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A Landscape Planning and Management Tool for Land and Water Resources Management: An Example Application in Northern Ethiopia

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Abstract Land and water degradation due to on-site soil/nutrient loss and off-site pollution/sedimentation are serious environmental problems. Landscape planning and management tools are essential to implement best management practices targeted at locations where they are needed most. Although many soil/water-landscape studies have been published in the last 2 decades, progress in developing operational tools for supporting landscape planning to minimize land and water degradation in developing regions is still modest. Some of the existing tools are data demanding and/or complicated to be useful to data scarce regions. Some require detailed understanding of the hydrological and modelling processes and thus less applicable to local stakeholders involved in land use planning and management. A user-friendly LAndscape Planning and MAnagement Tool (LAPMAT) developed to facilitate land management decision-making. LAPMAT is a menu-oriented interactive graphical user interface that can aid decision makers identify hotspot areas of soil erosion and evaluate the effects of alternative land use management practices at a catchment scale. The modelling framework and its interfaces are designed to guide the user through a series of menus that: 1) allow input model parameters, adjusting coefficients, visualizing input parameters and executing the model; 2) enable changing land use and management practices and re-evaluating potential consequences; 3) allow viewing results in tabular, graphical or map form side-by-side; and 4) (re)-evaluating the respective impacts of management/conservation options. The framework has been applied to assess the severity of soil erosion and simulate the impact of different land

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management practices using the Revised Universal Soil Loss Equation (RUSLE) adjusted for sediment delivery ratio in an example catchment of northern Ethiopia. The results showed average sediment yield rate of 55 t ha^{-1} y^{-1}. Conservation measures targeted at high soil loss areas and gullies gave the maximum reduction in sediment yield by about 80 %. Since LAPMAT allows users handle the selection of management/planning options and provide fast and responsive outputs, it can assist in effective multi-stakeholder negotiations over land-use planning where the minimization of land/water degradation is the ultimate goal.

Keywords Land and water degradation · Hotspot areas of erosion · Landscape planning and management · RUSLE · Sediment yield · Northern Ethiopia

1 Introduction

Land degradation is one of the most severe and widespread environmental problems of the 21st century (Dregne and Chou 1992; Reynolds et al. 2007, 2011). One of the critical challenges of land degradation is that, in addition to its direct effects on productivity, it also translates into an interlinked downhill spiral of declining production, increasing poverty and diminished potential productivity (Greenland et al. 1994; Nkonya et al. 2013). Such cyclic process is experienced mainly in poor societies with limited options of coping once degradation and productivity decline set in.

Soil erosion is one of the most serious forms of land degradation (Dregne 2002; Powlson et al. 2011). Soil erosion is a much more complicated problem as it not only leads to loss of the productive capacity of the soil on-site but it also results in the sedimentation and pollution of water resources off-site (Quinton et al. 2010). This means that attempts to reduce the processes and effects of soil erosion require an integrated watershed management plan that consider conditions and societies both upslope and downslope. While natural erosion is a long-term process with less impact on the overall soil balance of a site under consideration, accelerated soil erosion with significant impact on soils and overall land productivity comes with human interventions mainly in the form of land use and land use/cover change (Mitasova et al. 2001). Efforts to tackle soil erosion by water and its associated effects should therefore focus on measures that are directly related to land use activities (Tamene and Vlek 2007, 2008; Legas et al. 2012).

Appropriate land use and management practices that maintain extensive ground cover are useful for reducing soil loss and sediment delivery. Many studies reported that soil conservation measures based on contour grass stripes or hedgerows are very effective in reducing water runoff and controlling erosion on steep slopes (Melville and Morgan 2001; Blanco-Canqui et al. 2004; Pansak et al. 2008; Kaini et al. 2012). Since field-testing of the usefulness and limitations of such interventions is expensive, time-consuming and laborious, tools that can help analyze the impacts of different options are necessary. Especially, enhancing the capacity of stakeholders to be able to compare the results of different options themselves and choose the ones they think are acceptable for their conditions is essential. Land-use planning aimed at minimizing costs of land-use adjustments and maximize ecological services therefore requires a decision support tool that allows land management stakeholders to actively participate in its planning, development and implementation phases (Rao and Kumar 2004; Miller et al. 2007; Vervoort et al. 2010; Reed and Dougill 2010; McIntosh et al. 2011).

In this study, a LAndscape Planning and MAnagement Tool (LAPMAT) is developed to estimate the rate and spatial patterns of soil erosion and evaluate the relative potential of different land management/conservation options to reduce sediment yield. The LAPMAT graphical user interface is developed in NetLogo programming environment (Wilensky 1999) and mainly designed to: (1) be simple and flexible such that it can be effectively used and updated by local planners and decision makers; (2) incorporate options for ranges of possible soil erosion factors/coefficients for users to select; (3) simulate and update different land use and management activities and evaluate their role in reducing soil erosion and sediment yield; (4) allow users to visualize results of different management options in tabular, graphical, or map form side-by-side. In this paper, the application of LAPMAT is demonstrated using the Revised Universal Soil Loss Equation (RUSLE) adjusted for sediment delivery ratio (SDR) in an example catchment of northern Ethiopia, where soil erosion and reservoir sedimentation are serious problems.

