International Center for Tropical Agriculture
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The International Center for Tropical Agriculture (CIAT)
TMG-Think Tank for Sustainability

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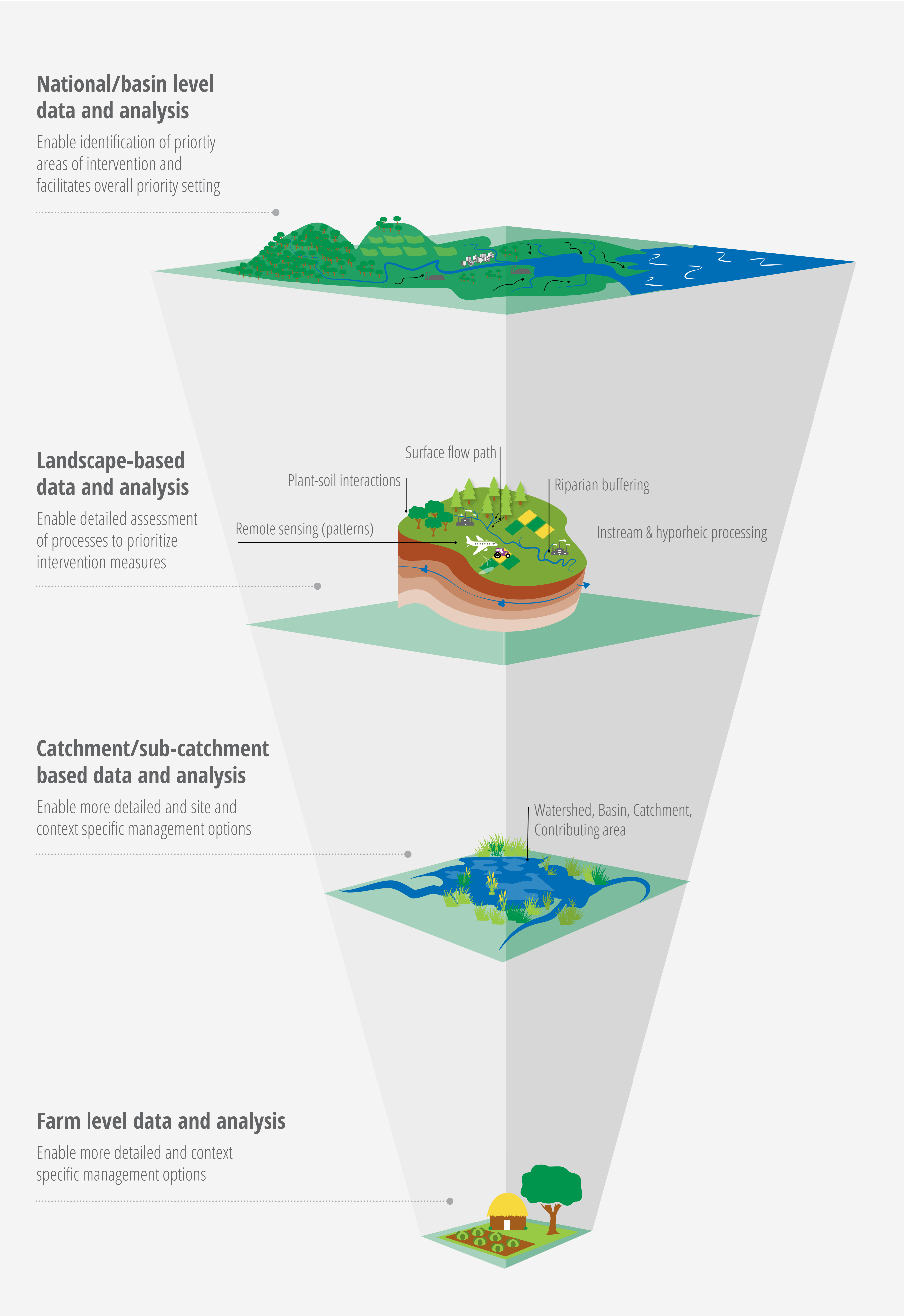
National/basin level data and analysis
Enable identification of priortiy areas of intervention and facilitates overall priority setting
Landscape-based data and analysis
Enable detailed assessment of processes to prioritize intervention measures
Surface flow path
Plant-soil interactions
Riparian buffering
Remote sensing (patterns)
Instream & hyporheic processing
Catchment/sub-catchment based data and analysis
Enable more detailed and site and context specific management options
Watershed, Basin, Catchment, Contributing area
Farm level data and analysis
Enable more detailed and context specific management options

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Abbreviations

AHP	Analytical Hierarchical Process
A.S.L	Above Sea Level
BAT	British American Tobacco
°C	Degree Celsius
DEM	Digital Elevation Model
EH	Erosion Hazard Index
FAO	Food and Agriculture Organization
GIS	Geographic Information Systems.
GPS	Global Positioning System
HRU	Hydrologic Response Units
H_2O	Water
ISRIC	International Soil Reference and Information Centre
M	Meters
MM	Millimeters
KM	Kilometers
Mt.	Mountain
NDVI	Normalized Difference Vegetation Index
NGO	Non Governmental Organization
SDG	Sustainable Development Goals
SWAT	Soil and Water Assessment Tool
SWAT-CUP	Soil and Water Assessment Tool-Calibration and Uncertainty Programs
t/ha/y	Tonnes/Hectare/Year

Executive Summary

This report provides a synthesis on land degradation assessments conducted for two countries (Kenya and Burkina Faso) at different scales. The task mainly involved identifying hotspot areas of degradation that require priority management interventions. The approach involves modelling, stakeholder engagement and field validation. In the report, we refer to land degradation as the persistent loss of ecosystem function and productivity caused by disturbances from which the land cannot recover unaided. Hotspots refer to places that, if left unattended, could prove harmful, both to the environment and to those dependent on it. These areas generally require priority management interventions due to the severity of the degradation problem and its associated cost. Considering the fact that land degradation processes differ across space and over time and that there will be no 'one-size-fits-all' approach to assess the severity of the problem and its spatial distribution, a multiscale hierarchical approach was followed. At the national level, we used time series satellite and rainfall data to trace the spatial distribution of land degradation and identify the major drivers (human caused versus climate induced). Results from such exercise would benefit national level planning and decision making. In addition, development organizations, donors and NGOs can benefit from such results to target their interventions. At the county/province/district level, we developed an 'index' that can help map land degradation risks using relatively higher resolution data. Such products can be beneficial to county/district level planners as well as stakeholders whose activities are relevant to this scale. The third and more detailed level of analysis employs a spatially distributed hydrological model to map land degradation hotspots at landscape and/or farm levels and assess the impacts of land management options. Outputs from this analysis can be used by development agents, extension workers as well as local communities and farmers to facilitate targeted decision making. The above sequential steps clearly demonstrate the need for context-specific analysis that fit to local and regional conditions. In addition to the modelling and analysis results, the report provides recommendations for farmers, policy makers, decision and development agents and researchers regarding the implications of the land degradation findings towards identifying technical, policy and institutional arrangements that will promote land restoration, agroecosystem health and food security in order to meet current and future human and environmental sustainability objectives.

1. Introduction

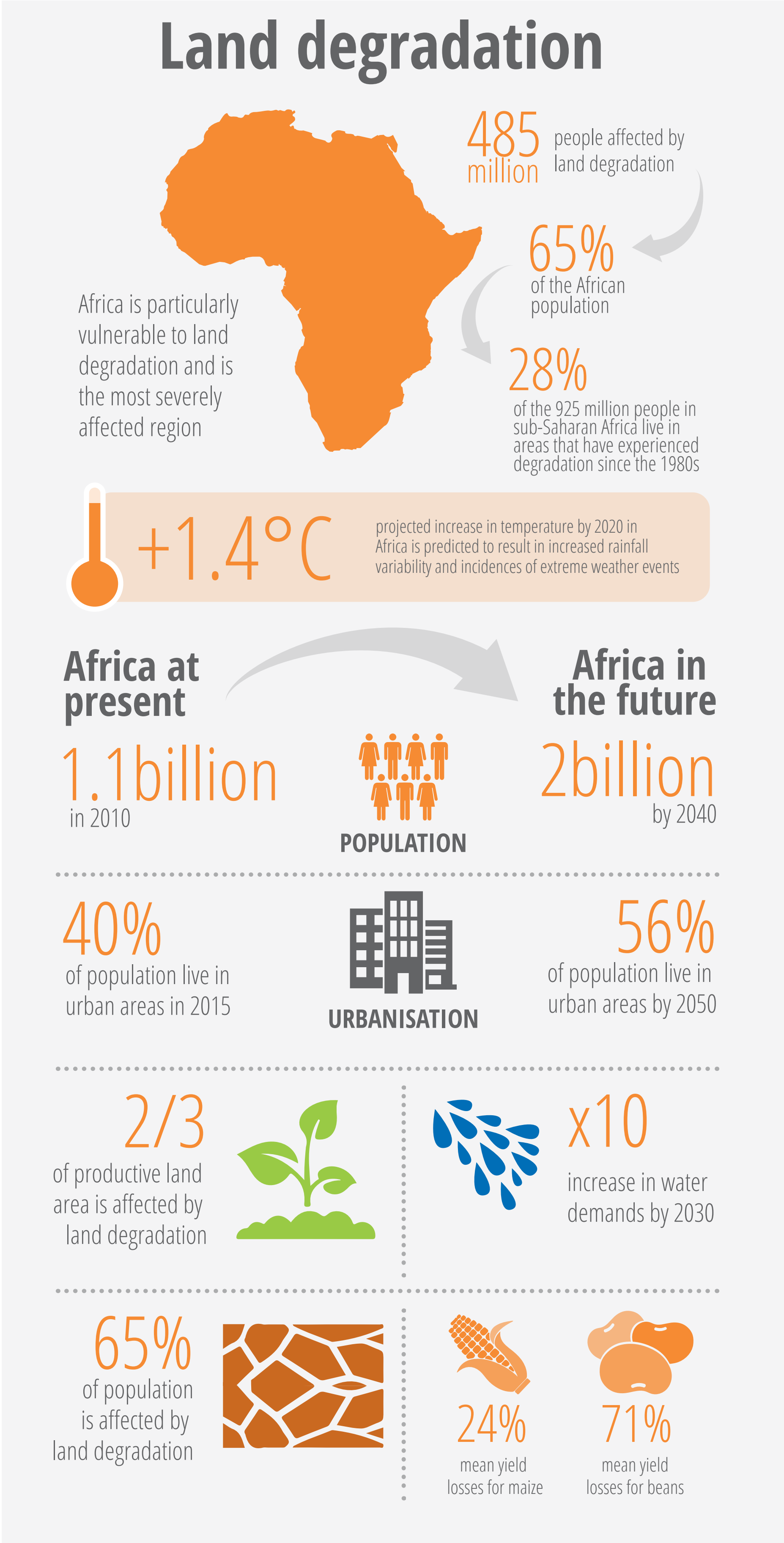
Land degradation is a serious problem in the world hugely affecting food security and livelihoods. Reviews of global land degradation affirm that Africa is particularly vulnerable to land degradation and is the most severely affected region (Obalum et al., 2012). Some estimates show that land degradation affects up to two thirds of productive land area in Africa (UNCCD, 2013; Jones et al., 2013) influencing at least 485 million people or 65% of the entire African population (ECA, 2007). Other evidences show that about 28% of the 925 million people in sub-Saharan Africa (SSA) live in areas that have experienced degradation since the 1980s (Le et al., 2014). Africa's population is also projected to increase from 1.1 billion in 2010 to about 2 billion people by 2040 and can eventually reach 4.2 billion by 2100 (UNDESA, 2013). With such population increase, the region needs to accelerate its food production (UNEP, 2016). Urbanization is also growing at an alarming pace. In 2015, 40% of Africa's population lived in urban areas and this proportion is projected to rise to 56% by 2050 (UNDESA, 2013), leading not only to an increase in the quantity but also in the variety of food demanded. The projected increase in population by 2030 is expected to lead to, at least, a tenfold increase in water needs for energy production to support industrial, social and economic growth (AUC-AMCOW, 2016). This points to a greater competition for available land and water resources in future resulting in land degradation while at the same time, climate variability and climate change also exacerbate the situation. In addition to land degradation, SSA is also highly vulnerable to the impacts of climate change (IPCC, 2014; Niang et al., 2014). Estimates show that there will be mean yield losses of 24% for maize and 71% for beans under warming conditions exceeding 4 degree Celsius (Thornton et al., 2011). The projected increase in temperature of up 1.4°C by 2020 in Africa is predicted to result in increased rainfall variability and incidences of extreme weather events. Hence, the planet's ability to support the over 9.6 billion people by 2050 (United Nations, 2015) will be hugely compromised due to land degradation and climate change.

The challenge of meeting the food and nutrition requirements of a growing population through sustainable and climate-resilient farming systems is one of the key issues facing African agriculture over the coming decades. This challenge is well recognized by African political leaders. Africa's Agenda 2063 endorsed by the African Union (AU) Summit of January 2015 and the AU Malabo Summit Declaration of June 2014 on Accelerated Agricultural Growth and Transformation both affirmed that African governments need dedicated commitment to eliminate hunger and food insecurity by 2025; and to enable resilience of livelihoods and production systems to land degradation, climate change and other shocks (AU, 2014). Meeting these commitments will critically depend, amongst other things, on how the land, soils, water, energy and agroecosystems in general are managed and sustained for the production of food and other basic human needs. As essential as these resources are, each one is coming under pressure due to demographic, economic and climatic changes.

The mounting pressure on natural resources from various angles and the risks that land degradation poses to the attainment of the Sustainable Development Goals (SDGs) in Africa point to the need to reexamine the linkages between land degradation, food insecurity, and social conflicts. The reexamination of such nexus is needed to identify technical, policy and institutional arrangements that will promote land restoration, agroecosystem health and food security with social harmony to meet current and future human and environmental security objectives. However, in order to understand how land degradation can be addressed and better managed, it is necessary to first assess the status and characteristics and quantify the impacts of on ecosystems in order to provide viable recommendations that would yield lasting solutions for improving food security on the continent.

Considering the combined impacts of land degradation on population and nature, the German Federal Ministry of Economic Cooperation and Development (BMZ) Program "One World No Hunger" identified soil health and sustainable land management as key interventions, especially in developing regions. Several countries were identified to implement the program complemented with an 'Accompanying Research Soil Protection and Rehabilitation for Food Security' to identify enabling conditions for more sustainable land management as well as context-specific entry points and processes to implement those options. The International Center for Tropical Agriculture (CIAT) and the TMG Thinktank for Sustainability have partnered to assess land degradation at different scales to support the soil health and Sustainable Land Management (SLM) activities of the German Agency for International Cooperation (GIZ) in Kenya, Burkina Faso, and Benin.

Recognizing the fact that different processes dictate the severity and spatial distribution of land degradation at different scales, it is not possible to apply the same approach across scale, biophysical and socio-economic contexts. Due to data availability, demand and relevance, it will also not be acceptable to present viable results for decision makers at different levels using the same dataset. It will thus be essential to follow a 'multiscale' approach to map land degradation hotspots, assess the major drivers and suggest potential management options at national, county/district and landscape levels. Against this background, we applied a multi-scale hierarchical approach to evaluate land degradation sensitivity and map hotspots. Results at the three scales were evaluated using literature review, google maps, biophysical modeling, expert-consultations, participatory and ground truthing approaches. Findings at the national and district levels for Kenya were also presented at a national level stakeholder workshop to discuss on findings and gather comments/suggestions for improvement. Such exercise was vital as local knowledge helped provide context-specific suggestions and enabled validating results.



2. Objectives

The main objective of the project was to produce detailed information on the spatial distribution of land degradation at different scales in Kenya and Burkina Faso, identify priority areas of intervention, and suggest context-specific measures. The main activities included mapping the status of land degradation risk:

a. at country/regional scale using time-series satellite and climate data;

b. at province/county level using high resolution data supported by stakeholder engagement and validation;

c. in selected sites/watersheds using hydrological/soil erosion model, and

d. implement participatory ground truthing of the analysis results at county and watershed scales.

The above were achieved using 'multiscale' approaches that considered understanding the different land degradation processes at different scales. These were accompanied by developing frameworks and tools that can be used by national/local stakeholders to map the spatial distribution of land degradation and facilitate informed decision making. This project contributes directly to the objectives of the BMZ-GIZ Soil program on 'Soil Protection and Rehabilitation for Food Security' as part of Germany's Special Initiative "One World – No Hunger" (SEWOH), which invests in sustainable approaches to promoting soil protection and rehabilitation of degraded soil in Kenya, Ethiopia, Benin, Burkina Faso and India. It furthermore supports policy development with regard to soil rehabilitation, soil information and extension systems. The land degradation assessment component can also allow GIZ to widen the scope of soil protection and rehabilitation for food security by deploying an option by context approach to facilitate targeting and informed decision making.

3. Study areas

3.1 Study area/site selection and national level description

The major reason for selecting the study countries was to align with the One World No Hunger project sites and also include an element of agroecological diversity. The initial countries identified for analysis were Kenya, Burkina Faso and Benin (Fig. 1). This report focuses on presenting analysis results of a multiscale approach

Fig. 1: *Study sites for the national level land degradation assessment using long-term satellite and climate data*

employed for three spatial scales in Kenya and Burkina Faso. Analysis related to Benin covered only the national scale and reported separately. The two countries presented in this report can be essential for scaling as they cover two contrasting agro-ecological zones representing the equatorial belt in East Africa (Kenya) and the sahelian zone in West Africa (Burkina Faso), hence work can be replicable elsewhere. The county/province level analysis in the two countries were focused on GIZ 'soil health and sustainable land management' project sites. The detailed landscape level analysis focused on 'hotspot' areas identified during the county/province level analysis. This 'sampling' design completes the multi-scale hierarchical land degradation assessment.

3.2 County level description – Kenya

As indicated above, the lower level analysis in the respective countries are selected considering their alignments to GIZ projects. As a result, the county level analysis in Kenya focused on Bungoma, Kakamega and Siaya Counties in the Nzoia basin (Fig. 2a). The Nzoia Basin lies between Latitudes 10 30′ N and 00 05′ S and Longitudes 340 and 350 45′ E in Western Kenya, covering a catchment area of over 12,000 km^2. The drainage system of the basin originates from Mount Elgon and Cherangani Hills. The area has a high topographic relief characterized by steeply sloping uplands and elevation ranging from 878 m a.s.l in the Nzoia valley to 4304 m a.s.l at the peak of Mount Elgon. The mean annual rainfall is between 1400 – 1800 mm and an average temperature of 14-24°C. The average annual rainfall is approximately 1572 mm in Siaya, 1628 mm in Bungoma and 1971 mm in Kakamega. The highest amount of rainfall is received in the months of April and May. The primary economic activity in the region is agriculture where it contributes enormously to the region's economy as well as providing employment to majority of the residents. The main crops produced in the region are sugarcane and maize, whereby sugar cane is produced as a cash crop while maize is mostly grown for subsistence.

