the national level. For analyses at a regional scale, terminology and classification systems need to be adapted to one common standard. This fell outside the scope of this study, but should be considered for future adaptations of the map.

Weighting of the USLE factors

As discussed before, the weighting of the different factors in the USLE equation is determined by the parameters of the factor equations. Without calibration there is a substantial uncertainty in the magnitude of the estimates. As the different order of magnitude of the USLE factors implicitly introduces a weighting, variables were converted to relative risk scores. Overall, this resulted in more similar magnitudes of the different factors. It should be realized though that it also led to a shift in the relative magnitude and thus weighting. For example, the magnitude of the K factor values becomes larger than that of the C factor. Without further calibration/validation, any choice remains arbitrary to a certain extent. Both the range and skewness of frequency distributions differ between factors and are site and scale specific, thus rendering the results scale sensitive. The practical implication of this scale sensitivity is that a potential erosion map needs to be created for the actual scale of analyses, with the standardization based on the mean of the area of interest. For the USLE, factors were divided by their mean values for the whole study area. The database also contains mean values per country as well as scripts to carry out different types of standardization, which can be used to create maps at a smaller scale.

Potential erosion map as a tool

Given the above-mentioned restrictions and assumptions of both methodology and data, a quantitative assessment of soil erosion is not possible, restricting us to the use of relative values, rather than mapping soil erosion in a quantitative way. However, having incorporated the major factors affecting erosion (Renard & Freimund, 1994), it offers a way to assess relative patterns and highlight hotspots of vulnerability for soil erosion across a large scale using widely available data. In combination with other information, e.g. on land-use pressure, land management practices, but also climate change prediction, the map could aid in identifying areas where erosion is, or is most likely to become, an impediment for further agricultural development, or the other way around, where current land-use practices or future land-use changes are more likely to exacerbate existing erosion risks. This in turn can be used to focus efforts of development or applying soil conservation measures and target agricultural technology and policy interventions that can mitigate the adverse effects of soil erosion on poor people's livelihoods. As an example, we overlaid the potential erosion map with population density in this paper. Other applications that can be envisaged are overlays with, e.g.: (a) targeted agricultural cropping systems, (b) livestock density, (c) food and feed demand and supply, (d) production system changes, and (e) climate change and variability. The methodology can be used to identify hotspots where erosion is more likely to affect agricultural production systems and people's livelihoods or *vice versa*.

CONCLUSIONS

Although having its own share of methodological problems, the methodology and potential erosion map presented in this paper provide an efficient way to assess large patterns of potential erosion at the sub-continental scale. In combination with additional information on (proxy) variables that potentially influence erosion rates, it offers a tool to identify hotspots where erosion related problems are more likely to have an impact on the sustainability of land use systems. Furthermore, the clearly defined role of the different USLE factors in the final potential erosion map makes it easier to link erosion risk to possible erosion prevention or mitigation strategies. However, it should be stressed that the potential erosion map is location and scale dependent. For future applications, the methodology should allow one to dynamically adapt standardization and scale specific parameters. To facilitate this, we did not develop one potential erosion risk map, but rather a set of data layers and accompanying scripts that can be used to produce potential erosion maps using adapted equations and input data layers. It is important to keep in mind the high degree of uncertainty in the relative importance of the different USLE components, which is linked to the lack of site-specific parameterization and validation possibilities. Options to compare the results with those of local studies are limited given the small number of such studies implemented within the study area. Nevertheless, the potential erosion map may facilitate comparative analyses of different studies across the study area and beyond.

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