2 Framework and Structure of the LAPMAT

2.1 General Framework

This first version of LAPMAT is mainly intended for management of upland catchments with the intention of reducing the on-site and off-site impacts of soil erosion, and to enhance adaptive land-use management and planning (Fig. 1). In general, the tool is designed to satisfy the following important components that are useful for sustainable landscape management:

- *Represent key environmental flows*. In the landscape context, the most profound environmental flow is the movement of matter (water and soils) along slope gradient leading to the redistribution of soil and water across the landscape. In this regard, soil erosion-sedimentation process is considered the central component of the LAPMAT framework. The tool is also aimed to enhance land management decisions with the objective of reducing sediment yield and on- and off-site damages.
- *Manage possible uncertainties in model parameter estimation*. Soil erosion-sedimentation models often use empirical parameters estimated for a given study area or derived for other locations that are not necessary in the same biophysical setting with the study areas. In this regard, uncertainty driven from ‘inheritance’ of parameters can cause problem of over- or under-estimation of a given process. Moreover, model users in many cases may not find values of parameters needed for their case studies, and rather use parameters borrowed from other sites based on the principle that they are correlative with other information, such as the use of empirical relationship between *R*-factor and annual rainfall or the citation of *C*-factor based on land cover types. LAPMAT is designed to handle the effect of such uncertainties to provide information on their impact as translated to the simulation results.
- *Facilitate active participation of stakeholders in the adaptive land-use learning/planning cycles*. Though land use planning decisions are made at higher level, the real ‘users and implementers’ are stakeholders (extension agents, farmers) at local level. “Easy-to-use” tools that consider the capacities and aspirations of local stakeholders are thus likely to be adopted and be more effective (e.g. Wilk and Jonsson 2013). In this regard, LAPMAT is designed to be easy to use and update such that planners and decision makers with no detailed knowledge of modelling and landscape processes can run the model and gain general feelings of the results. This is achieved through (a) improving stakeholders’ access to the tool including data input and direct visualization, (b) allowing stakeholders to be able to *define management parameters* based on their needs/preferences, (c) allowing stakeholders to handle the whole operational process such as importing data, setting management options and observing results in a *timely* fashion (e.g. less than a half of an

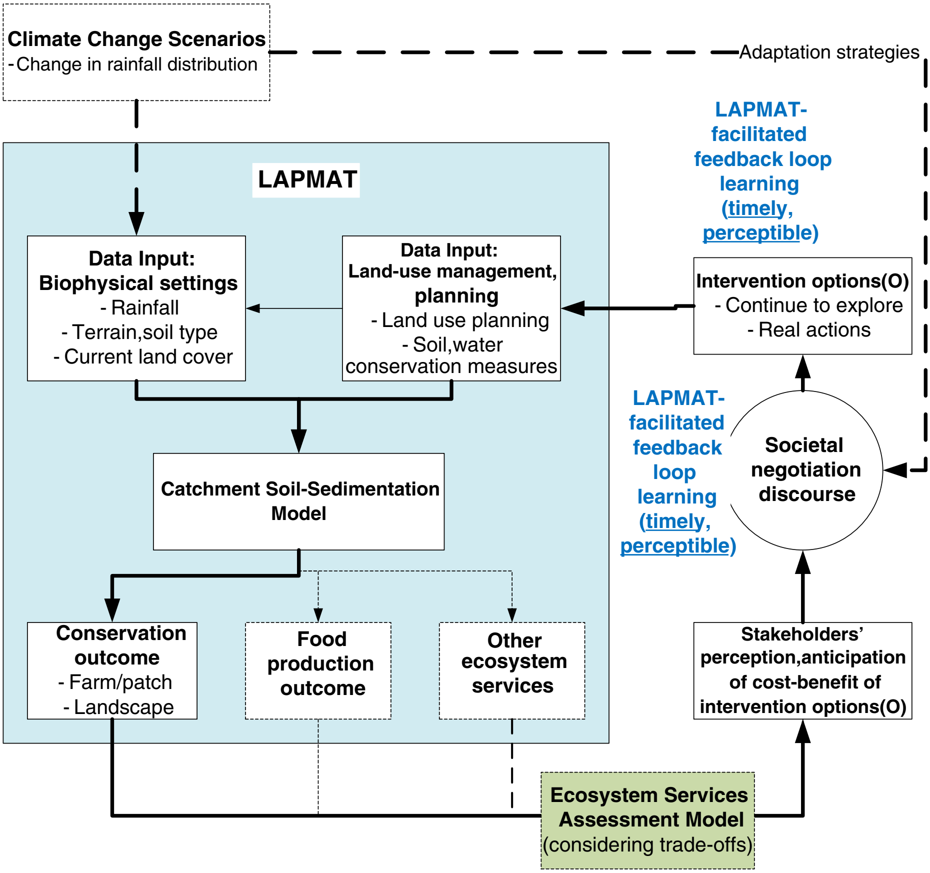


Fig. 1 Structure of LAPMAT for supporting adaptive land-use planning and management. Note: Elaborations and implementation of components with *dotted lines* will be the subjects of follow-up studies

hour) so that they can capture and understand the dynamics of the environmental feedback loop including changes due to different management options, (d) improving *capability to function with different level of data availabilities* by guiding users to select model parameters from *alternative values within some ranges* to avoid being stuck when some data or parameters are not available, and (e) providing *results in diverse and understandable forms* such as tables, graphs and maps.

In this first version of the LAPMAT, most of the above points and those outlined under Fig. 1 are addressed. The dotted components in Fig. 1 including cost-benefit analysis are the subjects of follow-up studies. The current version and its illustrative application provide a systematic demonstration of the concept and forms the foundation from which numerous extensions and elaborations can be made.