3.3 Province level description – Burkina Faso

For Burkina Faso, the province level study was conducted in the Black Volta river basin which is a transnational river system that runs from Mali, through Burkina Faso, Ivory Coast and Ghana. The Black Volta basin, the largest in the catchments of the Volta basin, has a total area of 142,056 km^2. It contributes about 18% of the annual flows of the Lake Volta (Andreini et al., 2000). The dominant soils in the basin according to FAO soil classification are Luvisols and Gleysols with altitudes ranging between 60 m and 762 m above sea level. In the Black Volta basin, rainfall and temperature are spatially variable. The mean annual temperature differs from 27 °C in the south to 36 °C in the north (with an annual range of 9°C). According to Shaibu et al. (2012), precipitation ranges respectively from 400 mm/year in the North to 1500 mm/year in the South. The highest amount of rainfall is received in the months of June, July, August and September. Rainfall totals of more than 500 mm during this period provide enough water for livestock and crops. The primary economic activity in the region is agriculture where it contributes to the region's economy as well as providing employment to majority of the community. The main crops produced in the region are sorghum, groundnuts, sesame and beans. Within this basin, detailed land degradation risk analysis was conducted for Houet and Tuy provinces (Fig. 2b), which are aligned to GIZ sites.

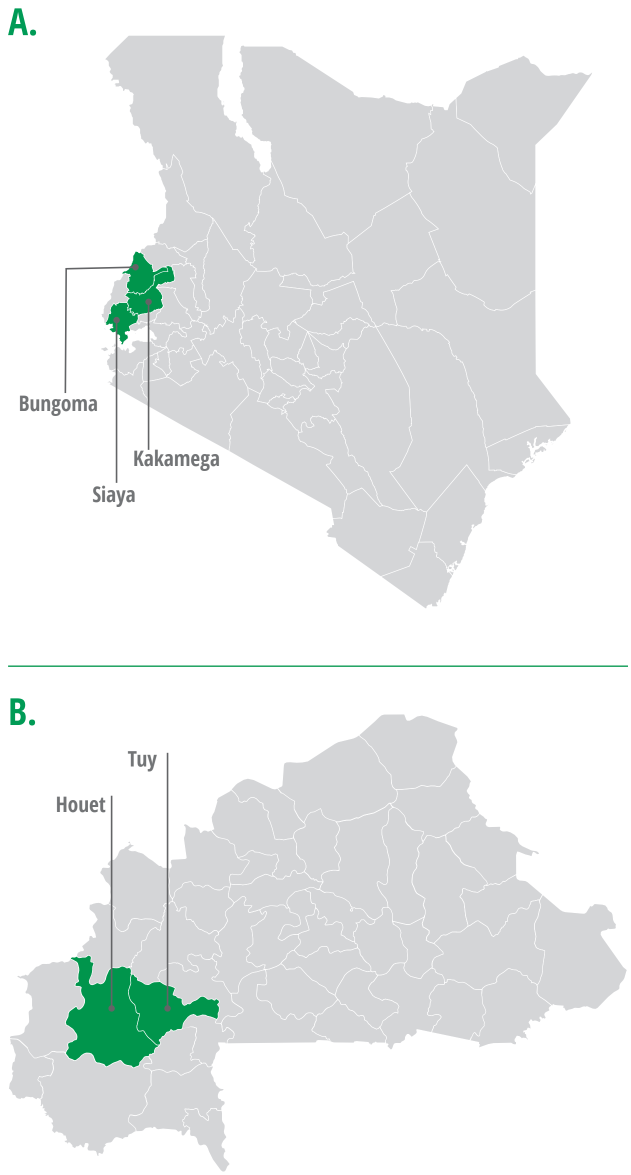


Fig. 2: *Locations of counties and provinces where intermediate level analyses of land degradation risk was conducted using erosion hazard and land degradation indices for (**a**) Kenya and (**b**) Burkina Faso*

3.4 Landscape/watershed level description

The next lower (more detailed) level of analysis was landscape/watershed scale. The specific study landscapes were identified based on analysis results at the county/province level. An erosion hazard index was used to identify areas that were more prone to erosion. The index (details given below) is built based on key biophysical data in order to map the erosion risk of areas at county/province or district levels. For the detailed analysis, the 'erosion risk maps' at county/province level were used to identify 'representative' landscape/watershed with high erosion severity in the two regions

(Fig. 3). More detailed data and modelling approaches notably using the SWAT model were then applied to quantify sediment yield and map its spatial variability as well as assess the potential impacts of management options (details are presented in the methods section).

The selected watershed in Western Kenya (Fig.3a) is found in Bungoma County, a tributary of River Nzoia from Mt. Elgon. Most of the area has a steep slope i.e., ranging between 1315 - 4292 metres a.s.l. The average annual rainfall is 1628 mm, the dominant land use is agriculture with sugarcane, maize, coffee and beans being the key crops that farmers have focused on. The watershed in Burkina Faso (Fig.3b) used for the detailed analysis is found in the Houet Province. It has a relatively flat slope ranging from 289 - 526 metres a.s.l. The main crops produced include sorghum, groundnuts, sesame and beans. Generally, the Kenya site represents more of a highland and steep slope system while that of Burkina Faso is dryland with dominantly flat areas covering the majority of the site.

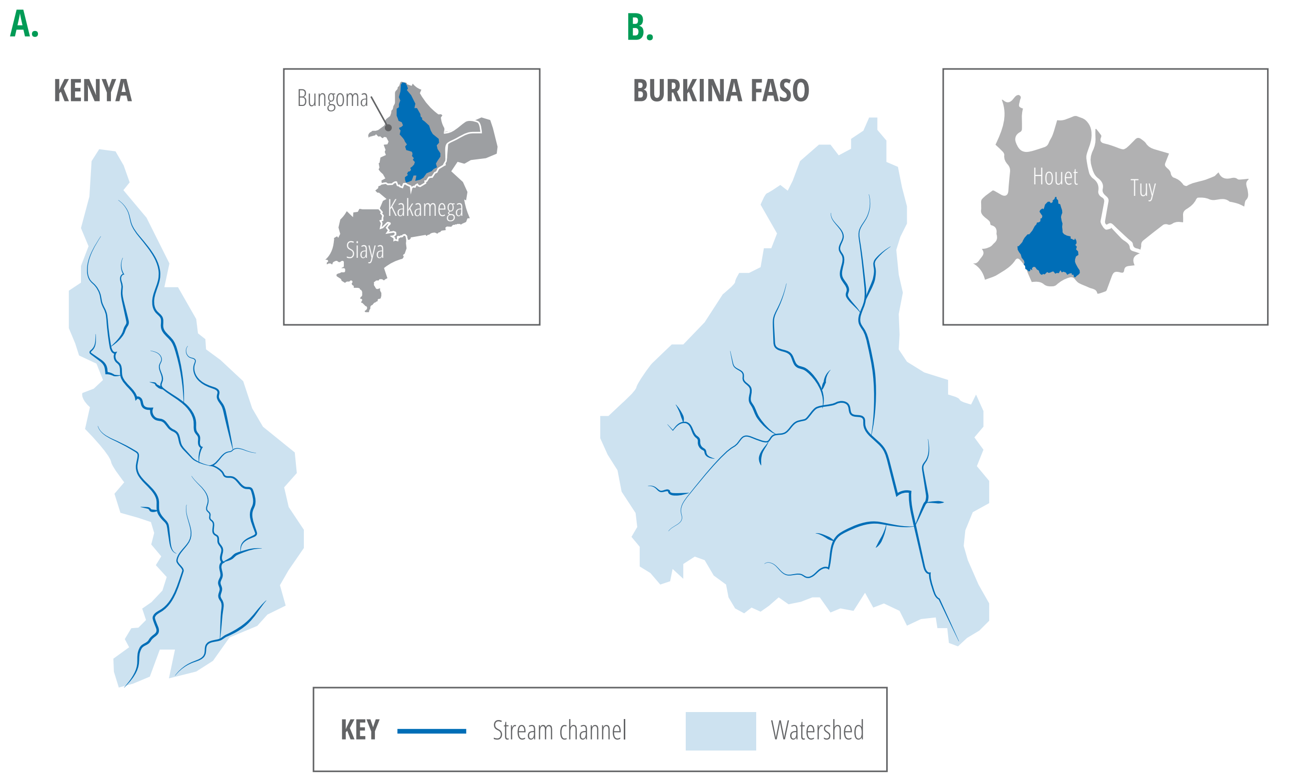


Fig. 3: Selected watersheds for detailed analysis of land degradation risk and assessing potential impacts of land management practices in the (a) Bungoma County, Kenya and (b) Houet Province, Burkina Faso

4. Methodology

4.1. Land degradation assessment approaches

Land degradation in general is defined as a persistent decline in the productivity of land as a result of which restoration/rehabilitation mechanisms are needed to stop complete collapse of the system and/or facilitate re-gaining its biophysical, environmental and socio-economic functions. In order to develop options of tackling land degradation, it will be essential to assess the severity and drivers of the problem. Against this background, various efforts have been made and a wide range of methods exist to assess the risk of land degradation and map hotspots. Due to differences in the approaches employed, there is generally large deviation in the extent and distribution of degraded areas at different scales. For example, a recent comparative review showed a global estimate of degraded areas to vary from less than 1 billion ha to over 6 billion ha, with equally wide disagreement in their spatial distribution (Gibbs and Salmon, 2015). This divergence can be related to a wide spectrum of data qualities, data resolutions, temporal and spatial aggregation of data, methods of analysis, indicators used as metrics and ways of treating confounding factors (Le et al., 2012). This means that accurate estimate of the severity of land degradation will be difficult at least at the current status of data availability and the complexity of land degradation processes. It will thus be preferable to focus on identifying areas that are at higher probability risk of degradation and thus delineate sites that require priority intervention. In this case, an approach employed to map hotspots which aims to identify and map high potential degradation risk areas with relatively high confidence is essential.

Understanding the severity of land degradation is a general prerequisite for geographical targeting and prioritization. Developing standardized approaches of land degradation assessment and monitoring may be difficult because land degradation has different forms, affects various sectors, embraces different categories, and is driven by numerous factors complicating the development of uniform monitoring tools. According to Warren (2002), land degradation is a very contextual phenomenon and cannot "be judged independently of its spatial, temporal, economic, environmental and cultural context". Another challenge is the fact that land degradation is a persistent decline in the productive capacity of the land and requires long-term follow up to evaluate its severity and trend. Additionally, it is generally difficult to 'validate' the observed trend as it involves wide time scale as a result of which validation data monitored over time could not be available. In light of these challenges, Earth Observation (EO)-based systems have become major candidates for establishing land monitoring networks at national, regional and global scales (Symeonakis and Drake, 2004; Bai et al., 2008; Vlek et al., 2008). However, the relevance of such options can be questionable at local scales where large scale satellite data are not available at the required temporal scale. In addition, the level of detail and accuracy required for informed decision making varies at different levels requiring the need to develop fit-to-purpose approaches to estimate land degradation risk at different scales. National government planners may be interested to have overall land degradation risk zones across the country while farmers may be interested to know the amount of annual soil loss and investment required to tackle the problem at their fields. As a result, multiscale/hierarchical approaches can be good alternatives to provide relevant information at different scales. Below we present the various approaches employed to assess degradation risk at the different levels.

4.2 The 'hierarchical' approach

Land degradation is a complex process, thus a variety of approaches are needed to adequately assess it (Mulunge et al., 2015). Since the processes mainly vary across scale, it is essential to develop and/or use models that fit a specific purpose. Considering 'scale and its relevance for different users', three approaches were employed to assess land degradation at national, county/province and landscape/watershed levels (Fig. 4). The approach is designed considering the fact that processes, drivers and end users vary over different scales (Le et al., 2012). For instance, national level analysis can target on identifying sub-regions where interventions should focus and thus can benefit planners and decision makers at higher levels while studies at landscape and farm levels can use detailed data to produce high resolution outputs that can interest farmers and local level decision makers. As a result, the project assessed land degradation at national, sub-national and watershed/landscape scales. The national level studies focused on the use of time series satellite and rainfall data to map degradation hotspots using normalized difference vegetation index (NDVI) as a proxy. The sub-national (e.g, county/province) level studies targeted the hotspot areas as identified based on the 'national level analysis' and locations corresponding to GIZ project activities. The landscape level assessments were identified considering the county/province level hotspots. Once those 'local hotspots' were identified, detailed hydrological/erosion models were used to estimate sediment yield and surface runoff, considering these are key components of land degradation at local levels. The results were then validated through expert consultations, stakeholder input, ground truthing, and Google maps. Along these lines, validation efforts captured various forms of land degradation and their causes were recorded from both field observations and information gathered from local communities and experts (also refer to Plate 1). Soil erosion was the primary degradation of concern for most stakeholders, particularly farmers and county governments (Plate 1).

Some studies reveal that participatory mapping using stakeholder insights are commonly used to provide scientists with better informed local level knowledge that refines the accuracy of model predictions (Rambaldi et al., 2006). In the national and county/province level analysis, we engaged with relevant stakeholders and local communities in order to solicit information about degradation trends, processes and drivers. The knowledge and insights gained from the multi-stakeholder dialogues were condensed into the analytical process that went into producing and validating the results. In addition, national level workshops were organized (in this case for Kenya) to discuss the results and implications with relevant stakeholders from national and the respective sub-national levels. Below we present the key approaches followed and data used to map land degradation hotspots at three hierarchical levels.

***Plate 1:** Example of gully erosion features in Western Kenya (Bungoma) that result in increased losses of valuable topsoil for crop production*

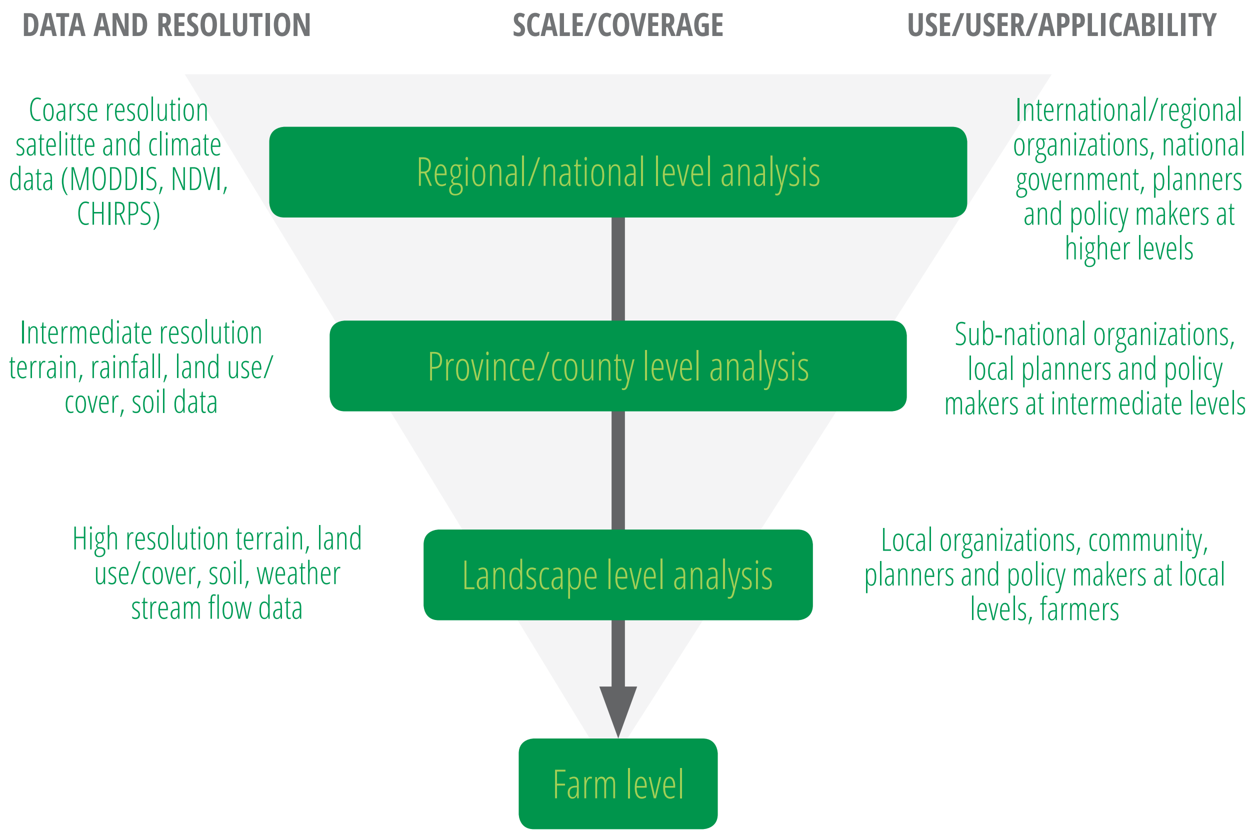


***Fig. 4:** Land degradation hotspot assessment at different scales following the hierarchical approach*

4.2.1 Land degradation risk mapping at national level using time series satellite and rainfall data

At global, regional and national scales, time series satellite data complemented with rainfall information have been used to assess land degradation risk. Because vegetation is related to various ecological processes including soil erosion, biodiversity, greenhouse gas emission, land productivity, water availability and quality, recent land degradation assessment and monitoring have been related to vegetation vigor and productivity analysis (Pickup, 1996; Walker et al., 2012). The potential of vegetation index variation as a measure of ecosystem health has been acknowledged for nearly 30 years (Tucker et al., 2005; Higginbottom and Symeonakis, 2014). The most frequently utilised method employing Earth Observation datasets is the Normalised Difference Vegetation Index (NDVI) based trend analysis (Justice et al., 1985; Tucker et al., 1985; Tucker et al., 1986; Reed et al., 1994). In arid and semi-arid lands seasonal sums of multi-temporal NDVI are strongly correlated with vegetation production (Prince and Tucker, 1986; Prince and Goward, 1995; Nicholson and Farrar, 1994; Prince et al., 1998; Nicholson et al., 1998; Wessels et al., 2007). In addition to NDVI, net primary productivity (NPP) is commonly used because it better reflects land/vegetation condition and is one of the primary processes describing the vegetation activity in terms of mass and energy exchanges between the earth's surface and atmosphere(Running et al., 2004). NPP can therefore be used to measure overall land productivity and ecosystem health and also to provide some indication of land degradation and soil productivity in particular land use systems (Bai et al., 2008). The availability of time series data from earth observation systems (EOS), enhanced computational power and improved statistical tools have promoted and facilitated analysis of land degradation/restoration. Taking advantage of this, various studies have been conducted to assess land degradation risk using satellite data adjusted for climatic variables (e.g. Bai et al., 2008; Vlek et al., 2008; Hellden and Tottrup, 2008; Le et al., 2014).

In this study we used the Moderate Resolution Imaging spectroradiometer (MODIS) NDVI and Climate Hazard Group InfraRed Precipitation with Station (CHIRPS) climate/rainfall time series data (2000-2015) to monitor land degradation trends and discern the major drivers (Fig. 5) in Kenya and Burkina Faso. The main objective was to map the spatial distribution of land degradation risk in order to prioritize intervention areas at national level. Though the 16-year timespan is not wide enough to capture detailed land productivity trends, we believe that it has enough temporal coverage to evaluate the overall direction and identify areas where degradation or greening is occurring. We calculated the linear NDVI trend by regressing NDVI over time and testing its significance. The long-term trend of annual NDVI was estimated using linear slope (A) of annual accumulated NDVI over time given as NDVI = A x Year + B. The NDVI slope was calculated as NDVI slope = ΔNDVI / year. The resulting map was classified into three levels: negative, neutral and positive trends. The negative trend depicted areas where there was consistent NDVI decline serving as a proxy for land degradation hotspot while positive trend was associated with consistent improvement in biomass and land productivity. The observed significant NDVI trend was also integrated with other biophysical and socio-economic data to evaluate associations and determine their potential impact in driving the observed trend. To disentangle climate-caused versus human-induced causes of the observed trend, we used CHIRPS rainfall data for the same period and evaluated its correlation with the NDVI using Spearman's coefficient of correlation. Areas with significant correlation at 90% level and with $-0.45 < |R| > 0.45$ were considered as places where there is high interrelationship between NDVI and RF trend (Vlek et al., 2008). The land degradation risk maps were also related with other land degradation hotspot maps generated by other studies.