2.2 Soil Erosion-Sedimentation Model

There are varieties of soil erosion models developed and calibrated for different regions. Empirical models such as the Universal Soil Loss Equation (USLE) and its derivatives

(Wischmeier and Smith 1958; Renard et al. 1997) are based on extensive experimental results and input–output relationships. Such models have constraints of applicability to regions and ecological conditions other than from which data were used in their development (El-Swaify 1990; Stefano et al. 1999; Merritt et al. 2003). Physical process-based models such as the Water Erosion Prediction Project (WEPP) (Nearing et al. 1989) and European Soil Erosion Model (EUROSEM) (Morgan et al. 1998) try to compute erosion using mathematical representations of fundamental hydrologic and erosion processes (Foster 1990). Such models can be applied across multiple landscapes and situations because the mathematical relationships are derived from physical laws (Maidment 1996; Merritt et al. 2003). The limitation of these models is that they require too much data and can be very expensive for initial assessment of erosion reconnaissance and suffer from high computational costs (Foster 1990; Mitasova et al. 1997; De Roo 1998; Garg and Jothiprakash 2012; Chowdary et al. 2013). As a result, there is no single best model for soil erosion assessment (Bogena 2001; Istanbulluoglu et al. 2002).

For data scarce regions in developing countries, models that require minimum data are more preferable compared to complex physical-based models (Garg and Jothiprakash 2012; Chowdary et al. 2013). Accordingly, the Revised Universal Soil Loss Equation (RUSLE) adjusted for sediment delivery ratio (SDR) is used to assess the ex-ante impacts of planned land use and soil conservation measures on soil erosion and downslope sedimentation. Besides its modest data requirements, RUSLE is also more appropriate for this study since some of its factors are calibrated for the region (Hurni 1985). The future version of LAPMAT will include the option to choose among a list of models based on user requirements and data availability.

RUSLE is used to estimate soil erosion mainly considering terrain, soil, rainfall, land use/cover and conservation factors and is given as (Renard et al. 1997):

$$RUSLE\left(\mathrm{t\,ha^{-1}y^{-1}}\right) = R \times K \times L \times S \times C \times P \tag{1}$$

where R=rainfall erosivity (MJ mm ha^{-1} h^{-1} y^{-1}); K=soil erodibility (t ha h (ha MJ mm)$^{-1}$); LS= slope length-steepness (−); C=land use/cover (−); and P=conservation/management (−) factors.

Considering the complexity of the landscape of the study area, the Stream Transport Capacity Index (STCI) is used to calculate the LS-factor (Moore and Burch 1986; Moore et al. 1991):

$$LS = (m+1)\left[\frac{A_s}{22.13}\right]^m \left[\frac{\sin\beta}{0.0896}\right]^n \tag{2}$$

where m and n are slope length and angle coefficients; A_s is the specific upslope contributing area per unit length of contour; β is the local slope gradient (degrees). A_s is calculated based on (Mitasova et al. 1996; Gallant and Wilson 2000; Park et al. 2001):

$$A_s = \frac{1}{bi}\sum_{i}^{N} a_i u_i \tag{3}$$

where a_i is the area of the i^{th} grid cell; b is the contour width of the i^{th} cell (approximated by cell resolution); μ_i is the weight depending upon the runoff generating mechanism and infiltration rates; N is the number of grid cells draining into grid cell i.

The RUSLE model estimates annual gross soil loss rate. However, all of the soil eroded from the upper portions of a watershed will not be delivered to a point downstream. Much of the material will be re-deposited at locations where the momentum of the transporting water is insufficient to keep the material in suspension or to move the soil particles along the watershed surface or channel (Ferro and Minacapalli 1995; McCuen 1998). The power of the transporting agent is likely to be low in areas of low slope or high roughness resulting in deposition of materials. The ratio of the sediment transported to a location in the channel system (that is, sediment yield) to the gross erosion from the drainage area above that point is called the sediment delivery ratio (Walling 1983; McCuen 1998). To estimate sediment yield or net soil loss (NSL) rate at a pixel scale, the annual gross soil loss rate in Eq. (1) has to be adjusted for SDR per cell (SDR_i). According to Stefano et al. (2005), SDR_i indicates the probability that eroded particles mobilized from an individual cell are transported to the nearest stream pixel and can be calculated as:

$$SDR_i = \exp\left(-\beta * \frac{L_i}{R_i S_i^{1/2}}\right) \tag{4}$$

where β is a routing coefficient; L_i is the length of segment i in the flow path and is equal to the length of the side or diagonal of a cell depending on the flow direction in the cell; R_i is coefficient based on surface roughness characteristics; S_i is the slope gradient (m/m).

The other region-specific RUSLE parameter (RKCP) values are derived from different sources as discussed in Section 3.2 and in the Online Resource.

2.3 Implementing Management Options Based on User-Friendly Graphic Interface

Generally, soil erosion control measures are targeted at erosion hotspots, as it is not economically and technically possible to conserve all problem areas. The most commonly used management option to tackle soil erosion is improving surface cover such as covering barren areas with trees or grasses. In this demonstration, users are provided with options to update three of the major RUSLE soil erosion factors: erosivity (R), surface cover (C) and management (P). Updating these components is chosen due to the fact that they are more sensitive to temporal dynamics due to either natural-induced or human-caused processes. The C and P factors can generally be modified through land use/cover or management change. Updating the R-factor is intended to provide the option to simulate the impact of possible climate change (in this example change in mean annual rainfall), and given as:

$$\begin{gathered} \mathit{Climate\ \ change\ \ scenario} \rightarrow P_a \\ R_i = f_1(P_a) \end{gathered} \tag{5}$$

where f_1 is an empirical relationship between R_i and annual precipitation P_a.

Land use/cover management factors are intended to reduce upslope erosion and downslope siltation by covering slopes with protective surface cover. Updating C-factor in LAPMAT is given as:

$$\begin{gathered} L_i = \text{“}\mathit{enclosed}\text{”}\ \ \mathit{if}\,(S_i > \Theta_1)\,\mathit{or}\left({}^0E_{n,i} > \Theta_2\right)\mathit{or}(G_i) \\ C_i = \Theta_3 \pm \varepsilon_3 \end{gathered} \tag{6}$$

where, L_i=land cover at location i, Θ_1 and Θ_2 are the user-defined thresholds of slope (S_i) and baseline soil erosion rate (${}^0E_{n,i}$), respectively. G_i=potential gully indicator. Parameter Θ_3 is an empirical C value corresponding for "enclosed" cover, and ε_3 is a stochastic number accounting for the uncertainty range of the assigned Θ_3.