4.2.2. Land degradation assessment at county/ province level using an erosion hazard index

One of the common forms of land degradation is soil erosion. It causes loss of fertile topsoil, delivers millions of tons of sediments into reservoirs and lakes, resulting in a significant negative environmental impact and high economic costs associated with its effect on agricultural production, infrastructure and water quality (Lal, 1995; Lal, 1998; Pimentel et al,. 1995; Tamene et al., 2005). With absence of management and surface cover,, accelerated erosion can result in gullies in addition to high nutrient loss as observed in various areas of Western Kenya (Plate 2). Not surprisingly, soil erosion and sediment delivery have thus become important topics for local and national policy makers. This has led to an increasing demand to delineate target zones where conservation, restoration and sustainable intensification measures can be targeted. As a result, there are several efforts to estimate soil loss and map its spatial distribution at different scales (e.g., Wischmeier and Smith 1978; Nearing et al. 1989; Renard et al., 1997; Morgan et al., 1998; and Arnold et al., 1998) to mention a few.

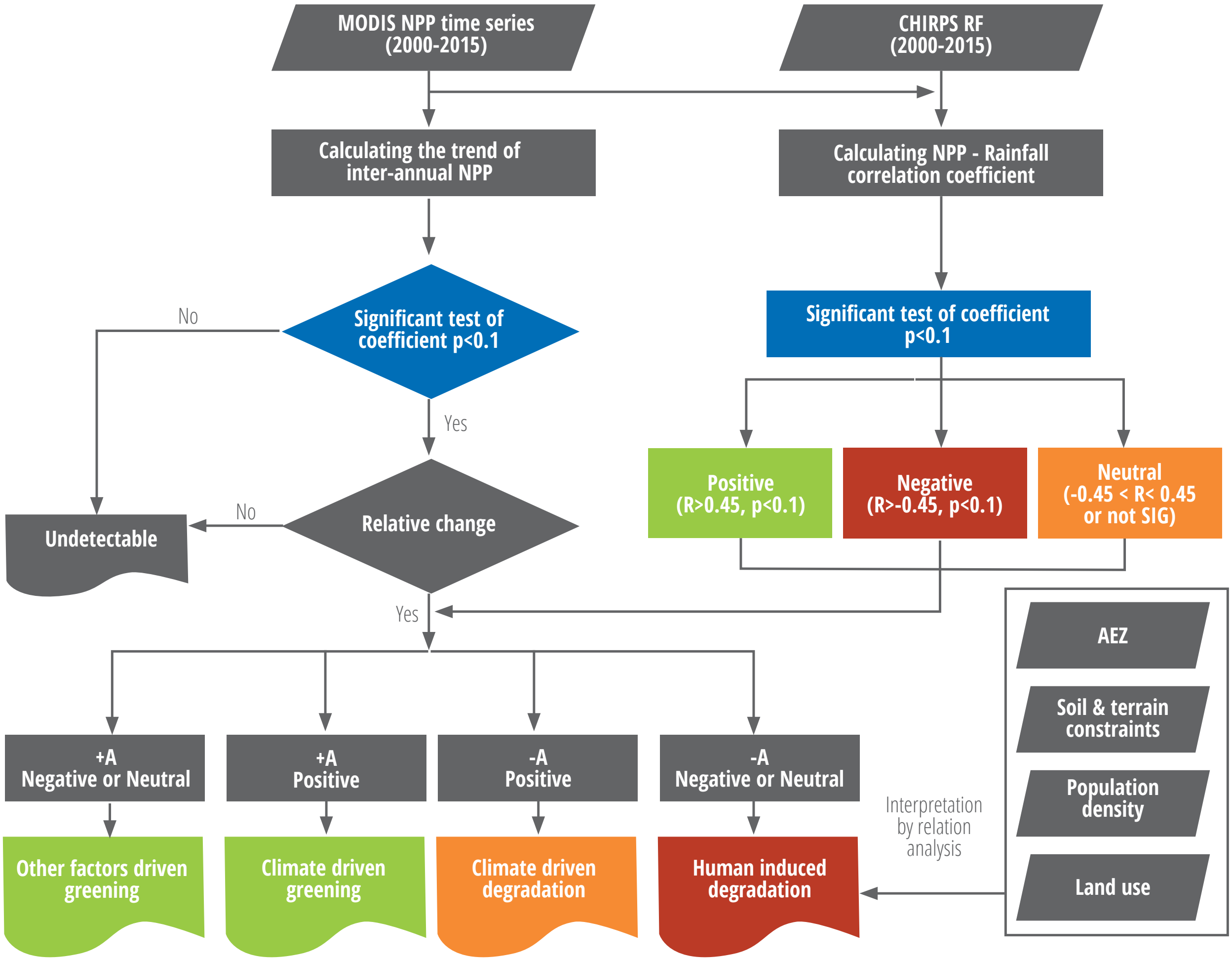


Fig. 5: *Flowchart representing the various steps and datasets used to assess land degradation trend and identify key drivers at national level (AEZ stands for agro-ecological zone)*

Plate 2: *Common erosion features in some stressed areas of Western Kenya*

The application of some erosion models, especially in developing regions, renders several challenges such as data availability at the desired scale, resolution and accuracy. Despite the fact that some of the erosion models are easy to use and have relatively modest data requirements, they are not flexible enough to be used by local partners and stakeholders. This leads to application of different models by users for similar geographical regions, in most cases leading to inconsistency of the results. Considering the fact that quantifying the exact amount of soil loss is not always possible or necessary, attempts have been made to develop easy to use tools to assess the erosion hazard of landscapes (e.g., PSIAC, 1968; Hadley et al., 1985; De Vente et al., 2006). Such tools can not only facilitate application by local stakeholders but also increase their adoption and out-scaling. Accordingly, various studies such as Verstraeten et al. (2003); Lawrence et al. (2004); de Vente et al. (2006); Wu and Wang (2007), Tamene et al. (2006a, 2011), applied a similar technique in their assessment of soil erosion risk and map hotspot areas of erosion that require prior intervention. Based on a number of thematic GIS layers and remote sensing data, they integrated a variety of physical and managerial factors that are dominant in water-based soil erosion in their study areas.

A challenging issue in the application of the majority of erosion/hydrological model is the lack of calibration data as most are developed in different regions than being applied. Because of this, the Universal Soil Loss Equation (USLE) and its variant are being commonly applied worldwide because of their simplified form and somehow 'universal' nature. However, these models require localized data for model input as well as model calibration and validation, which can make their application in data-scarce regions difficult. In such case, locally adopted semi-qualitative indices can be used especially to assess soil erosion risk and identify priority areas of interventions.

In light of the above considerations, we developed and automated a toolbox that combines different datasets and generates an erosion hazard index. The toolbox combines erosion hazard assessments with soil parameters specifically soil texture. To determine where denser vegetation slows runoff and thus reduces erosion, the tool uses NDVI cost weighted distance approach. This provides a variable-width buffer that is wider where vegetation is more sparse and narrower where it is dense. Terrain attributes including slope, flow direction, flow accumulation and stream power index were generated from a 90-meters digital elevation model (DEM). Similar to flow buffer, we used the cost weighted distance for slope, which gives a variable-width buffer that is wider where it is steep and narrower where it is flat. This step is based on the inverse of slope, since flatter ground slows runoff and therefore reducing erosion. To determine the role of rainfall in soil erosion, we used the CHIRPS precipitation data. To account the role of differences in land use/cover on soil loss, we used land use/cover data generated from Landsat satellite image analysis. The identified land uses for the three counties of Kenya (Bungoma, Kakamega and Siaya) and two provinces of Burkina Faso (Houet

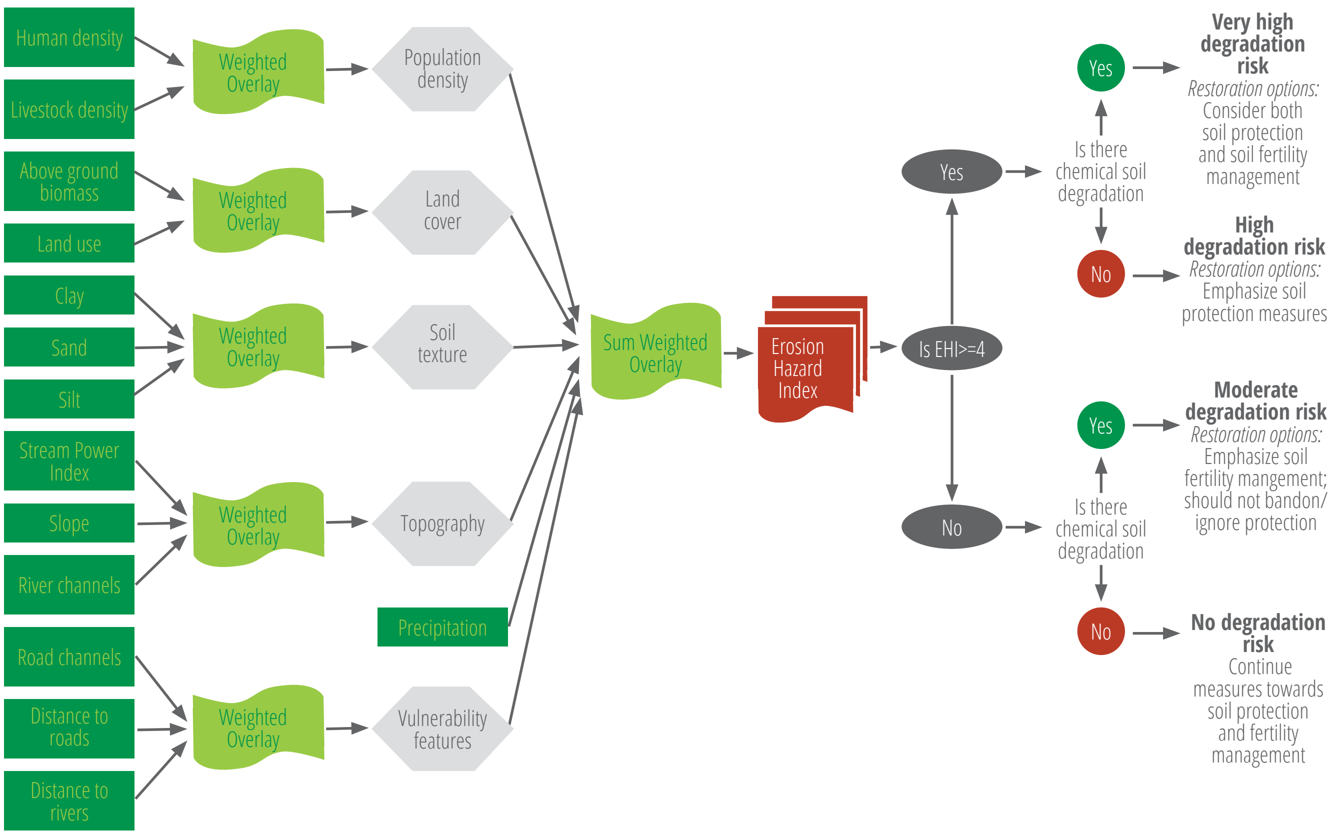


Fig. 6: *Flowchart representing the various steps and datasets used to build the Erosion Hazard Index (EHI) at the county/ province levels*

and Tuy) include: settlement, agriculture, forest, shrubland, grassland, wetland, water, and bareland. Soil erodibility potential was assessed considering major soils types of the study sites. The identified soils for the regions of interest are: Loam Sandy; Clay Loam; Loam; Sandy Clay; Clay; Sandy Clay Loam and Sandy Loam. Table 1 shows the major land degradation factors and associated thresholds used in formulating the erosion hazard index developed in this exercise.

Table 1: *Land Degradation factors used to calculate Erosion Hazard Index*

Degradation factors	Diagnostic factors and units	Degree of limitation
Land Cover	Season NDVI (reflectance)	<0.2
	Land Use (class)	Cultivated, Artificial surfaces, Bare and (1 - 3)
Soil characteristics	Texture (class)	Loamy Sand, Clay Loam, Loam, Sandy Clay (1-4)
	Coarse fragments (%)	Relevant literature not found
	Stream Power Index (percentile class - 95%)	>0.59
	Slope (%)	>32
	Season NDVI weighted distance to streams (percentile - 10%)	<519.02
Topography	Slope weighted distance to streams (percentile – 10%)	<13,908.38
	Season NDVI Distance to roads (percentile - 5%)	<562.42
Streams Sediment Runoff	Slope Distance to roads (percentile - 5%)	<11,323.08
	Season Precipitation- CHIRPS (mm)	>750
Roads Sediment Runoff	Season NDVI Distance to roads (percentile - 5%)	<562.42
	Slope Distance to roads (percentile - 5%)	<11,323.08
Precipitation	Season Precipitation - CHIRPS (mm)	>750

The calculation associated with the overall overlay of the land degradation risk integrates the reclassified raster layers namely i) erosion hazard index (EHI); ii) pH; iii) soil organic carbon and iv) cation exchange capacity. The associated thresholds are informed by scientific literature and expert consultations pertinent to the area of interest. After establishing the criteria and thresholds from literature for the degradation assessment (Table 1), the land degradation index is then computed with a raster calculator. This was then classified into four categories: i) Very high degradation risk; ii) High degradation risk; iii) Moderate degradation risk; iv) No degradation risk .

The degradation risk calculation is based on a series of conditional computation statements dependent on the thresholds established from the EHI and soil chemical properties (pH, CEC and SOC) (Table 2). EHI varies between 1 - 4 such that 1 depicts low erosion and 4 high erosion. Cation Exchange Capacity (CEC) based on meq/100 g; ranging between 0.4 through 4.3 meq/100 g. It has been reported that soils with a low CEC are more likely to develop deficiencies in potassium (K+), magnesium (Mg2+) and other cations while high CEC soils are less susceptible to leaching of these cations (CUCE, 2007) and would thus support optimal plant growth. pH thresholds are derived from the UC Davis and USDA Plant & Soil Sciences eLibrary complemented by literature for the African context (https://passel.unl.edu/pages/). The thresholds used here were between 6-7 as being optimal for crop production (Crop and Soils Database Library, 2014, WEAP).

The EHI maps for both the Kenya Counties and Burkina Faso Provinces were calibrated and results validated using field observation. A team of experts from CIAT and national partners followed a random sampling approach whereby the team visited different places to acquire an overall information about the extent and severity of erosion as well as its major drivers. Part of the dataset were used for model calibration while the rest was used for model validation.

Table 2: *Thresholds for EHI, SOC, pH and CEC used to estimate land degradation risk in Western Kenya*

EHI level (Pixels)	SOC (%)	pH	CEC (cmolc/kg)	Raster Algebra	Category generic description
< 2.5 Below moderate	>=2	>=6 and <=7	>= 10	("EHI"<4)&("CEC">= 10)&("SOC" >=2)& ("pH>=6 and <=7)	*No degradation risk* (low erosion risk and good fertility status)
>= 4 Above moderate	>=2	>=6 and <=7	>= 10	("EHI">=4)&("CEC">= 10)&("SOC" >= 2)& ("pH>=6 and <=7)	*Moderate degradation risk* (high erosion risk but good fertility status)
< 4 Below moderate	<2	>6 and or <7	<10	("EHI"<4)&("CEC"<= 10)&("SOC"<2)& ("pH>6 or <7)	*High degradation risk* (low erosion risk but poor fertility status)
>= 4 Above moderate	<2	>6 and or <7	<10	("EHI">=4)&("CEC"<= 10)&("SOC" <2)& ("pH>6 or <7)	*Very high degradation risk* (high erosion risk and poor fertility status)

4.2.3 Soil erosion and hydrological modeling at landscape scale using the SWAT model

For more detailed process understanding and priority mapping at local or landscape scale, the Soil and Water Assessment Tool (SWAT) which is a hydrological model was used. The SWAT model is a physically based distributed model designed to predict sediment yield, runoff etc. and can assess the impacts of land management practices on water, sediment, and agricultural chemical yields in complex watersheds with varying soil, land use, and management conditions over long periods of time (Neitsch, et al., 2011). The SWAT model subdivides a basin into sub-basins connected by a stream network and further delineates each sub-basin into hydrological response units (HRUs) consisting of unique combinations of slopes, land use and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. This increases accuracy and gives a much better physical description of the water balance.

The SWAT model partitions the hydrology into land and routing phases. In the land phase, the amount of water, sediment and other non-point loads are calculated from each HRU and summed up to the level of sub-basins. Each sub-basin controls and guides the loads towards the basin outlet. The routing phase defines the flow of water, sediment and other nonpoint sources of pollution through the channel network to an outlet of the basin.

4.2.3.1 SWAT Modelling: Data Processing and model set up

The key data used as input in SWAT are elevation, soil, land use, weather, and streamflow. The Soil Data was obtained from ISRIC 250 metres Spatial resolution (Hengel et al., 2015), the SWAT soil database was developed using a computation soil macro function. A 30 meters resolution DEM was obtained from CGIAR CSI Website (http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1). Weather data was obtained from Global Weather Data for SWAT database (https://globalweather.tamu.edu/). For Kenya, land use/cover data was produced from LANDSAT 8 satellite at a resolution of 30 meters. For the Burkina Faso site we used land cover map obtained from GlobeLand30 (2010) Website (http://www.globallandcover.com/GLC30Download/index.aspx). All the data were processed and aligned to have the same spatial resolution of 30 meters. We noted that a 250 m resolution soil data could affect the final model output but we were not able to get other sources with improved resolution.

All relevant datasets were acquired, processed and modified to suit applicability in the SWAT model as depicted in the key workflow to set-up the model (Figure 7). The data were then simulated for definition of the land use, soil types and slope. After incorporation of the relevant dataset, model was run for the time period 1990 through 2016 using a daily time step.

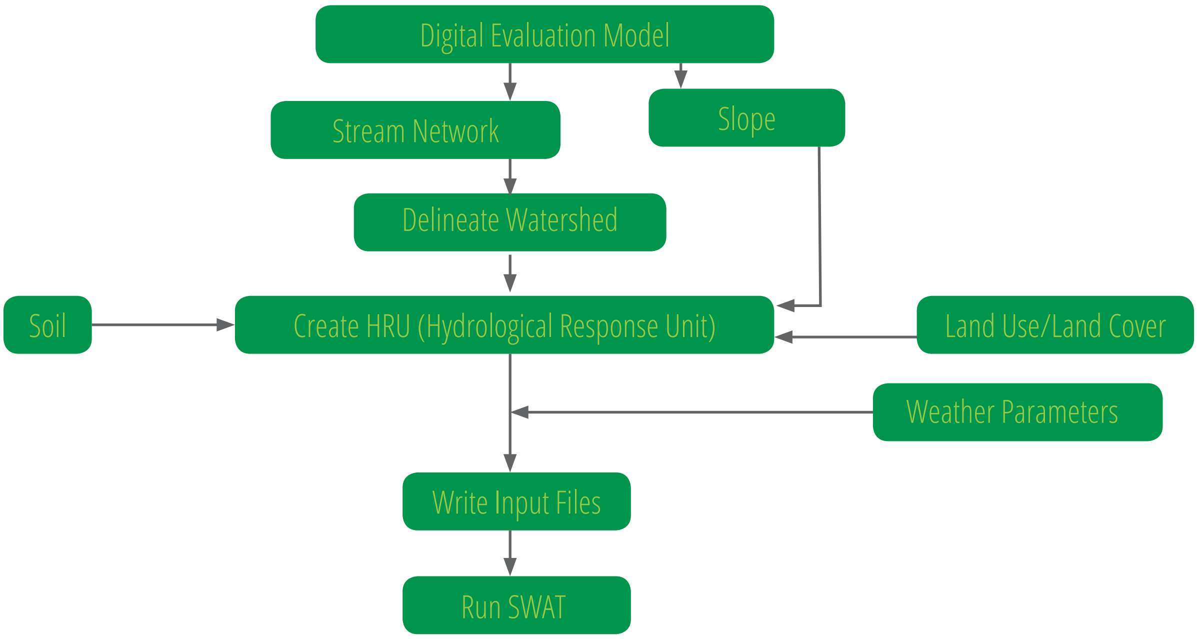


Fig 7: *Procedure for simulation of runoff and sediment yield using the SWAT model*

4.2.3.2 Simulation of the impacts of best-management practices in reducing sediment yield

The SWAT model was integrated into the APEX tool: Agricultural Policy Extender to form SWAT-APEX exchanging the output of SWAT into the APEX tool in an ArcSWAT environment. The SWAT results were plugged in as input for comprehensive assessment of agricultural technologies/interventions that are designed to increase food production, and minimize negative environmental consequences for smallholder farms. For both Kenya and Burkina Faso, we selected subwatersheds that were "hotspots" with high erosion risk based on the EHI model. Thereafter, the 4 different interventions for restoration or remediation were deployed within the sub-areas to assess their impact on sediment yield and water yield.

5. Results and discussion

5.1 Land degradation trends and hotspot areas in Kenya

5.1.1 National level analysis

Figure 8A shows the long-term trends of annual NDVI estimated using the linear slope method representing the trend in annual accumulated "biomass" over time. Areas represented with GREEN indicate positive trend while the ORANGE to RED transition regions show a negative trend. When the significant level is tested (at 90% level in this case) the extent and spatial distributions of 'improvement and degradation zones changed (Fig. 8b). As indicated in Fig. 8b, the land degradation risk areas were classified into three categories of improving, neutral and declining trends. Generally, the negative trend category (RED) indicates significant reduction in green biomass over time (2000 – 2015). As can be seen, the major parts of western and southern Kenya experience significant decline in green biomass depicting land degradation. Places which experienced significant positive trend, which are represented with GREEN, are associated with sites where green leaf biomass has increased during the study period (Fig. 8b). Based on Fig. 8B, the North western part of Kenya showed a significant increase in green biomass compared to the central and southwestern region which experienced significant decline in productivity. However, the majority of Kenya did not show significant trend (associated with no significant change in green biomass over time) represented in GREY. The majority of the eastern part of the country generally shows no significant change in biomass and land productivity, with some scattered areas rather characterized by significant declining trend.

While interpreting such national level 'satellite-derived' results, it will be necessary to take caution. We have noted for example that the 'green' areas associated with significant improvement in biomass do not necessarily be associated with improved productivity. This is because the national level expert consultation highlighted that some areas in the north are characterized by 'invasive species' and unpalatable bush encroachment which can conceal real degradation and undermine the significance of the problem. There is thus a need to conduct field visits and detailed stakeholder consultations before the results are used to guide planning and decision making. In an upcoming study, we aim to 'map' bush encroachment potential and relate with long-term land productivity maps to understand the significance of invasive species in undermining land suitability/capability.

The next effort made in this study was to separate whether the observed trends were caused/driven by climate- or human-related factors. A closer assessment of the observed NDVI trends indicates that some of the areas (YELLOW) show significant negative trend in NDVI but not affected by annual changes in rainfall (Fig. 8c). This could be attributed to human impact on vegetation or land use, which can be possibly linked with deforestation, intrusion of cultivation into bush/forest areas, intensional bushfires and the likes. Some areas (light RED) show significant improvement in NDVI but with no significant relationship with rainfall trend. This can be due to improved land management and restoration practices that enhanced land productivity. For those areas that have experienced significant decline in NDVI while there is positive relation with rainfall (RED), the possible attribution could be to declining or variable rainfall that undermined land productivity. The other situation (GREEN) observed is a significant improvement in NDVI associated with positive relationship with rainfall whereby declining/improving NDVI is associated with declining/increasing rainfall. This could be due to 'climate-impact' such that good rainfall seasons over the years have improved overall land productivity. It is however important to note that the 'greenness' can be due to bush/shrub encroachment. Generally, the results show that observed NDVI trends in some parts of the western and southern parts of Kenya can be attributed to human intervention, while most of the northern parts of Kenya shows that change in vegetation productivity would likely be due to changes in rainfall.

Tabular representation of the aforementioned results is given in Table 3. Results from this table indicate that at national level, about 72% of Kenya, which hosts about 61% of the population, shows no significant land degradation trend. From the table, we can also see that about 12% of Kenya is degraded due to human induced causes. This area is occupied by about 27% of the population. On the other hand, about 5% of the total area of the country hosting about 6% of the population shows positive trend mainly due to improved land restoration and reforestation practices while about 9% of the area hosting 4% of the population has experienced increasing productivity possibly due to improving rainfall conditions.

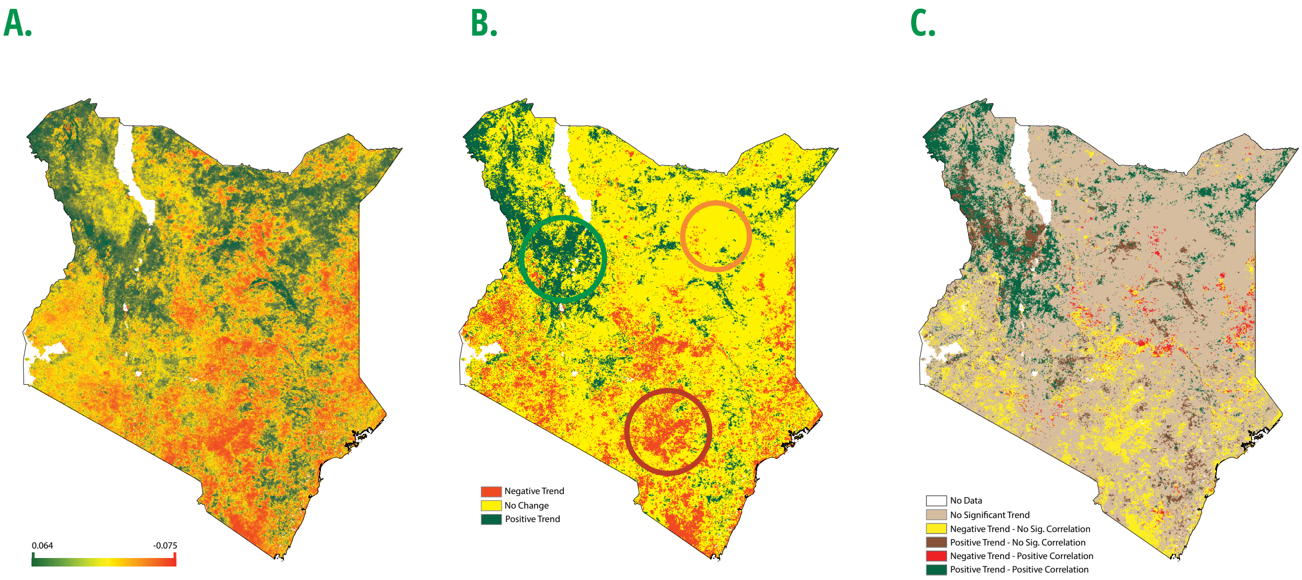


Fig. 8: *National level land degradation analyses using long-term satellite and climate data (2000 – 2015) for Kenya depicting (**a**) overall NPP trend; (**b**) NPP significance trend, and (**c**) NPP trend in response to rainfall trend*

Table 3: Areal extent and proportion of human population in relation to different levels of land degradation in Kenya based on long-term analysis of NDVI and rainfall data

NDVI trend and relationship with rainfall	Area sq. km	% area	% Population
No Data	1,067.73	0.19%	0.51
No Significant Trend	415,144.22	72.37%	60.72
Negative Trend – No Sig. Correlation	69,015.55	12.03%	27.44
Positive Trend – No Sig. Correlation	26,822.48	4.68%	5.85
Negative Trend – Positive Correlation	8,761.88	1.52%	1.11
Positive Trend – Positive Correlation	52,811.98	9.21%	4.38

Previous studies to identify degrading areas based on loss of NPP between 1981 and 2003 found that 18 percent of Kenya's total land area was degraded (Bai et al., 2008). A 2006 pilot study found that potential degraded areas occupied 17% of Kenya and 30% of its cropland (Bai and Dent, 2006). Another study characterized that in early 2000s, about 30% of Kenya was affected by very severe to severe land degradation (UNEP, 2002; UNEP and DRSRS, 2004) and ca. 12 million people depended on land that is degrading (Bai et al., 2008). Bai et al. (2008) depicts that about 30% of Kenya's total land area was subject to very severe land degradation problems in the early 2000s. Muchena (2008) showed increasing land degradation severity and extent whereby over 20% of cultivated areas, 30% of forests, and 10% of grasslands are subject to degradation in Kenya. More recently, Le et al. (2014) estimated that 22% of the Kenyan land area has been degraded between 1982 and 2006, including 31% of croplands, 46% of forested land, 42% of shrub lands, and 18% of grasslands. An overall agreement between our study and other land degradation maps (Fig. 9) highlights that time series satellite and rainfall data can be used to gain an overall idea of the spatial variability of land degradation at national level.

The national level land degradation trend map was presented at a national workshop organized in the town of Kisumu (Western Kenya) and discussions were conducted to verify the overall accuracy and relevance of the results. Generally, it was highlighted that the maps reflected the overall land degradation condition in the country. However, comments were given that detailed validation of the maps would be necessary as in some cases invasive species and unwanted shrubs can appear green on satellite imagery and may be wrongly classified as areas of significant improvement. Example areas that might have experienced degradation but showing positive trend could be those around Baringo

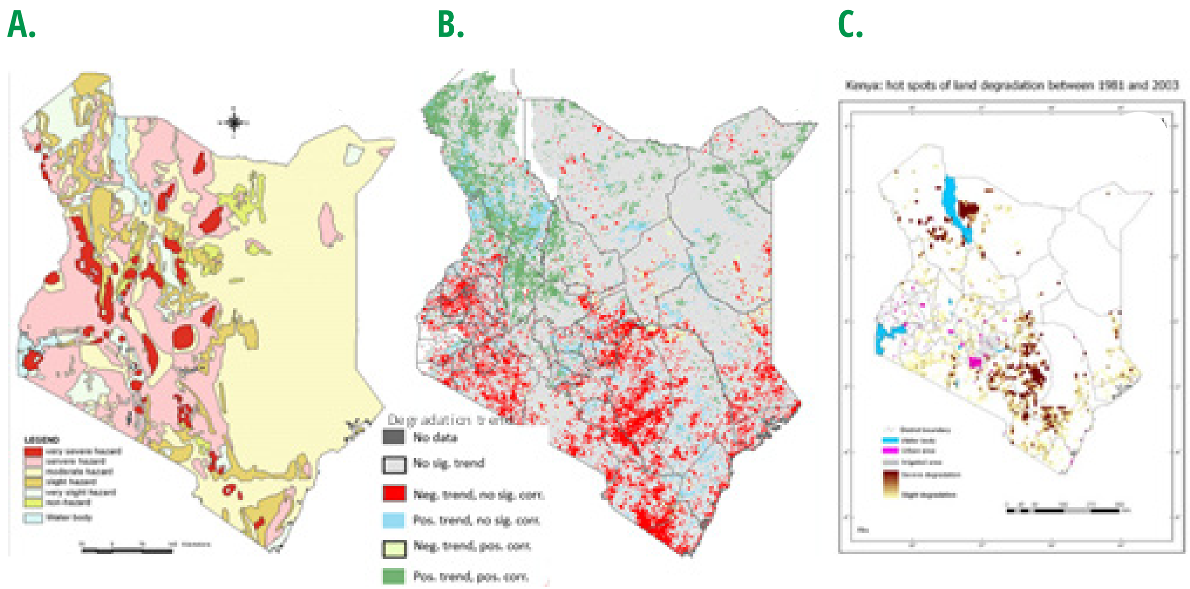


*Fig.9: Land degradation risk based on (**a**) Kenya soil survey, (**b**) this study and (**c**) Bai et al. 2008*

in northern Kenya which have high incidence of invasive species. Concerns also included the issue of the striga weed which participants highlighted could have been represented by positive trend. Becker et al. (2016) investigated the spread rate, and the extent of bush encroachment by invasive alien species Prosopis juliflora and their impact on the environment in Baringo area. In addition, the trend analysis using climate and satellite data could conceal other forms of degradation such as erosion at relatively smaller scales (Le et al., 2012).

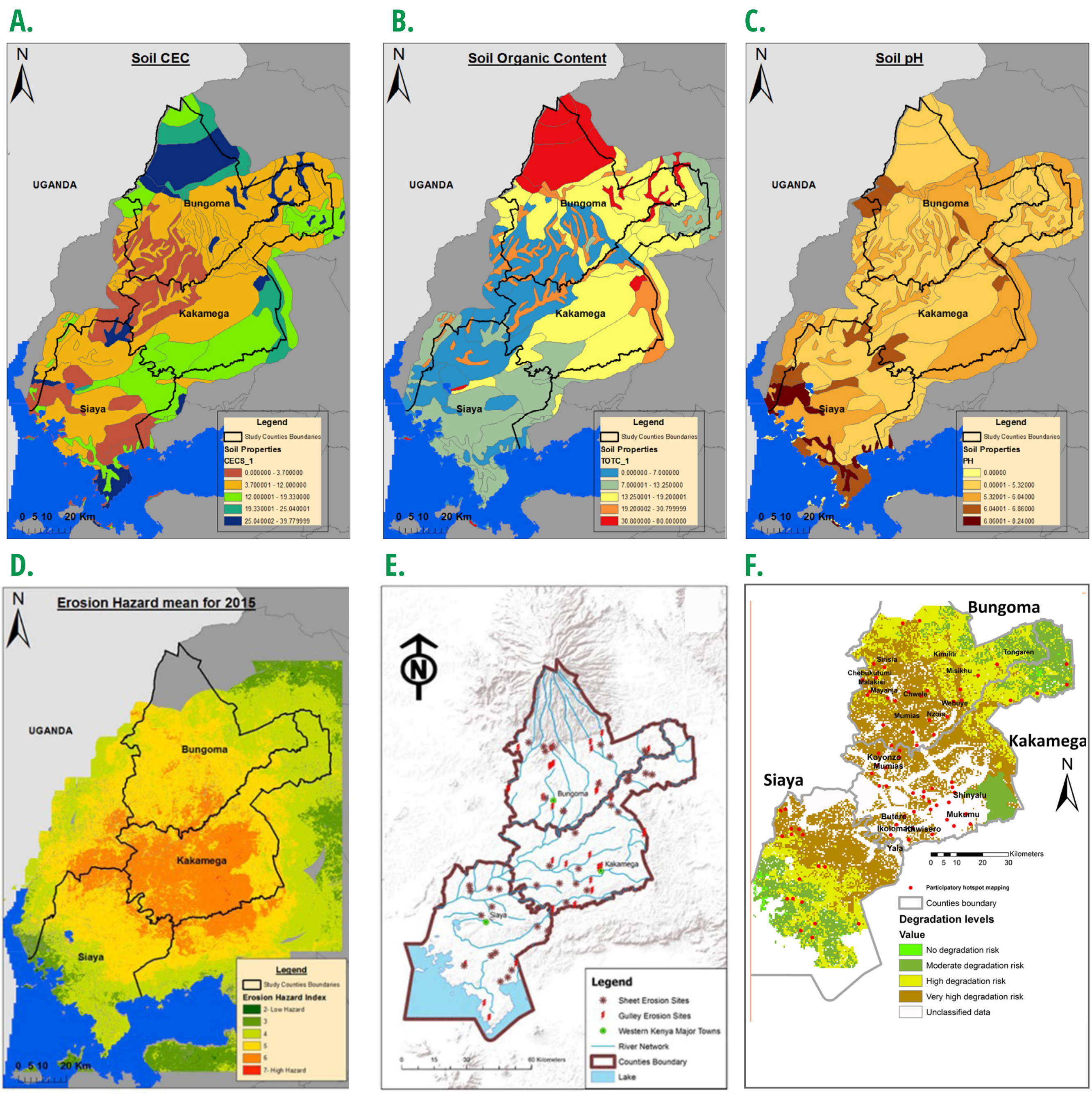


Fig. 10: Soil chemical properties for the three counties: (a) CEC; (b) OC and (C) pH; (d) Land degradation map pre-workshop; (e) Field observations post-workshop with validation of erosion prone areas; and (f) Post workshop land degradation map informed by modeling, stakeholder proceedings and field validation results for the three counties in western Kenya

5.1.2 County level analysis

The county level land degradation analysis focused on evaluating the erosion hazard in the selected areas. The data sets that informed this process (as indicated in Section 4.2.2, Table 1.1) included soil cation exchange capacity, soil organic carbon and Soil pH. (Figs. 10 A, B and C respectively). The pre-workshop land degradation analysis results (Fig. 10 D) revealed the spatial distribution of degradation areas within the 3 counties. Fig. 10 E shows post workshop filed validation of erosion prone site specific areas. The results in both 10 D and 10 E informed the modeling process for the overall degradation risk mapping (Fig. 10 F). The expert workshop and validation exercises where very useful in that some seemingly low risk areas as simulated by the modelling were highlighted as high risk areas during expert evaluation discussions in the workshop especially in some parts of Siaya and Bungoma counties. On the other hand, the model tended to have over-predicted soil erosion risk for the Kakamega country as opposed to the participatory expert assessment. These anomalies were associated with finer level scales where participants were pointing out zones or areas they were sure of but at a much smaller scale than the resolution precision of the model data.

As exemplified by Fig. 10 F, the land degradation risk levels were categorized into 4 distinct categories: no degradation risk, moderate/medium degradation risk, high degradation risk, and very high degradation risk levels. In an effort to relate the magnitude of degradation in relation to human and livestock population, population rasters were overlaid onto the degradation map and the percent number of pixels within each category were computed (Fig. 11). For Bungoma county, the major areas that deserve attention were the medium to high risk categories in terms of land area and both human and livestock population. For Kakamega county the predominant sites are those with the high to very high risk categories of degradation in terms of land area and both human and livestock population while in Siaya the three categories of low, medium and very high are more or less similar in percent with the difference being the high risk category, though high risk areas coincide with high population areas.