The P-factor, which is intended to capture the role of soil conservation practices, is given as:

$$\begin{gathered} M_i = \text{“}\mathit{terrace}\text{”}\ \ \mathit{if}\ \ G_i \\ P_i = \Theta_4 \pm \varepsilon_4 \end{gathered} \tag{7}$$

where M_i=soil conservation measure applied at location i. Parameter Θ_4 is an empirical P value corresponding for the "terrace" measure, and ε_4 is a stochastic number accounting for the uncertainty range of the assigned Θ_4.

The user can decide whether all or some of the options and relationships defined in Eqs. (5), (6) and (7) should be used by switching on or off in the LAPMAT graphical interface. In addition to deciding on which management options to apply, the user is also provided with the option to modify associated coefficients in accordance with the management option selected. Users are also provided with a range of values to choose as input related to tolerable soil loss, the maximum amount of soil loss that is acceptable considering the soil formation rate in the area. The relative efficiency and sustainability of each management option can be evaluated based on the selected threshold value.

During soil erosion/hydrological modelling (e.g. as applied in LAPMAT), two types of uncertainties are expected. One is uncertainty generated when deriving the data for the main factors in RUSLE model based on literature that provides the relationships between the factors and commonly available data, such as mean annual rainfall (*R*-factor), land use/cover type (*C*-factor), and soil types/conditions (*K*-factor). The second is uncertainty emanating from relating the thresholds assigned for translating changes in rainfall, land use/cover, conservation measure to respective changes in the data of *R*-, *C*- and *P*-factors, respectively. In LAPMAT, these uncertainties are represented using random numbers within ranges around the expert- or literature-based values. Therefore, given a set of input data and parameters, every model run will give different simulation results and allows users to calculate the confidence interval of the means of gross and net soil losses. In this way, the uncertainties associated with input data/parameters are translated into the simulation results.

3 Demonstration of LAPMAT in an Example Catchment

3.1 Study Area

The prototype LAPMAT has been applied in the Adikenafiz catchment of Tigray region, northern Ethiopia located between 12–15° north and 36.5–41.5° east (Fig. 2). The catchment has an area of 1,400 ha, which is dominantly cultivated with varying proportions of pasture and scattered bush/shrub covers. Leptosols, cambisols and vertisols dominantly occupy the upper, middle and lower slopes, respectively. The topography of the catchment is rugged making it sensitive to erosion. Vegetation cover is sparse and rills and gullies are widespread.

A reservoir dam is constructed at the outlet of the catchment to harvest run-off water and supplement rainfed agriculture. However, sustainability of the micro-dam is challenged by high soil erosion and sedimentation problems as a result of which the reservoir has been virtually silted and unable to provide irrigation water within in a few years of its construction (Tamene et al. 2006).

3.2 Region-Specific Parameterization of Erosion Factors

One of the aims of this demonstration is to evaluate the impact of possible land management options to tackle sedimentation of the Adikenafiz reservoir using a user-friendly interface. To achieve this, key components of the RUSLE factors that are adapted for the Ethiopian condition (Table 1) have been processed for model input. Satellite images have been classified to extract land use/cover maps and derive *C*-factor values. *K*-factor values are derived from soil maps and field observation. *P*-factor values are defined from field survey. All the data

Fig. 2 The Adikenafiz catchment in Tigrazy, northern Ethiopia

were integrated in a GIS at a spatial resolution of 10 m^2. Description of data processing approaches employed to derive the above factors is presented in the Online Reference.

The surface roughness coefficient (R_i) used in the calculation of SDR per pixel is estimated from land use/cover types, as suggested by Maidment et al. (1996); Jain and Kothyari (2000);

Table 1 R-, K-, C-, and P-factors adapted for the Adikenafiz catchment based on Hurni (1985), Machado et al. (1996)

Geomorphological unit (Machado et al. 1996)	*K*-factor	Land use/cover (Hurni 1985)	*C*-factor
Erosion remnants with soil cover	0.03	Dense forest	0.001
Erosion remnants without soil cover	0.01	Dense grass	0.01
Badlands	0.04	Degraded grass	0.05
Scarps/rock slopes	0.02	Bush/shrub	0.02
Alluvial fans	0.04	Sorghum, maize	0.10
Alluvial plain and terraces	0.03	Cereals, pulses	0.15
Infilled valleys	0.03	Ethiopian Teff	0.25
Management type (Hurni 1985 and Eweg and Lammeren 1996)	*P*-factor	Continuous fallow	1.00
		R = −8.12 + 0.562RF	
Ploughing up and down	1.0	Hurni (1985) is used to estimate *R*-factor, where RF is mean annual precipitation (mm).	
Strip cultivation	0.80		
Stone cover (80 %)	0.50		
Stone cover (40 %)	0.80		
Protected areas	0.50		
Ploughing on contour	0.90		
Terraces	0.60		

Table 2 Surface roughness coefficient (R_i) adapted for the Adikenafiz catchment based on Maidment et al. (1996); McCuen (1998); Stefano et al. (2005); Mutua et al. (2006)

Land cover description	R_i
Urban and built-up land	6.3398
Irrigated cropland and pasture	2.7737
Grassland	0.6401
Dryland cropland and pasture	0.4572
Shrubland	0.4572
Savanna	0.4267
Cropland/Grassland mosaic	0.3962
Cropland/Woodland mosaic	0.3962

Fernandez et al. (2003); Stefano et al. (2005); Mutua et al. (2006). Table 2 shows the estimated values for the velocity coefficient and adopted in this study. Within LAPMAT, a range of values is provided with those mentioned in Table 2 suggested as default.