Although it is difficult to directly attribute the 'association' between high risk of land degradation with high population and livestock density, the results indicate that the highly populated areas are at high degradation risk and thus require urgent attention. This is because, in those places, the high land degradation risk can make large number of livestock and people vulnerable, thus attention should be paid to find remedies. Generally, Bungoma shows limited areas with none to low erosion risk levels compared to the Kakamega and Siaya counties. However, the later ones also show larger portions of their areas under high and very high risk. Regional planning should thus consider such observations when prioritizing their areas of interventions. This can enable assigning adequate resources to more vulnerable areas. Detailed analysis may provide information on the measures that need to be in place to tackle the observed degradation risk.

Field evidences and stakeholder discussions revealed that soil erosion is the primary degradation concern for most stakeholders, particularly farmers and county governments in Kenya. Various forms of soil erosion and their artifacts including sheet erosion, rills and gullies were observed during field visit to calibrate the EHI model at county level (Plate 2). The problem is observed in both croplands as well as in other areas of the landscape. The issue seems to have persisted for a long time and there have been various attempts in the past aimed at mitigating against the risk. In some areas intervention programs were initiated and structures such as terraces have been built, but many of these seem not to have been maintained after the respective projects ended. Consequently, there is a need for efforts to re-establish these interventions and rehabilitate aging erosion control structures. Equally important may be the need for more awareness and capacity building among locals to give them the impetus and ability to maintain the structures in their farms by themselves. As evidences within Kenya and other countries show, integrating management options with income generating ones will be more desirable and act as incentive for smallholders to adopt land management measures. Since the benefits of land restoration efforts are long-term, integrating options and providing access to technologies that can provide short-term benefits are also necessary.

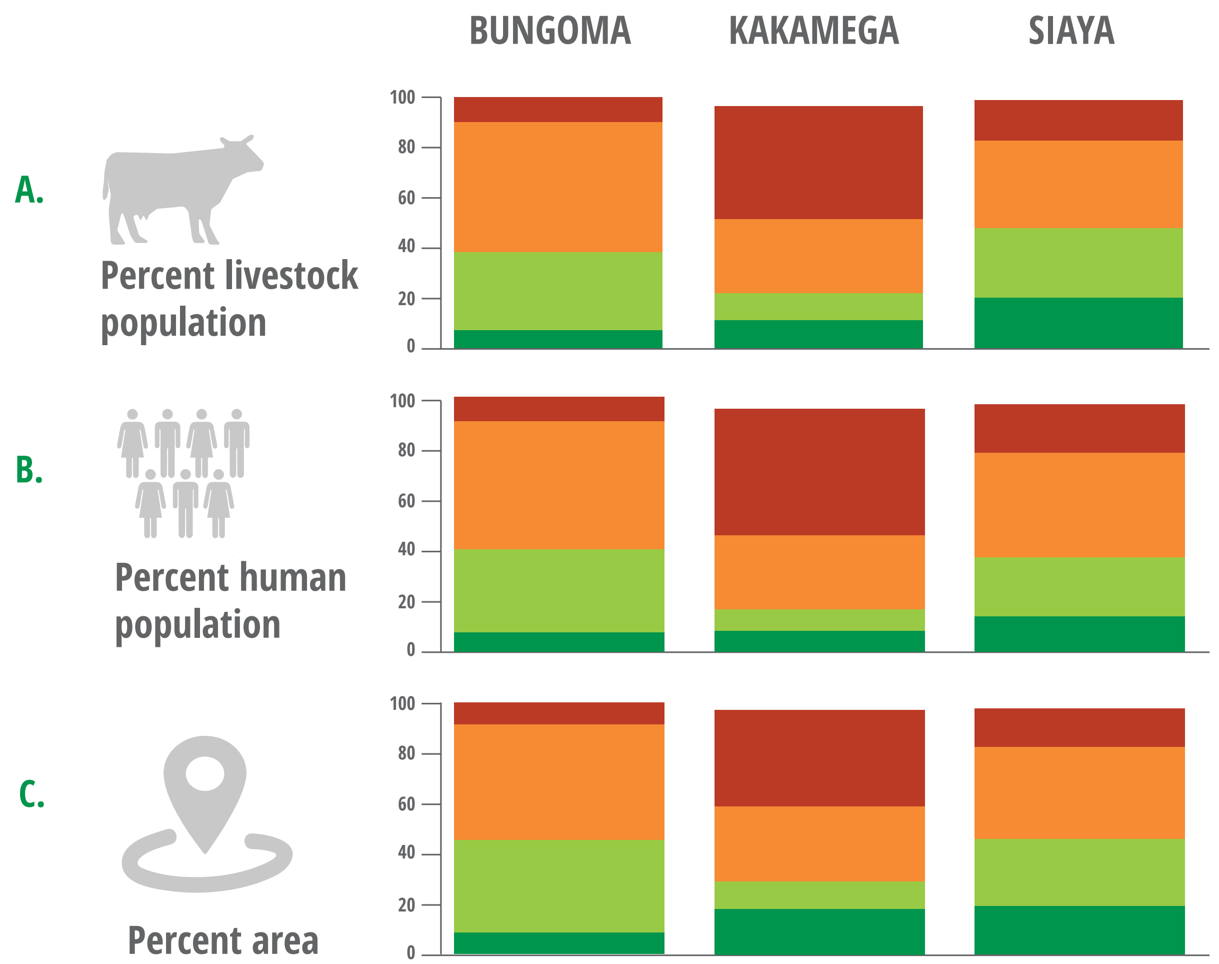


*Fig. 11: Depiction of (**a**) percent livestock population, (**b**) percent human population and (**c**) percent area in relation to degradation risk categories in three counties of Western Kenya*

5.1.3 Participatory mapping of food insecurity and vulnerable areas

The objective was to use local knowledge (experts from each county and at national level) to identify hotspot areas of food insecurity and vulnerability then relate these to the land degradation hotpots. To accomplish the task, consensus was reached with the stakeholders during the workshop on indicators of food security and vulnerability so that evaluation by each county team would be consistent across the board. This was then followed by the formation of three groups by each of the counties (Bungoma, Kakamega and Siaya) where each group discussed and mapped their ideas. To facilitate this exercise, Google earth images complemented formation of detailed maps for each county by the stakeholders. Complementary land degradation risk maps based on modelling approaches were also provided to each team. The core question for each team was "where are the food insecure people in each county"? The group placed stickers to show severe areas of food insecurity and areas that are perceived as vulnerable. In addition, each group provided key drivers for the observed conditions (mapped areas). The major results of the three county groups are presented below.

5.1.3.1 Bungoma County participatory mapping

Discussion question: Where do poor households (food insecure) in your county live?"

Participatory Response: The area that had been designated as food insecure was categorized into three zones: (a) Bungoma Area 1: The sugarcane belt that stretches all the way from Mayanja, Mateka to Tongaren; (b) Bungoma Area 2: The tobacco zone that covers the Sirisia, Malakisi, Mayanja, Mateka, and another extended tobacco zone that covers the Chebuyuk and Webuye areas.

The Bungoma Area 1 (Fig 12, labeled as Sugarcane area) is where 4 sugar companies are operating namely Mumias, Nzoia, West Kenya, and Butali while Bungoma Area 2 is where the BAT, Mastermind Tobacco Company is located (Fig 12, labeled as Tobacco area). The reasons for the food insecurity in the 'sugarcane belt' is related to striga weed infestation, low soil fertility with declining trends as well as mono-cropping of sugarcane all year round. A closer investigation of stakeholder input with the soil maps (Fig. 10 A, B, and C) show clear agreement of these observations with these zones as areas with low Cation Exchange Capacity (CEC). The CEC refers to the exchange of one cation for another on the surface of a soil particle or colloid measured in milliequivalents /100 grams. The CEC value of a soil is mainly a function of clay content and organic matter of the soil (Neil Brady, 2016). The Bungoma Area 2 was characterized by low soil pH and encroachment on community agricultural lands by tobacco companies and Webuye paper mill. The area has vast expanses of bare hills and boulders exposed as a result of deforestation from the mounting population pressure which in turn is believed to cause regional food insecurity (Fig 12, labeled as Tobacco area). The extended zone, also labelled as a tobacco zone extends from the first zone and originally had the Webuye Paper Mill Company which collapsed and left the community very vulnerable. In this region, deforestation and encroachment on catchments between hills and Saboti Land Defense Forces (SLDF) has been intense. The displacement of squatters caused food insecurity (Fig 12, labeled as the Tobacco zone).

According to local residents, some of the cash crop areas (sugarcane, tobacco) are exposed to food insecurity for different reasons including the longer time that sugarcane takes to provide income which in turn results in delayed payments with unfair terms for those who work with the companies. This therefore shows that some areas could experience food insecurity and vulnerability due to other reasons than the direct result of land degradation pressures.

5.1.3.2 Kakamega county participatory mapping

Discussion question: Where do poor households (food insecure) in your county live?"

Participatory Response: The participants indicated that Kakamega is more degraded (an aspect that is consistent with the land degradation assessment findings). Three distinct areas were identified as major food insecurity and vulnerability hotspots (see Fig. 13): A southern section that surrounds Kakamega including areas around the towns of Butere, Butsotso and Mukumu (termed as the tea zone), a northwestern section including areas around the towns of Mumias and Koyonzo (termed as the sugarcane zone) and a northeastern section including areas around Lugari town (termed as the sugarcane zone). With regards to the aforementioned three zones, the Ikolomani,

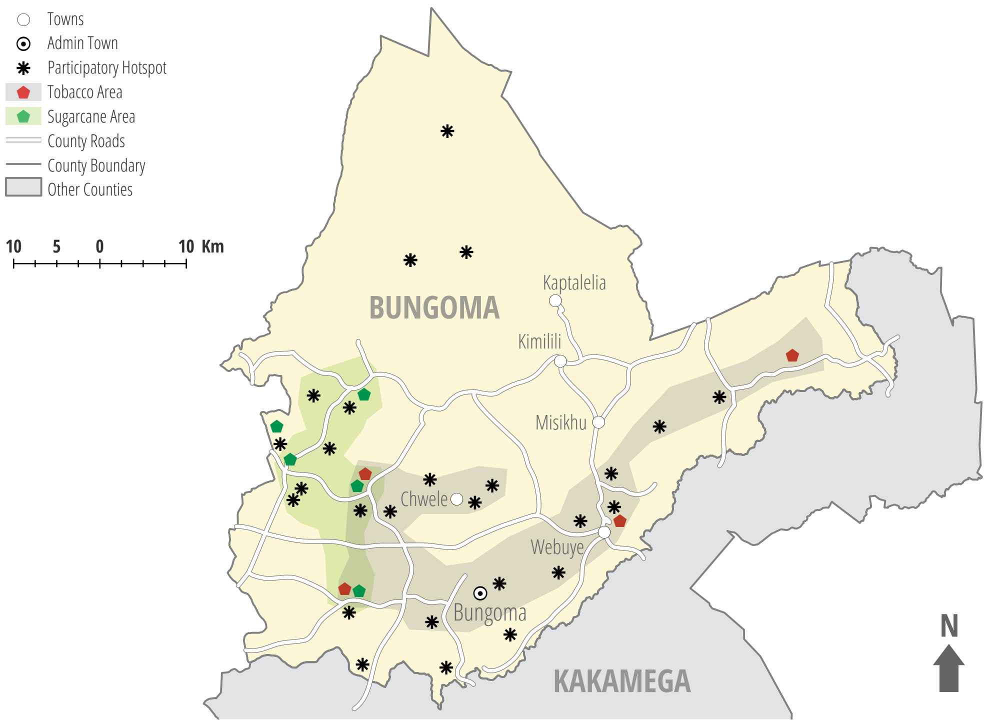


__Fig 12:__ Food security vulnerables sites mapped based on participatory approaches in the the Bungoma country of Western Kenya

Shinyalu, Khwisero (in the southern section) communities are exposed to poverty and food insecurity leading to loans. This forms a cyclic challenge leading into a vicious circle. For the Mumias zone (as most area is devoted to sugarcane), there are significant payment delays hence people do not have working capital to purchase improved maize varieties in a timely manner in order to optimize agricultural productivity which in turn leads to poverty and food insecurity.

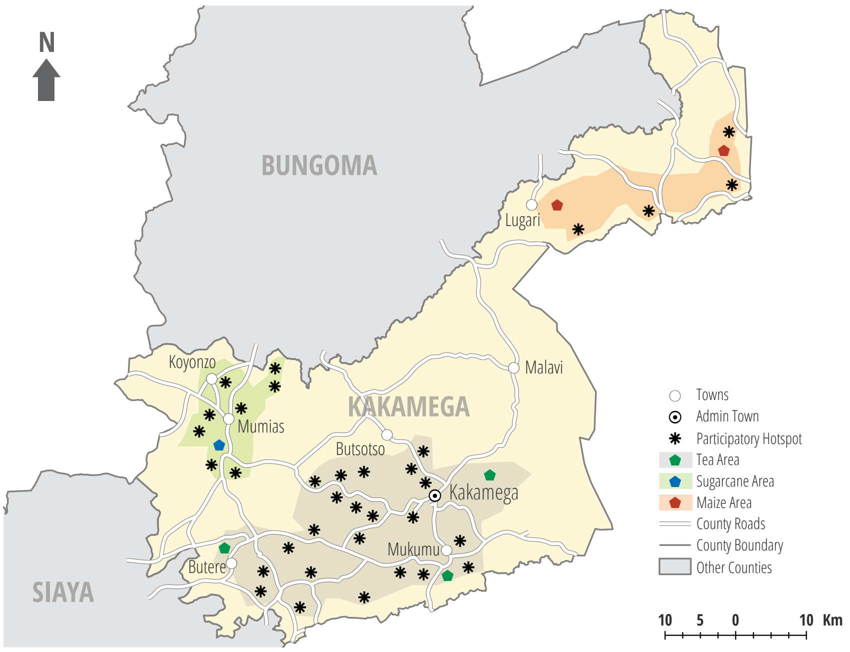


Fig. 13: Food security vulnerables sites mapped based on participatory approaches in the the Kakamega country of Western Kenya

For the northeastern section with maize (Lugari and Likuyani towns), short term food insecurity due to market challenges and low soil pH are considered to contribute to food insecurity. Generally, this zone doesn't seem to have a poverty problem but rather marketing constraints where farmers sell the majority of their produce at once and face challenges during the main (lean) season. Market information through 'linking farmers to markets' may be a critical intervention in this zone.

5.1.3.3 Siaya county participatory mapping

Discussion question: Where do poor households (food insecure) in your county live?"

Participatory Response: For the Siaya county, participants identified six major food insecurity hotspots (Figure 14) with corresponding justifications for the selected areas. Despite the fact that the role of some drivers vary even within a county, the dominant causes of food insecurity in the Siaya county include poor resources management, drought, soil erosion, pollution and in some cases small plot sizes when considering the major hotspots identified. But the extent and severity of these drivers change within different sites.

- For Siaya Area 1, the main reasons identified for food insecurity were: resource endowment constraints (the area is generally resource poor), large number of people are not well educated (low literacy level), there is generally poor technology uptake and the area experiences frequent droughts.
- For Siaya Area 2, participants cited shallow soils and marginal agricultural areas as the major causes of food insecurity.
- For Siaya Area 3, marginal areas, lowlands with poorly drained soils and poorly weathered soils with shallow depths were cited as causes of food insecurity.
- For Siaya Area 4, the lack of using improved seeds, droughts, late planting and poor crop husbandry such as lack of weeding were cited as causes of food insecurity.
- For Siaya Area 5, small agricultural parcel sizes and presence of fisher folk (non-farm activities such as quarrying and sand mining) are drivers of food insecurity in the area.
- For Siaya Area 6, the majority of the causes mentioned for Siaya Area 3 plus drought, poorly weathered soils and soil erosion were causes of food insecurity and vulnerability in Siaya Area 6.

Based on the above participatory input, it was generally clear that land and water management constraints coupled with climate-related challenges were the dominant drivers of land degradation in Siaya county. For Bungoma and

Kakamega while biophysical issues were important, there seemed to have numerous socio-economic challenges which played shaped the direction of food insecurity issues in both counties.

5.1.3.4 Land degradation and food insecurity nexus

Comparison of land degradation assessment map (Figure 10 F) with the participatory-based food insecurity hotspots show overall agreement whereby degradation risk areas are associated with food insecurity/vulnerability. This can be either because poor areas can't provide adequate support to their hosts and/or the communities are vulnerable and poor and that they do not afford application of appropriate inputs or land management measures to improve land productivity. As a note of caution, there is a need for detailed mapping and analysis because it will not be fair to compare the two approaches quantitatively.

As exemplified by Figures 12-14, there are specific pockets of food insecurity areas identified in the three counties based on the participatory feedback from the stakeholder and experts workshop. In order to explore further, the participatory 'food insecurity/vulnerability' maps were related with yield estimates available for the three counties (Figure 15). Despite variation in scale and data collection approach, this comparison provided an indication of the drivers of food insecurity. For example, for Siaya County (Figure 15) the data derived from the rainfed production (yield/ton) for major staples in the area depicts that the lower left portion has production capacities above 1.00 ton/ha. When verified from Google Earth Imagery, this is an area with intensive rice production supplemented with irrigation. Conversely, the adjacent portions that show production levels of less than 0.25 ton/ha are heavily impacted by erosion within the landscape and surrounding areas as exemplified by the two huge gullies (Figure 15).

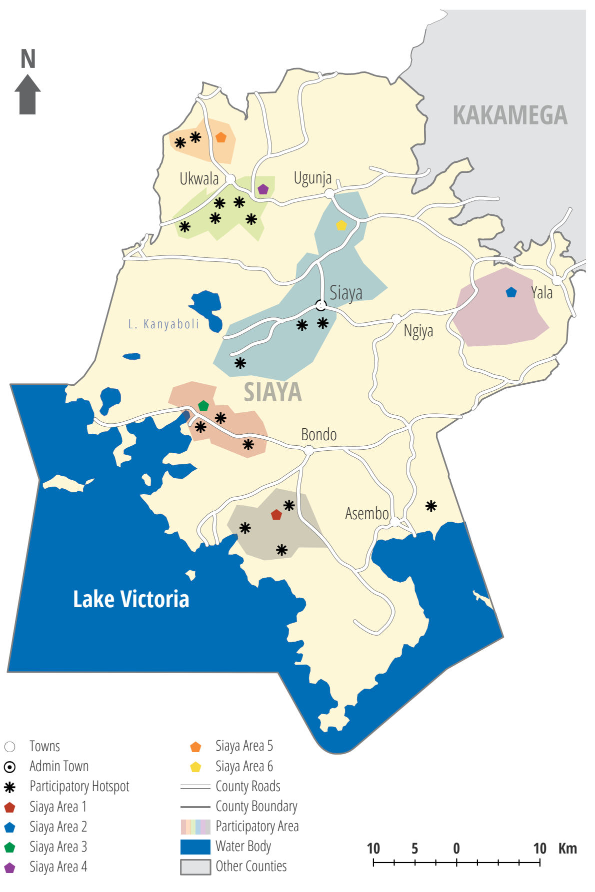


Fig. 14: Food security vulnerables sites mapped based on participatory approaches in the Siaya country of Western Kenya

Over the last couple of years, rainfall deficits have hit portions of western Kenya, and rainfed crop production has been reduced to below average (FEWS, 2017). Exacerbating this is the fact that the main season, the long rainy season, continues to perform poorly with erratic distribution patterns. Recent data (FEWS, 2017) points towards increased staple food prices due to low supplies and high demand, hence the access to food is likely to be more constrained. The majority of poor households in Western Kenya are likely to intensify their reliance on coping mechanisms to bridge food and income gaps, thereby remaining food insecure in the near to midterm future years and would likely lead to unfavorable cropping conditions. The data in Fig. 16 provides a seasonal cropping calendar that provides guidance for farmers in Western Kenya to better plan their farming activities and adapt to varying climatic conditions.