3.3 Selecting Landscape Planning/Management Options

To assess soil loss and prescribe possible landscape planning and management options, users should be able to evaluate what type of management action taken in a certain location can be effective considering the problem at hand and the resources available. In LAPMAT users can simulate the possible outcomes (in terms of reducing sediment yield) of different options targeting different intervention areas and identify the one that produces minimum sediment yield. The management areas identified and tested in this study include steep slopes, gullies and hotspot areas of erosion. Gullies are included in the target areas because of their significant role in the region (Tamene et al. 2006, 2011). Once areas of possible intervention are identified, different land use/cover redesign and conservation options are applied, and the resulting soil loss compared with the status quo condition to tentatively evaluate the performance of each option. Description of the different options applied is given in Tamene and Vlek, (2007) and outlined below.

Planning option 1: Estimate soil loss based on current condition

This option is based on the business as usual management practices with no specific conservation measures. It estimates the maximum possible soil loss and displays the spatial pattern of soil loss as well as plots its magnitude based on user-defined classes. The result gives an impression of the magnitude of the problem and the hotspot areas where soil erosion is more than the tolerable limit. The result also serves as a benchmark against which the results of the different options will be compared.

Planning option 2: Conservation measures targeting gullies

This scenario is intended at conserving gullies with the aim of reducing their sediment contribution as well as retarding their sediment delivery efficiency (Steegen et al. 2000; Poesen et al. 2003; Tamene and Vlek 2007). This can be achieved by protecting gullies and their buffers through terraces and dense grass (Haan et al. 1994; Verstraeten and Poesen 2002; Borin et al. 2005). In this example, a 25-m buffer was used to include areas along concentrated flow that experience high soil loss. The user can use a range of *P* and *C*-factor values considering their local conditions and the effectiveness of the proposed management efforts. In the default example, *P*- and *C*-factor values of 0.6 and 0.01, respectively are offered.

Planning option 3: LUC-redesign targeting 'steep slope' areas

Conservation practices focused on steep slopes are intended to reduce the rate of soil loss and its downstream delivery by reducing flow rates and stream power (Zevenbergen and Thorne 1987). Covering steep slope areas with vegetation can also prevent development of new gullies or revival of the old once. LAPMAT is thus equipped with an interface where the user can introduce management targeting *steep slope* areas. Because the definition of steep slopes in the context of soil loss could differ from place to place, a range of possibilities (from 5 to 50°) is provided in the model. In the default example, areas of slopes more than 25° are converted to enclosures (areas protected from human and livestock intervention) and assigned C-factor=0.01 (planning option 3a). In addition, simulation was run with terraced (P-factor=0.6) and grassed (C-factor=0.01) gullies (planning option 3b) to assess the impact of integrated management on sediment yield reduction.

Planning option 4: LUC-redesign targeting hotspot areas of erosion

One of the scenarios designed in the LAPMAT considers targeting hotspot areas experiencing high soil loss. Hotspot areas can be selected based on the tolerable soil loss limit in each specific region. In this example, LAPMAT provides wider options of identifying hotspots with a soil loss range between 5 and 50 t ha^{-1} y^{-1}. This wider range is provided for users to experiment with different levels of soil loss if the tolerable amount is not known. To guide users a default value of soil loss of above 25 t ha^{-1} y^{-1} is also offered. Once hotspot areas are selected, they will be covered with dense cover (C-factor=0.01) and soil loss calculated (planning option 4a). In addition, LAPMAT offers simulation to be performed by including conservation of gullies (terraced and grassed) along with enclosing high erosion-prone areas (planning option 4b).

3.4 Validation of Model Results

Quantitative data from different sources were used to validate the applied model. In addition, sediment yield data from the catchment's reservoir (Tamene et al. 2006) was used to assess the relative impacts of the different management options.

4 Results and Discussion

4.1 Key Features of LAPMAT in Supporting Adaptive Land-use Planning

LAPMAT has different features designed to facilitate end users identify high erosion risk areas, define suitable management options and evaluate their relative significances (Fig. 3). Initially, users choose model of interest (in this case RUSLE) and the frameworks defaults to input relevant erosion factors and allows users to display and visualize the spatial dynamics of the different erosion factors and check for any issues in the dataset. The interface also provides a range of erosion factor values (e.g. R-factor) and coefficients (e.g. m and n slope length and steepness coefficients), whereby users can choose one based on literature review for locally calibrated coefficients. To increase flexibility for the user, commonly used values are also provided as default. Another key component of the modelling framework is the ability to display results in tabular, graphical or map form (Fig. 3), where users can identify areas of concern and/or be able to evaluate the significances of different management intervention. With regards to

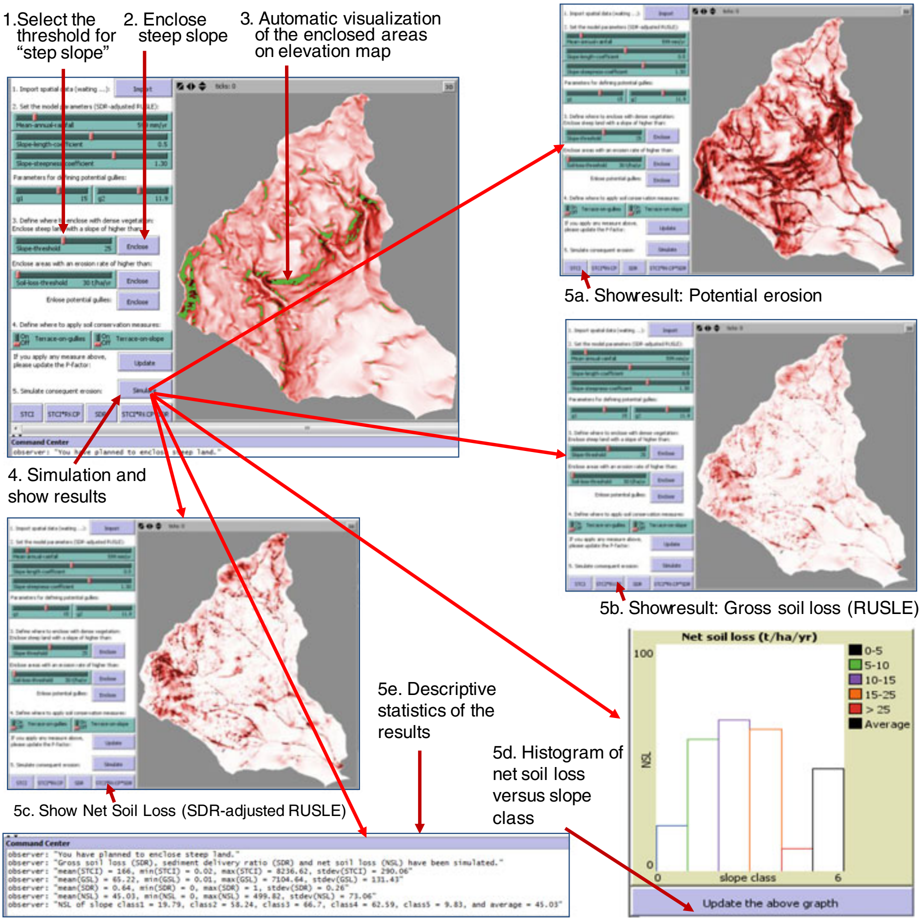


Fig. 3 LAPMAT's Graphical User Interface (GUI) designed to: input data, visualize inputs, adjust coefficients, select simulation options, run simulations and display and visualize results in different forms

defining and assigning suitable management options aimed to tackle erosion and sediment yield, users for instance can change (re-design) land use/cover types or introduce other management options such as enclosures or terraces. This is an interesting component as it encourages local users to think of specific problems (areas) and assign site-specific and problem-oriented management options. This step aids stakeholders evaluate the significance of different options and choose those that are appropriate for their conditions. Users not only can visualize input factors and simulation results in different forms but also export them for further analysis and combine with other GIS data. Additional key feature and advantage of LAPMAT is that all the data input, coefficient adjustment, simulation of management options and visualization of results can be performed in rapid sequence, which facilitates users' understanding of processes and impacts of conservation measures (McIntosh et al. 2011). It also gives the freedom and confidence to utilize the tool as it is customized to be simple and user-friendly (Sugumaran and DeGroote 2011).

4.2 Sediment Yield Estimate

The average sediment yield estimated for the Adeikenafiz catchment is about 55 t ha^{-1} y^{-1}. The sediment yield estimate in this study agrees well with sediment deposition rate estimated using bathymetric survey of 49 t ha^{-1} y^{-1} (Tamene et al. 2006). The result is also close to sediment yield estimates of 40–65 t ha^{-1} y^{-1} by Gebrehawariat and Haile (1999) and Aynekulu et al. (2000) for small reservoir with an area of about 5 km^2 located very close to the Adikenafiz catchment. With such an agreement users can have the confidence to delineate the patterns of erosion severity classes and target management interventions to those areas experiencing high soil loss.

Figure 4a shows the spatial patterns of net soil loss (NSL) of the Adikenafiz catchment based on the current condition (with no management activities in place). Figure 5a shows the corresponding graphical representation of NSL estimated for current condition. The figures show that areas with slope lower than 5° experience NSL rate of about 21 t ha^{-1} yr^{-1} whereas areas with slope range between 15 and 25° experience NSL rate of about 78 t ha^{-1} yr^{-1}. These areas as well as the actively collapsing gullies receive the highest amount of average NSL. Steep slope areas of over 25° are characterized with relatively low NSL. This can be attributed to the fact that these areas are covered with bushes/shrubs with minimum cultivation and those locations are also dominantly covered with resistant rocks. Such classification can be applied to identify areas where soil loss is comparatively high and thus immediate management measures are needed.