5.1.4 Landscape level land degradation analysis in Kenya

5.1.4.1 Landscape assessments for sediment and water yield with SWAT

We used the SWAT model to estimate sediment yield and runoff risk in a watershed that revealed high vulnerability based on the EHI analysis. The watershed sediment yield ranged between 0 to 14 t ha^{-1} $year^{-1}$ with an average sediment loss of about 4.1 t ha^{-1} $year^{-1}$ (Fig. 16a). The highest net soil loss was experienced in sub-watersheds 3, 9, 11 and 13, mostly likely due to intense farming activities in these areas. In order to have an idea about the level of soil erosion risk in the study area, we categorized the sediment yield into three classes: below the minimum tolerable limit, between the minimum and maximum tolerable limits and above the maximum

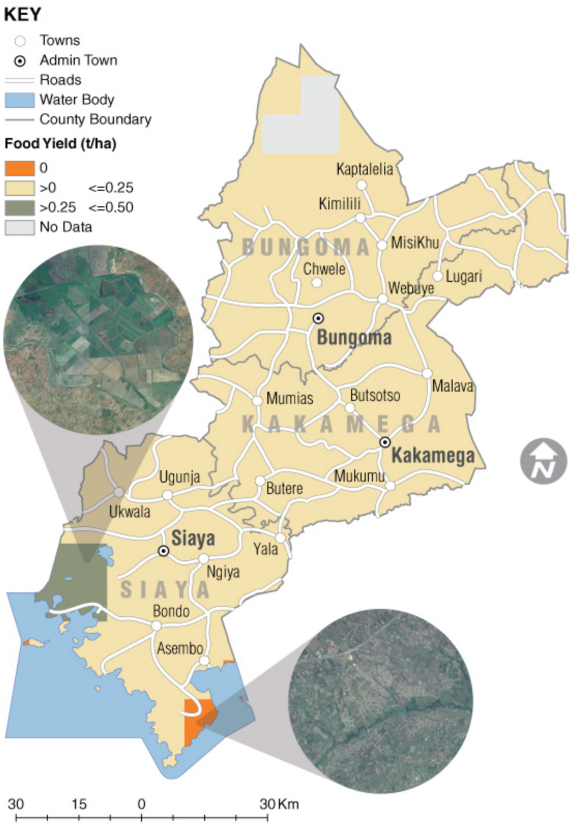


Fig. 15: *Food insecurity hotspots from participatory stakeholder feedback mapped against the rainfed production layer*

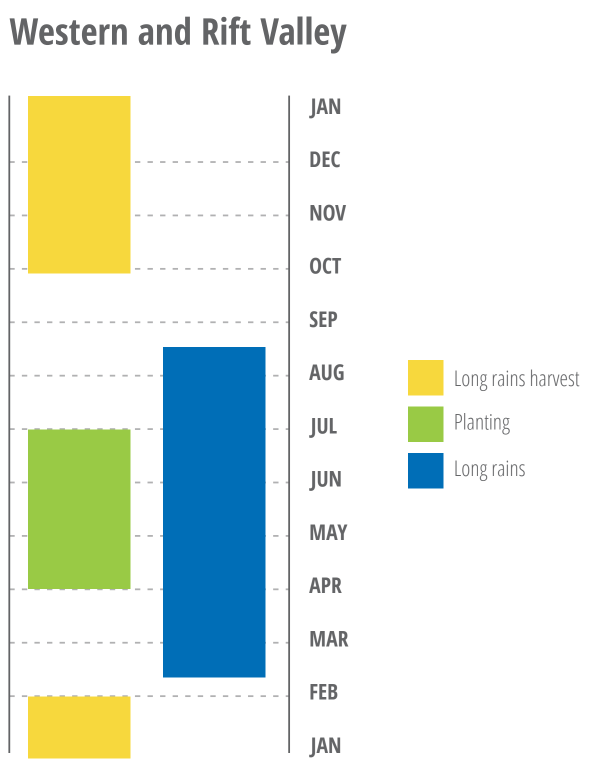


Fig. 16: *Seasonal rainfed agricultural calendar for Western Kenya (Adapted from FEWS, 2017)*

tolerable limit. For Kenya, soil loss rates of less than 2 t ha^{-1} year^{-1} are considered to be the minimum tolerable limit while more than 10 t ha^{-1} year^{-1} is considered the maximum limit (Li et al., 2009; Verheijen et al., 2009). The tolerable soil loss rate is defined as the upper limit at which the dynamic equilibrium between soil formation and soil loss is balanced, and the functions of the soil in regard to its agricultural productivity and nutrient status are maintained (Li et al., 2009; Verheijen et al., 2009). The concept of tolerable soil loss is used as a first valuable benchmark to identify areas that might be at risk. In these areas, continuous agriculture without additional fertilizer input and land conservation measures can lead to land degradation and deterioration of soil quality in the near future.

Based on the above categorization, about 24% of the study watershed experiences soil loss rate of more than 10 t ha^{-1} year^{-1} (Table 4), which is beyond the maximum tolerable limit for Kenya. On the other hand, about 50% of the watershed experiences soil loss rate within the minimum tolerable limit. This implies that priority management interventions can be planned for those areas which are experiencing higher soil loss rate.

Table 4: *Watershed area statistics against sediment yield*

Average Annual Sediment Yield (t ha^{-1} year^{-1})	Area (ha)	Area (%)
< 2	45,862	50
2-10	24,414	26
> 10	22,450	24

It is important to recognize that about 20% of the study area have slope more than 20% with net soil loss rate of around 5 t ha^{-1} year^{-1} (Table 5). About 50% of the areas lies within slope category of less than 5% with relatively low soil loss rate. The fact that the lower slope zones (<5%) cover a larger area (more than three fold) indicates that the majority of the areas falls within gentle slope where net soil loss is generally low but a note of caution is that since these slope zones are dominantly cultivated, their erosion risk can be higher. It is also important to note that about 50% of the areas which has slope greater than 20% is experiencing soil loss more than the minimum tolerable limit (Table 4). This requires attention since such fragile areas could easily be susceptible to accelerated erosion even with minimum human interference. Field visits and consultations with local communities revealed that land use and management systems were major erosion factors.

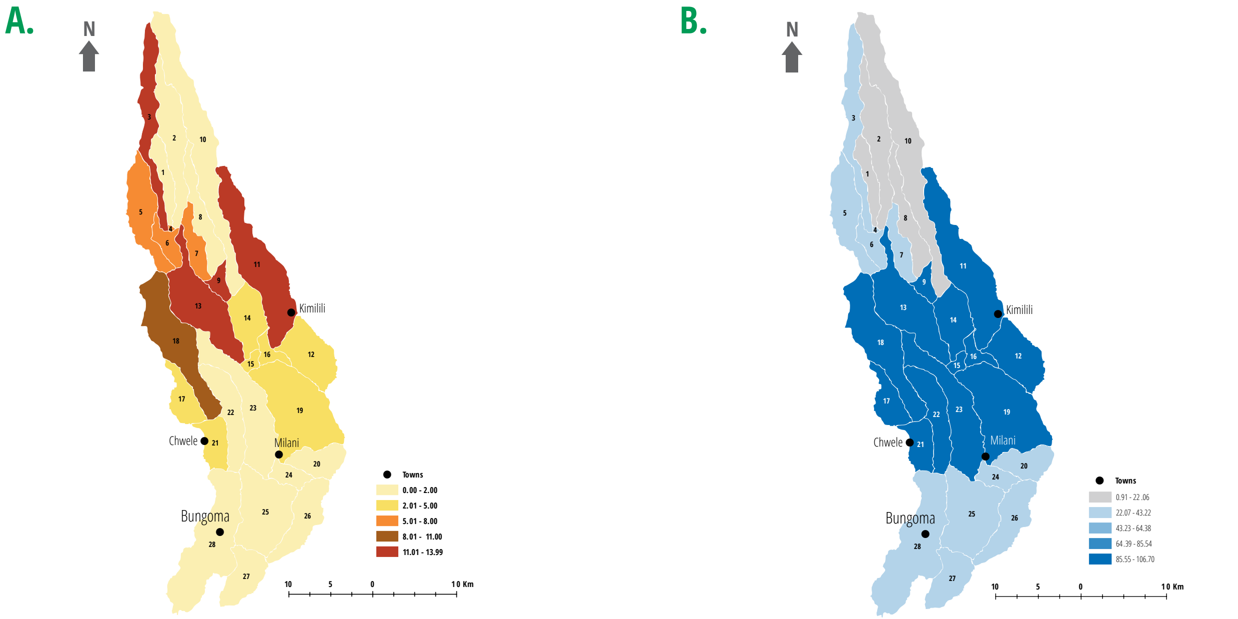


Fig. 16: *(**a**) Average annual sediment yield and (**b**) Average annual surface runoff in a watershed within the Bungoma county in Kenya*

Generally, cultivated areas and barren lands experience high rate of soil loss compared to others (Table 6). Though the difference in sediment yield between cultivated land and other land uses is not significant (Table 6), the relatively higher loss from agricultural lands (higher than the tolerable soil loss) reflects the need to prioritized interventions. As sustainable intensification is expected to enhance crop yields and overall system productivity, it will be important to develop complementary options that can provide multiple benefits to multiple users. Without sustainable use and management of land and soil resources, global sustainable development and environmental sustainability are unlikely to be attained (Mulinge et al., 2015).

In both slope and land use/cover, the high erosion risk zone (more than the maximum tolerable limit) covers relatively smaller (50% less) geographical area (compared to the less erosion risk areas), thus knowledge of such will facilitate planning and targeting. Since the sediment yield map shows where within the watershed we should focus (Fig. 16a), this further simplifies implementing site-specific measures. According to Fig 16b, there is an annual average 59 mm surface runoff from the watershed. As can be seen, there is high surface runoff in the central part of the watershed which is mainly an agricultural zone in the lower parts of Mount Elgon. Improved management can be essential to both reduce sediment yield and enhance soil moisture for improved productivity.

Table 5: *Average sediment yield per slope class for the example watershed in the Bungoma county of Western Kenya*

Slope class (%)	Average sediment yield ($t\ ha^{-1}\ year^{-1}$)	Area (ha)	Area (%)
0 - 5	3	46,698	51
5 - 10	6	14,094	15
10 - 20	6	13,124	14
>20	5	18,5778	20

The growth of agricultural output in Kenya is constrained by many challenges including soil erosion, low productivity, agro-biodiversity loss, and soil nutrient depletion (GoK 2007). Land exploitation devoid of proper compensating investments in soil and water conservation will lead to severe land degradation (GoK 2013a). The result observed in the watershed highlights that the majority of the watershed experiences soil loss is within the tolerable limit. Our result is also generally lower compared to studies by others such as de Graff (1993) who estimated soil loss by water erosion in Kenya to be at 72 tons ha^{-1} yr^{-1} and Dregne (1990) who reported a permanent reduction of soil productivity from water erosion in about 20% of the Kenyan territory. Despite the fact that the two studies date well back over a long time and the scale of analysis is different to ours, it will be essential to see whether soil erosion rates have declined over time and explore the possible reasons.

Table 6: *Average sediment yield per land use/cover type for the example watershed in the Bungoma county of Western Kenya*

Land use/cover type	Average sediment yield ($t\ ha^{-1}\ year^{-1}$)	Area (ha)	Area (%)
Cultivated	6	618,008	68
Grazing/ Grassland	5	9,855	11
Bush/shrub	4	6,834	8
Barren Land	5	644	1
Forest	3	11,408	13

5.1.4.2 'What-if' scenario assessments for best management practices with SWAT-APEX

This study further analyzed the sediment and runoff load reductions obtained from simulated scenarios for current (business as usual) and proposed best management practices within the Bungoma Watershed as a means to explore possible intervention options that can be promoted by decision makers for implementation by local communities. We describe the identification of dominant sediment and runoff delivery mechanisms in the watershed with readily available tools consisting of SWAT and Agricultural Policy and Environmental Extender (APEX) models for conducting the "What-if" scenarios. These tools also developed multiple regression equations to estimate the sediment and runoff ratios for the subwatershed areas of interest. The models used 35 years of weather data from 1981 to 2016.

The "What if" scenarios that were conducted in the SWAT-APEX interface were selected based on Kisumu workshop participants inputs (See Sections 5.1.3.1-5.1.3.4) and Section 5.1.4 which provided quantitative data on the current status quo or business as usual in case no interventions were done. Below are the five "What if" scenarios that were conducted for two selected subwatersheds in the Bungoma county:

1. Current conditions (BAU)
2. Forage vegetative strips (Napier grass with Desmodium-FVS)
3. Contours (1 meter width at 10 m intervals- CONT)
4. Terraces (2 meters width at 10 m intervals- TERR)
5. Contours with forage vegetative strips combined (ContFVS)

The explanatory variables considered for the delivery ratios were water yields resulting from flow and sediment loads leaving sub-areas within specific sub-basins. The SWAT-APEX results indicate that the flow from each of the sub-areas is the dominant factor affecting sediment delivery within the sub-basins. Together, the explanatory variables considered under the multiple linear regression framework were able to estimate sediment and runoff with satisfactory regression parameters. The R2 values for the regression relationship between the sediment and their counterparts estimated with multiple linear regression method were 0.8 for sediment, 0.96 for runoff.

Table 7: Simulation results for water yield (mm) and sediment yield t/ha) from 23 sub-areas with four interventions using SWAT APEX

	Current conditions		Forage Vegetative Strips (FVS)		Contours (CONT)		Terraces (TERR)		Contour + VEgetatiove STrips (ContFVS)	
APEX Subarea	WYLDmm	SYLDt/ha	WYLDmm	SYLDt/ha	WYLDmm	SYLDt/ha	WYLDmm	SYLDt/ha	WYLDmm	SYLDt/ha
1	17.73	20.56	20.39	15.42	21.27	17.48	23.05	13.37	25.70	7.20
2	1.43	79.82	1.64	59.86	1.71	67.84	1.86	51.88	2.07	27.94
3	16.16	22.14	18.58	16.60	19.39	18.82	21.01	14.39	23.43	7.75
4	23.12	20.52	26.59	15.39	27.75	17.44	30.06	13.34	33.53	7.18
5	10.55	20.26	12.13	15.20	12.66	17.22	13.72	13.17	15.30	7.09
6	10.21	20.28	11.74	15.21	12.25	17.23	13.27	13.18	14.80	7.10
7	5.29	22.48	6.08	16.86	6.35	19.10	6.88	14.61	7.67	7.87
8	20.78	22.33	23.90	16.75	24.93	18.98	27.01	14.52	30.13	7.82
9	3.26	22.75	3.75	17.06	3.91	19.34	4.24	14.79	4.73	7.96
10	19.98	22.39	22.98	16.79	23.98	19.03	25.98	14.55	28.97	7.84
11	5.51	22.45	6.34	16.84	6.62	19.08	7.17	14.59	7.99	7.86
12	4.14	20.72	4.76	15.54	4.97	17.61	5.38	13.47	6.00	7.25
13	5.11	20.66	5.88	15.49	6.13	17.56	6.64	13.43	7.41	7.23
14	2.89	20.92	3.32	15.69	3.47	17.78	3.76	13.6	4.19	7.32
15	4.57	20.72	5.26	15.54	5.49	17.62	5.95	13.47	6.63	7.25
16	11.01	22.16	12.66	16.62	13.21	18.83	14.31	14.4	15.96	7.75
17	4.73	20.70	5.44	15.53	5.68	17.60	6.15	13.46	6.86	7.25
18	0.01	0.91	0.01	0.68	0.01	0.78	0.01	0.59	0.01	0.32
19	5.14	20.65	5.91	15.49	6.17	17.56	6.68	13.43	7.45	7.23
20	3.99	22.64	4.59	16.98	4.79	19.25	5.19	14.72	5.79	7.93
21	5.15	20.65	5.92	15.49	6.18	17.55	6.7	13.42	7.47	7.23
22	5.26	20.65	6.05	15.48	6.31	17.55	6.84	13.42	7.63	7.23
23	4.73	20.68	5.44	15.51	5.68	17.58	6.15	13.44	6.86	7.24

As exemplified from Figure 17, one of the sub-watersheds that was a hotspot (subwatershed 13) and another sub-watershed that was a greenspot (subwatershed 25) were further re-modelled for finer scale interventions in comparison to the current conditions which we described as "Business as usual". The interventions on the "hotspot" subwatershed 13 would be remedial and restorative while those for the "green spot" subwatershed 25 would be preventive.

The parameterization and analysis in SWAT-APEX resulted in 23 sub-areas that covered about 94 hectares (Figure 17). Clear gains are evidenced by the % increases in water yields and % reductions in sediment yields. As shown, Figure 17 provides a graphical representation of the actual quantities of both water yield and sediment yield. The best case scenario was observed when the combination of contours and vegetative strips were implemented in the landscape.

As Cramb et al. (2006) surmised, if the proposed interventions are to make a difference, commitment is an essential condition for sustainability, in that people must want it, but it is not a sufficient condition. It is also important that commitment is matched with resources if these landscape based approaches are to be effectively disseminated on a broader scale. Cramb et al. (2006) further advised that all implementation procedures should be documented in order to measure performance and evaluate effectiveness of approaches.

Regions that are agriculturally important within Bungoma were selected and analyzed from sub-watershed level down to the lower farm levels. This kind of integrated assessment for multi-scale analyses of the impact of introducing

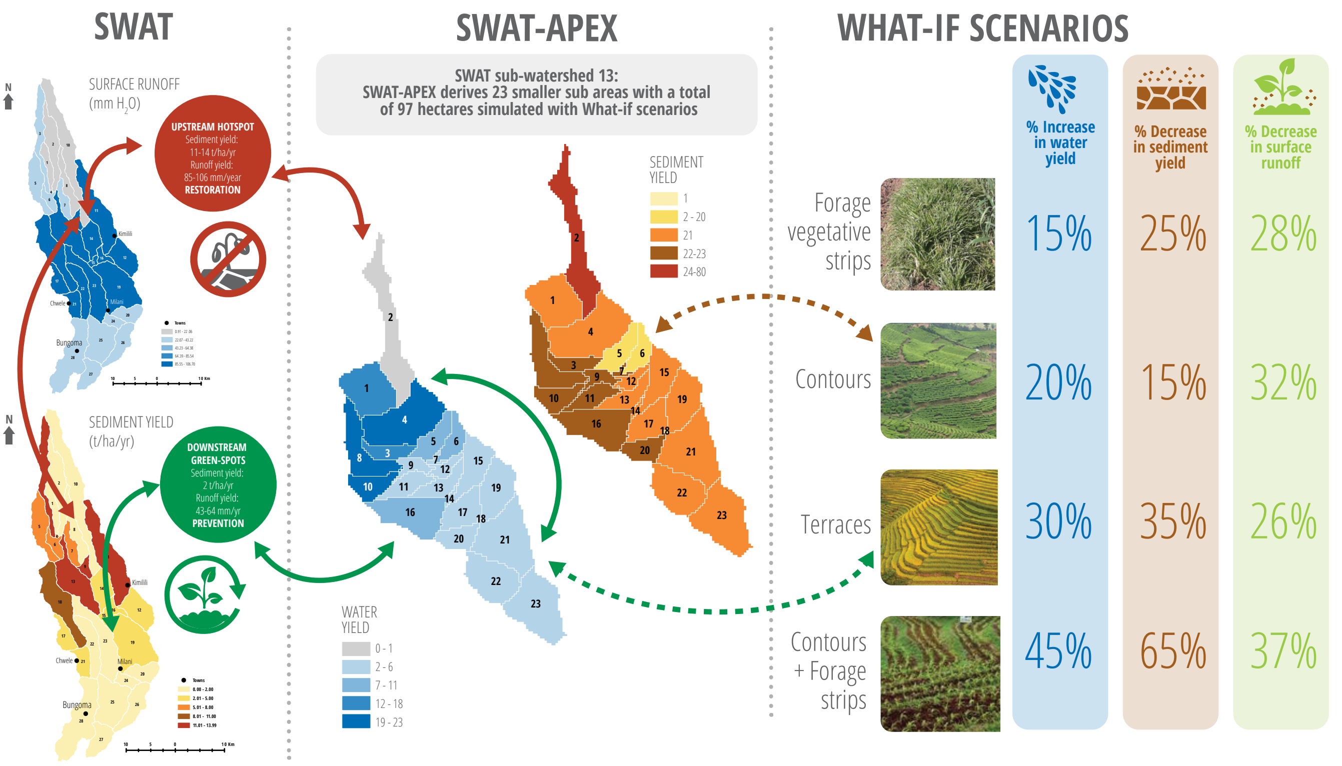


Fig. 17: What if scenarios derived from a selected subwatershed (Subwater 13 from SWAT) for restoration and prevention interventions into various subareas (23 sub-areas from SWAT-APEX) for water yield and sediment yields

new interventions at the sub-watershed and sub-areas (farm) levels of scale was quite informative from a management point of view. The results of the interventions were positive and demonstrated that when implemented would enhance the sustainable agricultural production.

Clearly, the successful implementation of the proposed intervention or farming practices would require substantial development of supportive policy environments. The results demonstrate the ability to predict the consequences/outcomes of interventions using quantitative methods to improve the livelihoods of subsistence farmers while evaluating the environmental consequences at multiple levels of scale, which adds unique value to the current knowledge in agricultural research.

We offer potential options that different groups of society can play towards restoration and prevention of erosion and sedimentation in Table 8.

Table 8: Roles of stakeholders on land degradation coupled with implementation guidelines and upscaling options

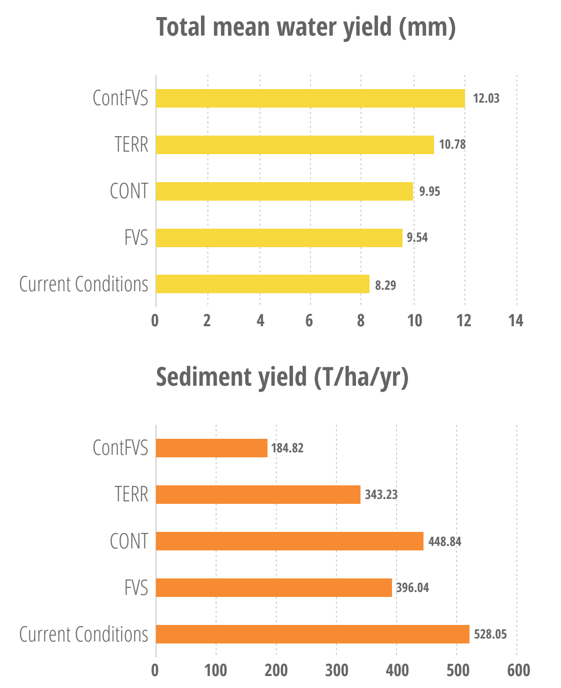


Fig. 18: What if scenarios with graphical representation of water and sediment yields for the different basket of intervention options

Stakeholder Type	Roles of stakeholders towards restoration and prevention of land degradation
Government	• Sensitization and awareness creation at various levels • Capacity building of extension officers • Establish strategic partnerships with relevant institutions • Establish monitoring and evaluation systems
Development partners and NGOs	• Provide technical assistance • Foster intervention uptake by farmers • Upscale best management practices/ interventions • Facilitate capacity building interventions
Research partners and civil society	• Participatory action research on improved technologies and practices • Steer communities of practice through learning and practice alliances • Solicit land degradation and restoration options information • Promote indigenous knowledge, practices and technologies
Private sectors	• Identify investment opportunities • Seek profit maximization ventures • Develop and implement risk management strategies • Investing in land restoration implementation and upscaling
Farmers and local resource users and stewards	• Identify land restoration champion stewards • Engage in learning alliances and field schools • Participate in farm research • Share indigenous knowledge
Media and social platforms	• Disseminate researched land restoration information • Produce and share knowledge products • Disseminate land restoration guidelines in media platforms • Create public awareness program on land restoration related issues
Donor society	• Invest in landscape restoration options • Facilitate/shape government policies for land restoration options
Academia (Schools and Universities)	• Establish intervention programs on restoration in school curricula • Participate in civil society restoration options • Forge partnerships with NGOs to support restoration programs
Water Resources Users (CLE)	• Streamline management and governance of reservoirs and surrounding catchments • Implement bye-laws that are community friendly

5.2 Land degradation trend assessment in Burkina Faso

5.2.1 National level analysis

Similar to work conducted for Kenya, we present the overall degradation trend, areas of significant trend and the trend map correlated with rainfall for Burkina Faso. Figure 19(a) shows the long-term trends of annual NDVI estimated using the linear slope method to represent annual accumulated NDVI over time. In the Figure, GREEN indicates positive trend while ORANGE and RED show transition to neutral and negative trend, respectively. Figure 19b is the trend after significant test has been done while Fig. 19c shows the correlation between NDVI trend and rainfall supply over time.

The results (Table 9) show that the majority of the country (about 53%) experiences no significant change in land condition followed by significant degradation trend (33%) over the 15-year period of analysis. This is in general agreement with an observation by the FAO Global Forest Resource Assessment (FRA) which estimated the loss of forest areas in Burkina Faso to be around 56 490 km^2, representing 21% of the country (FAO, 2009). About 13% of the county shows improvement which can be attributed to either improved land management (for those with no significant correlation with rainfall) or due to improved climatic/rainfall condition (those areas that have significant relationship with rainfall trend).

From Table 9, it is possible to see that about 30% of the areas supporting about 28% of the population experience declining land productivity possible due to human-related causes, which can be in the form of deforestation, soil surface crusting overgrazing and/or poor land management and gullies infringing on cropland areas as exemplified by Plate D. The majority of the areas experiencing such degradation are located in the western, southern and southeastern parts of the country.

A land use/cover change-based analysis conducted in southern Burkina Faso showed progressive conversion of forest land to croplands due to massive migration of farmers from the north and central regions of the country due to decreasing rainfall and arable land (Pare et al., 2008; Ouedraogo et al., 2010; Etongo, et al. 2015). A study by Dimobe et al. (2015) in southwestern Burkina Faso also showed land degradation trends mainly due to land conversion (from forest/woodlands to bushland/cropsland). About 7% of the areas that support about 10% of the population showed improved land condition possible due to improved land management practices. These are mostly observed in the north and northeastern parts of Burkina Faso (Fig. 19). The improved land condition can possibly be due to restoration to

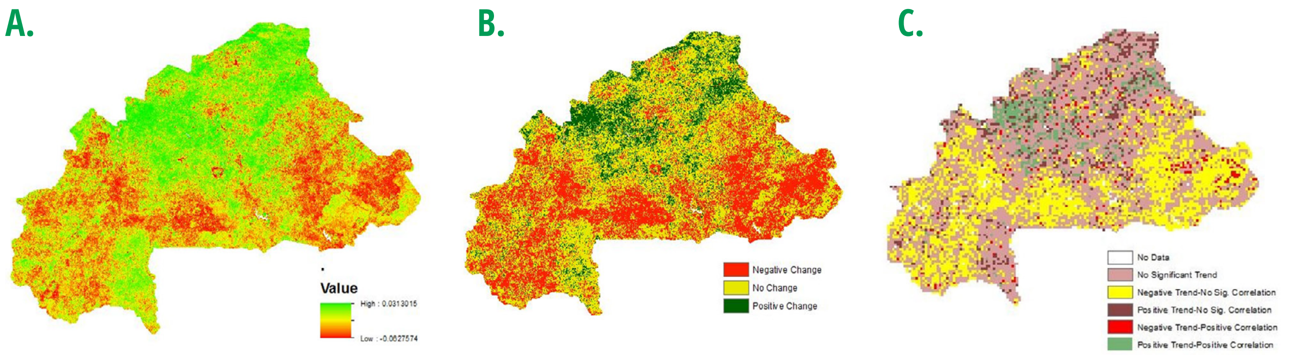


Fig. 19: *(**a**) Long-term trends of annual NDVI; (**b**) trend after significant test and (**c**) correlation between NDVI and rainfall in Burkina Faso.*

withstand the successive droughts, demographic pressures and the encroaching Sahel that have exposed the area to the impacts of climate change as a result of which smallholder farmers adapted to these pressures by reclaiming land through the adoption of soil and water conservation techniques (e.g., Lenhardt et al., 2014; Etongo et al., 2015; Etongo, 2016). It may also be the case that the 're-greening' of the Sahel phenomena could have resulted in the observed increased productivity and/or absence of significant degradation in some areas (Anyamba & Tucker, 2005; Olsson et al., 2005; Seaquist et al., 2006, 2009; Fensholt et al., 2006, 2012; Fensholt & Rasmussen, 2011; Rasmussen et al., 2014). The fact that the majority of areas that did not show significant change in land productivity in the central and northern parts of the country can also means that vegetation cover is already limited in those areas to reflect meaningful change within the period of analysis. This can be plausible reason considering the fact that over 80% of the country's forests are found in the southwestern and eastern region (FIP, 2012).

About 6% of the area in the central part of the country has shown increased productivity due to improved rainfall conditions. Generally, it is also wise to recognize that despite land degradation risk areas are generally associated with high population density (about 30% of the population residing in areas characterized by land degradation), areas of highest population are not necessarily associated with significant land degradation (51% of the population reside in areas with no significant change in land condition). But it is also important to note that less degraded areas could have better soils and resources and attract more population compared to relatively degraded areas. This can be generally the case in arid and semi-arid areas where climatic factors drive population to less risk and relatively high potential areas (Ouedraogo et al. 2009; Lenhardt et al., 2014; Etongo, 2016).

Plate 3: *Examples of land degradation features represented with prevalence of: (**a**) Deforestation; (**b**) Soil surface crusting (**c**) Poor land management and (**d**) Gullies infringing on croplands in south western Burkina Faso*

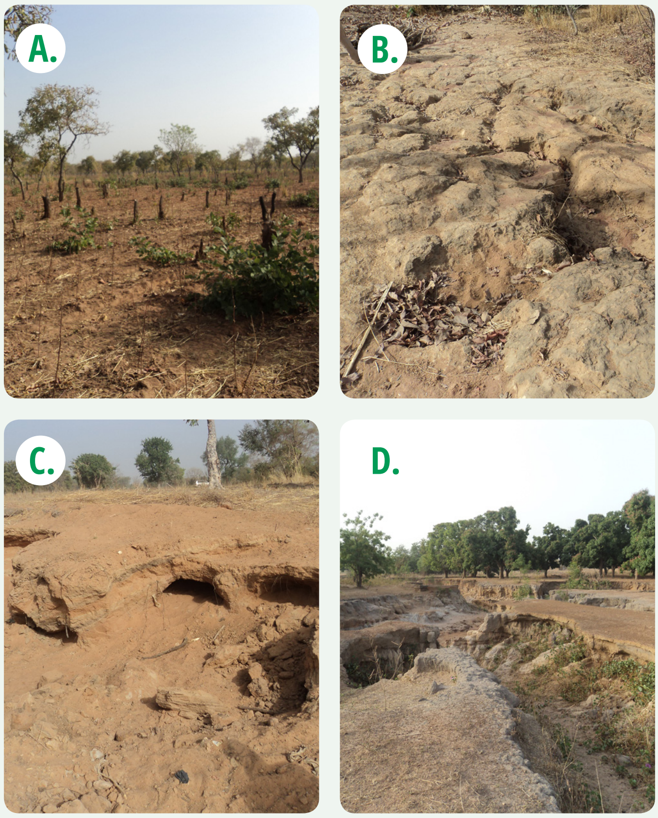


Table 9: *Land degradation trend in relation to proportion of population residing in each land degradation zone of Burkina Faso*

Class	Area sq. km	Area (%)	Population (%)
No data	2,101,896	1	1
No significant trend	150,882,048	53	51
Negative trend – no significant correlation	86,745.816	31	28
Positive trend – no significant correlation	21,132.576	7	10
Negative trend – positive correlation	6,334.092	2	3
Positive trend – positive correlation	16,871.976	6	7
Total	153,115,028	100	100

Comparison of the spatial distribution of land degradation assessment with other studies also shows general correspondence (Fig. 20). The maps generally show that the extent of land degradation is lower in the central and northern parts of the country compared to the southern and western part. This implies that the approach used in this study can be used to identify hotspot areas that need priority intervention. However, it should be noted that it will not be possible to strictly compare the maps due to differences in the data and methods used to generate the results. Some of the maps available are at regional scale which can 'omit' details while some are at more detailed scale whereby our maps would have 'skipped' some of the detailed observations. Though the purpose and scale for which the maps are produced vary, it will generally be essential to develop standardised approach to estimate the extent and risk of land degradation as well as its spatial distribution. This can reduce confusion and facilitate informed decision making.

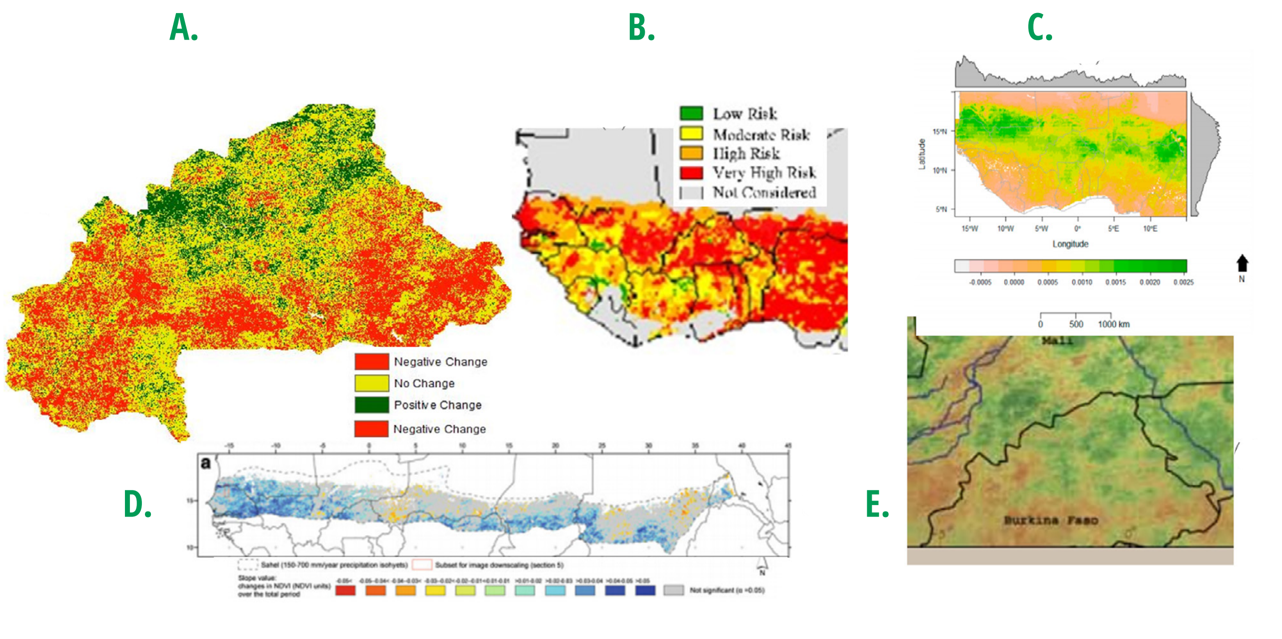


Fig. 20: *(**a**) NPP trend for the period 2000-2015 based on this study; (**b**) land degradation in West Africa (Knox Academy, 2016); (**c**) Spatial pattern of slope of the linear regression of NDVI against soil moisture (1982-2012) (Ibrahim et al., 2015); (**d**) GIMMS3g NDVI linear trend 1982–2010 based on annually integrated NDVI; and (**e**) Trends in increment of enhanced vegetation index for the period 2001 to 2006 (Vågen and Gumbricht, 2012).*

5.2.2 Province level analysis

Based on the province level scale of land degradation assessment that uses both the erosion hazard index computation and soil chemical properties (pH, SOC and CEC), the risk of land degradation in the Houet and Tuy provinces of Burkina Faso were categorized into five levels (Figure 21): i) low; ii) moderate; iii) medium; iv) high; and v) extreme. As noted earlier, the calculation associated with the overall overlay of the erosion hazard index is based on a Raster calculation that integrates the reclassified raster layers namely i) Erosion hazard index; ii) pH; iii) Soil organic carbon and iv) cation exchange capacity. The associated thresholds are informed by scientific literature and expert consultations pertinent to the area of interest, thus providing categorization that is evidenced based on spatial relevance. After establishing the criteria and thresholds from literature for the EHI degradation assessment (Table 10), the land degradation index is then computed with conditional raster simulations. This was then classified into four categories: i) severely degraded; ii) degraded ; iii) transitional zone "non-degraded; iv) not degraded. Validation of the map using the randomly sampled validation data produced a Kappa index of 0.814, which translates to an accuracy of 81%. The EHI map is a thematic type of map showing different levels of degradation risks using a color scheme. In this instance the color scheme runs from light brown to dark brown showing an increase in the erosion risk (Figure 21). The darker shades indicate where the highest risk of erosion is to be found. In most places there are gradual transitions between the extremes of the risk but in some places a sharper transition boundary is discernible. The results for the two regions indicate an overall spread of different degradation categories principally driven by erosion. There appears to be more degradation on the western side of the region while the midsection and eastern side vary from medium to low. These results are going to be complemented with an in depth analysis using a hydrological model characterization to assess amounts of sediment and water yield from the various sections.