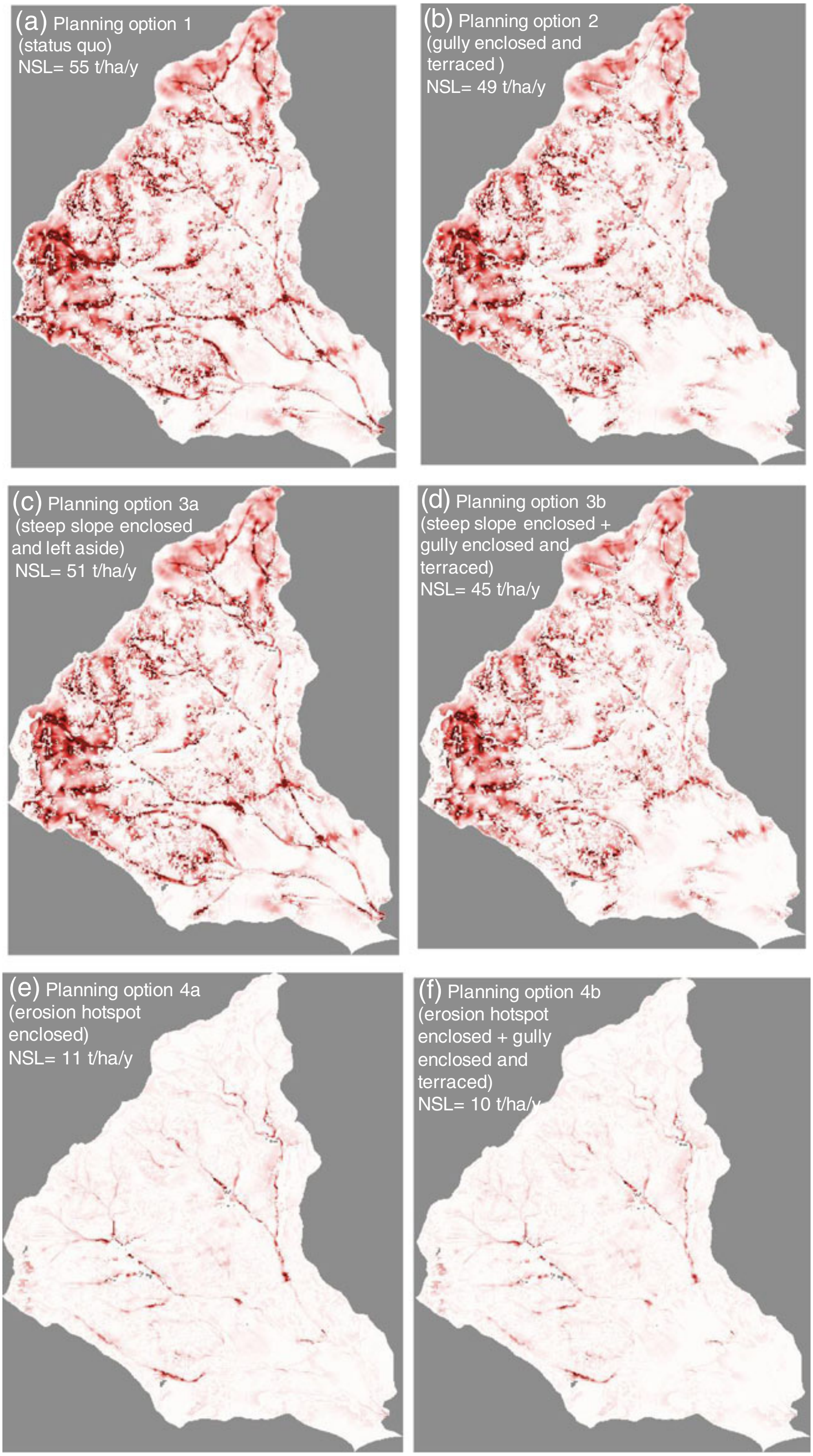
4.3 Sediment Yield Estimate with Management Options

Figures 4b–f and 5b–f show NSL estimates (spatial and graphical representation) in relation to different management options targeting different areas. The results show that the level of NSL reduction is a reflection of where management options are introduced. For instance, when hotspot areas are targeted for management (planning option 4a), there will be significant NSL reduction of about 80 % (from about 55 to about 11 t ha^{-1} y^{-1}). NSL reduction when hotspot areas and gullies are conserved (planning option 4b) does not show significant difference compared to scenario 4a because 'gullies and their 25-m buffer' are also within the hotspots category. In addition, the RUSLE is not a process-based model that can handle soil loss specific to gullies.

Enclosing steep areas (> 25 %) to foster dense vegetation cover as well as protecting them from cultivation and/or free grazing (scenario 3a) results in relatively low potential sediment yield reduction. This is because most steep slope areas are less accessible and not much subjected to disturbance by livestock and humans (Tamene and Vlek 2007). When steep slopes and gullies are managed (planning option 3b), the potential sediment yield had declined relatively though not significantly. The results demonstrate the need for integrated landscape management plans mainly focusing on hotspot areas that experience high NSL compared to the others.

Simulation of potential sediment yield with and without management measures using the tool demonstrated here can be essential to design appropriate land conservation plans to reduce erosion and increase the lifetime of water harvesting schemes and increase their economic benefits (Tamene and Vlek 2007). The upcoming version of LAPMAT will incorporate

Fig. 4 Spatial patterns of distributed net soil loss (NSL) (t ha−1 yr−1) in the Adikenafiz catchment. Note that since there were 30 replicated simulations for each planning option, the reported NSL in each map is the mean of these 30 replications. In all cases, the confidence intervals of the mean NSLs (p<0.05) are less than 0.5 t/ha/y ▶


(a) Planning option 1
(status quo)
NSL= 55 t/ha/y
(b) Planning option 2
(gully enclosed and
terraced)
NSL= 49 t/ha/y
(c) Planning option 3a
(steep slope enclosed
and left aside)
NSL= 51 t/ha/y
(d) Planning option 3b
(steep slope enclosed +
gully enclosed and
terraced)
NSL= 45 t/ha/y
(e) Planning option 4a
(erosion hotspot
enclosed)
NSL= 11 t/ha/y
(f) Planning option 4b
(erosion hotspot
enclosed + gully
enclosed and
terraced)
NSL= 10 t/ha/y

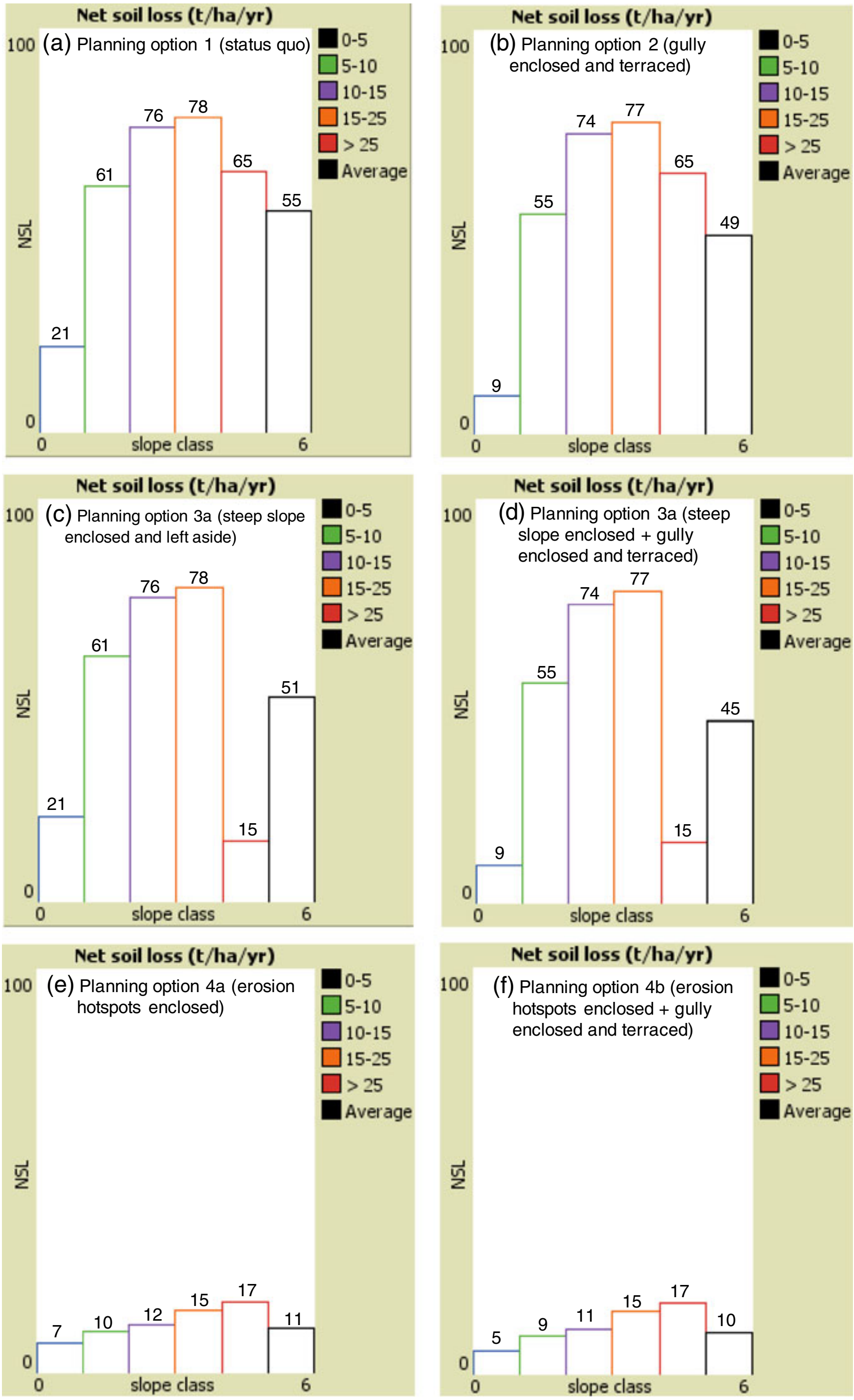


Fig. 5 Sediment yield (i.e. net soil loss—NSL) (t ha−1 yr−1) versus slope class for the status quo condition and five different planning options

different soil erosion models for users to choose one they think is applicable for their conditions. In addition, cost-benefit and tradeoff analysis in relation to each management options will be incorporated to determine the economical and ecological implications of the different options (Le et al. 2012) and quantitatively estimate the cost of action versus in action (Kaini et al. 2012; Nkonya et al. 2013; Sun et al. 2013).

5 Conclusions

The Revised Universal Soil Loss Equation (RUSLE) has been integrated into NetLogo, an agent-based programming platform, to develop a landscape planning and management tool (LAPMAT) prototype. LAPMAT is designed such that stakeholders can employ to allocate and evaluate the potentials of best management practices that are intended to reduce land/water degradation. The operational model was designed in such a way that fast and robust sensitivity analyses can be performed, where users are allowed to select and set different physical parameters, and choose different sets of land-use management and planning options. The possibility to choose and adjust different soil erosion parameters and coefficients facilitates its application in data-scarce and developing regions. As the tool allows front-end users to handle the selection of management/planning options, and provide fast and responsive outputs (in terms of both maps and graphs), LAPMAT can assist in effective multi-stakeholder negotiations over land-use planning where the minimization of land/water resources degradation is the ultimate goal. Another important feature of LAPMAT is that users at local level with short training and exposure to soil erosion process can understand and utilize the model. In addition to the current demonstration at a catchment of less than 20 km^2, the framework has also been tested for a landscape size of about 100 km*2* and performed well. This means that the model can be applied at multi-scale level provided that relevant data are available at appropriate scale.

Soil erosion models involve different factors derived from different sources and using different approaches. Sensitivity assessment of parameters and their estimates is thus necessary. In this study sensitivities related to rainfall, land use/cover and management options is incorporated. However, detailed sensitivity analysis including comparison with well established parameter estimation options such as erosivity estimate from rainfall intensity need to be conducted and compared with those derived based on mean annual rainfall. These and detailed uncertainty analysis with regards to climate change and variability (e.g. Korteling et al. 2013) will be incorporated in the upcoming version.

For land management options to be acceptable and adopted by users, their real benefits in terms of reducing degradation and improving productivity should be demonstrated. In addition, any potential impacts on the environment need to be assessed. In this study local thresholds can be used to assess the significances of different options in reducing erosion. Future version of LAPMAT will incorporate detailed cost-benefit and tradeoff analysis of options in order to assess their social, economic and environmental significances. To enable comprehensive simulation of environment-community interactions, the LAPMAT will be coupled with agent-based models (e.g. Le et al. 2012; Nikolic et al. 2013). Future development will also incorporate a host of different erosion/hydrological models for users to choose those suitable for their conditions and plausibly calibrate the models for diverse environmental conditions of sub-Saharan Africa by establishing long-term research catchments.

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