Table 10: *Thresholds for EHI, SOC, pH and CEC used to estimate land degradation risk in Burkina Faso*

EHI level (Pixels)	SOC (%)	pH	CEC (cmolc/kg)	Raster Algebra	Category generic description
<5 Below moderate	>=20	>=6.5	>= 10	Con[("EHI" <5) & ("CEC" >=10) & ("PH" >=6.5) & ("SOC" >=20)], 1	*No degradation risk* (low erosion risk and good fertility status)
>= 5 Equal or Above moderate	>=20	>=6.5	>= 10	Con[("EHI" >=5) & ("CEC" >=10) & ("PH" >=6.5) & ("SOC" >=20)], 2	*Moderate degradation risk* (high erosion risk but good fertility status)
< 5 Below moderate	<20	<6.5	<10	Con[("EHI" <5) & ("CEC" <10) & ("PH" <6.5) & ("SOC" <20)], 3	*High degradation risk* (low erosion risk but poor fertility status)
>= 5 Equal or Above moderate	<20	<6.5	<10	Con[("EHI" >=5) & ("CEC" <10) & ("PH" <6.5) & ("SOC" <20)], 4	*Very high degradation risk* (high erosion risk and poor fertility status)

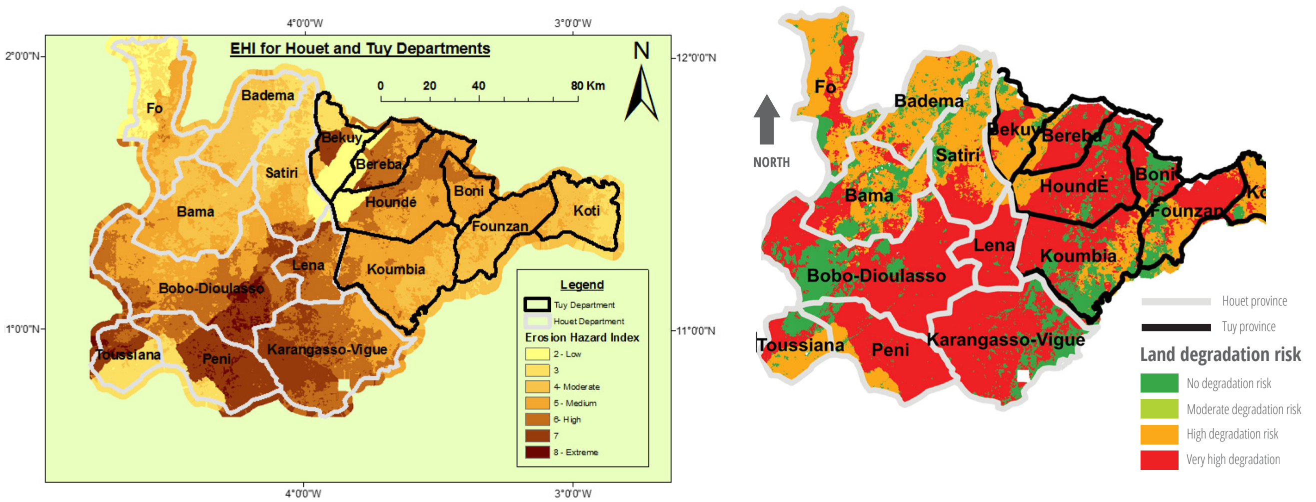


Fig. 21: *(**a**)Erosion Hazard Index map of the Houet and Tuy provinces in Burkina Faso (**b**) Land degradation risk map of the Houet and Tuy provinces in Burkina Faso*

Figure 21 shows that the highest risk of erosion is concentrated in the Eastern portion and in the southeastern part of the study area, running diagonally from the northeast to the southeast. Although the major high degradation risk areas are observed in the eastern part (Fig 21), it is also essential to recognize some areas with low erosion risk. Based on the field visit conducted for model calibration and validation, we observed that some of the sites are covered by protected areas which is dominated with forest with heavy natural tree cover. Aside from this degradation risk corridor running diagonally through the study area, the rest of the region seems to have intermediate to low risk, though there are sporadic areas with high degradation risk. This dovetails well with the field observations and validation data, and provides a good indicator of the spatial patterns of land degradation (particularly soil erosion) in the study area.

5.2.3 Landscape level analysis

5.2.3.1 Landscape assessments for sediment and water yield

At the landscape/watershed level, we used the SWAT model to estimate sediment yield (net soils loss) and runoff for an area that revealed high vulnerability based on EHI analysis. The watershed is located in the southern part of the Houet province. Based on calibration results, the model performed quite robustly with the simulated flow often mimicking the measured values both in low and high flow regimes. The Houet watershed experiences sediment yields ranging between 0 to 26 t ha^{-1} $year^{-1}$ with an average sediment yield of about 7 t ha^{-1} $year^{-1}$ (Fig. 22a). The highest net soil loss was experienced in sub-watersheds 8, 11 and 19. Results also show that 14% of the area experiences soil loss rate of more than 10 t ha^{-1} $year^{-1}$. The region is generally flat and based on field observations the majority of soil erosion in the area is a result of lack of vegetation cover especially during the onset of the rainfall period. This correlates to heterogeneous data gathered via farmer interviews which confirmed that the highest risk of erosion exists right at the start of the rainy season, which relates to the time when ground cover is at its minimum due to the dry season which is coming to an end. The ground is typically exposed at this time resulting in soil erosion when the initial rains fall. The situation persists until the ground cover grows back during the course of the rainy season. Other than the above, it is also clear that croplands are the most affected land cover type when it comes to erosion risk. Particularly those croplands located on slopes longer than 2 kilometers are at high risk of degradation. Such insights can guide the process of implementing interventions by suggesting target areas and their locations in the landscape. According to Fig 22b, there is an average 36 mm of surface runoff from that particular portion of watershed per year.

The major sediment yield controlling variables across the catchments and sub-catchments within the observed watershed can be explained by differences in management practices, size of rainfall events and intensity (rainfall characteristics), vegetation-cover dynamics or land-use changes. While in most instances size of catchment determines the amount of sediment yield (mostly inverse relationship), there are also evidence indicating that the amount of rainfall might be more decisive for the quantity of sediment yield than the size of the catchment (Gresillon and Reeb, 1981). However, these observations are mainly reflected when comparing sediment yield across wider areas.

There is an observed disconnect between the levels of sediment yields in certain areas compared to the surface runoff. The eastern ridge clearly portrays higher surface runoff value but not significant losses of sediment yield. This is likely an artifact of the current land cover in this area.

Generally, erosion rates between 10 and 200 t ha^{-1} y^{-1} are reported as typical for the savannah ecosystems including West Africa (Mati and Veihe, 2001). Measured data from some experimental stations in the region also show that soil erosion rates under similar climate conditions (500-1300 mm rainfall) usually range from 0.1 to 26 t ha^{-1} y^{-1} on cultivated soils with slope gradients between 0.5 and 4 %, but might reach up to 85 t ha^{-1} y^{-1} on leached, sandy clay soils with slope gradients of 4 % (Roose, 1976 and 1994). The soil sediment yield estimate in this study is within the ranges of other assessments. However, it will not be possible to strictly compare the different measures unless their data sources, analysis methods and scale of analysis are standardized.

In order to have a better context about the severity of soil loss in the study watershed, we categorized the average rate as per the tolerable soil loss in the region (Table 11). For Burkina Faso, we used a threshold value of less than 2 t ha^{-1} $year^{-1}$ to classify areas to potential hazard zones where the tolerable soil loss rate was exceeded based on Schmengler (2010). Additionally, all areas with soil loss rates higher than 5 t ha^{-1} $year^{-1}$ were identified as severely affected zones (Schmengler, 2010). In these zones, soil erosion has led or will lead to considerable soil degradation, reduction in land productivity and/or deterioration of soil quality on-site and/or off-site. Off-site impacts might include road, bridget etc. damage, siltation of reservoirs and watering points, and pollution among others.

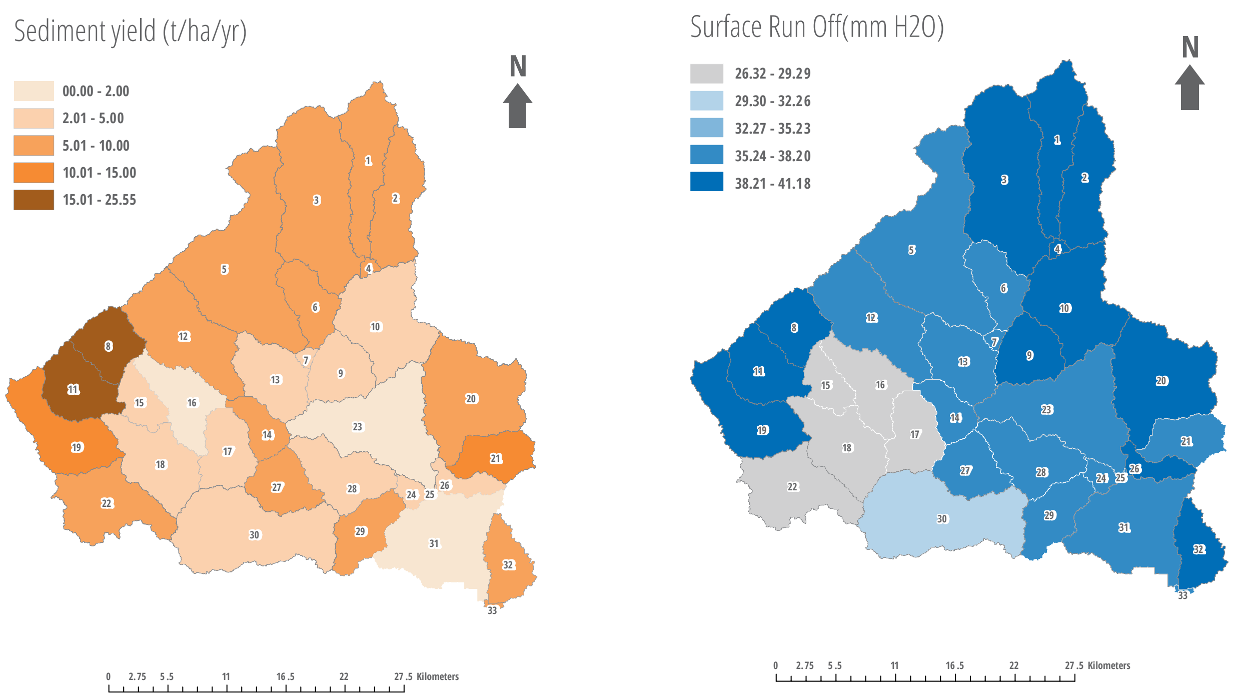


Fig. 22: (a) Average annual sediment yield and (b) average annual surface runoff in a selected watershed within the Houet province in Burkina Faso.

Table 11: Watershed area statistics against sediment yield

Average Annual Sediment Yield	Area (ha)	Area (%)
< 2 t/h/y	10,214	8
2-5 t/h/y	49,526	36
> 5 t/h/y	76,326	56

Based on Table 11, the majority of the areas in the study watershed (44%) experience soil loss rate within the overall tolerable limit rate (less than 5 t ha^{-1} year^{-1}). This is in agreement with an observation by Schmengler (2010) who identified similar results for a watershed within the Houet province. In her study, two catchments in south western Burkina Faso (Wahable and Fafo) are less threatened by soil erosion since approximately 16% and 12%, respectively, of the catchment areas are affected by sediment loss more than the tolerable amount. One of the reasons for the lower soil loss in the study site can be attributed to the near-flat terrain with only few areas characterized by slope gradients more than 5% (Table 12). Though only few areas have slope greater than 10%, it is important to note that those areas are characterized by high soil loss of 10 t ha-^{1} year^{1} (Table 12).

Table 12: Average sediment yield per slope class for a study watershed within the Houet province of southwestern Burkina Faso

Slope class (%)	Average sediment yield (t ha^{-1} year^{-1})	Area (ha)	Area (%)
0 - 2	6	46,367	34
2 - 5	6	71,337	52
5-10	7	15,824	12
>10	11	2,538	2

Though there is no significant difference, the results in this study show that bush/shrub lands experience relatively higher soil loss (Table 13). Other studies in different regions however show that potential erosion hotspots often appear on continuously cultivated fields and areas of sparse cover. In some parts of Africa, there is general association that settlements are established on areas that are open, relatively degraded, overgrazed, and prone to soil erosion (Schmengler, 2010). As a result, areas around settlements show high erosion risk though it will be necessary to establish this fact with more detailed study as some studies show reverse relationship (Verstraeten and Poesen, 2001, 2002).

Generally, it is necessary to understand that the simulated soil erosion hazard maps present only a first step in estimating the magnitude of soil loss and thus should be considered as an initial steps to estimate the severity of the problem. In addition, it will be necessary to be cautious of the interpretation involving the tolerable soil loss limits as those thresholds can vary and mislead recommendations. This means the suggestion made in this report need to be considered as preliminary indicators and not as an ultimate and definitive soil loss risk assessment.

Table 13: *Average sediment yield per land use/cover class for a study watershed within the Houet province of southwestern Burkina Faso*

Land use/ cover type	Average sediment yield (t ha^{-1} yr^{-1})	Area (ha)	Area (%)
Cultivated	6	29,893	22
Grazing/ Grassland	6	96,518	71
Bush/ shrub	9	1,453	1
Forest	6	7,830	6

5.2.3.2 'What-if' scenario assessments for best management practices with SWAT-APEX

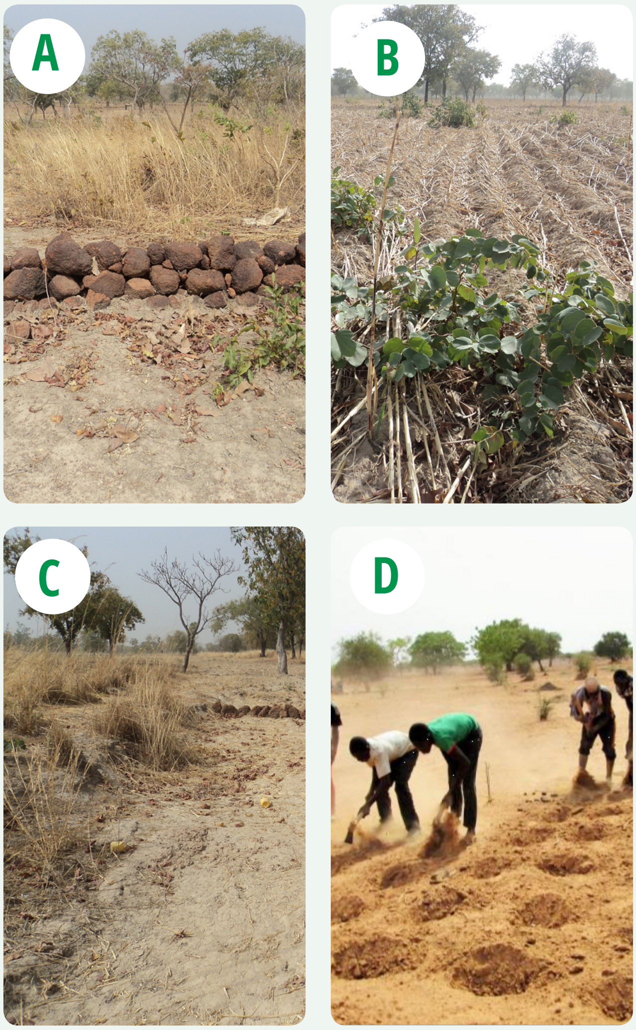
In order to assess the impacts of sustainable land management and soil and water conservation measures in tackling soil erosion and reducing excessive runoff, we also conducted 'what-if' scenario assessments for best management practices with SWAT-APEX similar to the case in Kenya. The results show significant decline in both sediment yield and runoff associated with improved land and water management options for a selected portion of the Houet province. The options provided can be used to explore possible intervention options that can be promoted by decision makers for implementation by local communities. The SWAT-APEX model used 35 years of weather data from 1981 to 2016.

The "What if" scenarios that were conducted in the SWAT-APEX interface were selected based on field validation efforts (See Plate D and Plate E). Below are the five "What if" scenarios that were conducted for two selected sub watersheds in the Houet Province. These interventions (as depicted in Plate E) were compared against a baseline that we refer to as current conditions or business as usual in case no intervention were done.

1. Current conditions (BAU)
2. Stone bunds along contours (0.5 meter strip width at 20 m intervals- SBC)
3. Ridge planting (raised beds) (1 meter strip width at close intervals- RPRB)
4. Half moon bunds constructed in intervals (5 meter width at 10 m intervals- HMO)
5. Zai pits (Zai)

The explanatory variables considered for the delivery ratios were water yields resulting from flow and sediment loads leaving sub-areas within specific sub-basins. The SWAT-APEX results indicate that the flow from each of the sub-areas is the dominant factor affecting sediment delivery within the sub-basins. Together, the explanatory variables considered under the multiple

Plate 4: *Interventions that were captured during field validation studies and informed on "What-if" scenarios to be conducted with **(a)** Stone bunds; **(b)** Ridges with raised beds; **(c)** Half moon with stone bunds; **(d)** Zai pits in agricultural fields.*



linear regression framework were able to estimate sediment and runoff with satisfactory regression parameters. The R2 values for the regression relationship between the sediment and their counterparts estimated with multiple linear regression method were 0.75 for sediment, 0.82 for runoff.

Table 14: *Simulation results for water yield (mm) and sediment yield t/ha) from 33 sub-areas with four interventions compared with current conditions using SWAT APEX*

	Current conditions (BAU)		Stone bunds on contours (SBC)		Ridges with raised beds (RPRB)		Half moon (HMO)		Zai pits (ZAP)	
APEX Subarea	WYLDmm	SYLDt/ha	WYLDmm	SYLDt/ha	WYLDmm	SYLDt/ha	WYLDmm	SYLDt/ha	WYLDmm	SYLDt/ha
1	8.27	21.7	9.75	18.44	9.51	19.53	8.93	20.18	9.51	17.36
2	8.29	21.7	9.78	18.44	9.53	19.53	8.95	20.18	9.53	17.36
3	8.27	21.70	9.76	18.44	9.51	19.53	8.93	20.18	9.51	17.36
4	8.29	21.70	9.78	18.44	9.53	19.53	8.95	20.18	9.53	17.36
5	11.22	21.5	13.24	18.27	12.91	19.35	12.12	19.99	12.91	17.20
6	11.25	21.5	13.28	18.27	12.94	19.35	12.15	19.99	12.94	17.20
7	11.26	21.5	13.28	18.27	12.94	19.35	12.16	19.99	12.94	17.20
8	10.26	21.5	12.11	18.27	11.80	19.35	11.08	19.99	11.80	17.20
9	8.29	21.7	9.78	18.44	9.53	19.53	8.95	20.18	9.53	17.36
10	8.29	21.7	9.78	18.44	9.53	19.53	8.95	20.18	9.53	17.36
11	10.31	21.5	12.16	18.27	11.85	19.35	11.13	19.99	11.85	17.20
12	11.23	21.5	13.26	18.27	12.92	19.35	12.13	19.99	12.92	17.20
13	11.25	21.5	13.28	18.27	12.94	19.35	12.16	19.99	12.94	17.20
14	14.62	21.15	17.25	1 7.98	16.82	19.03	15.79	19.67	16.82	16.92
15	11.39	21.5	13.44	18.27	13.10	19.35	12.31	19.99	13.10	17.20
16	11.4	21.5	13.45	18.27	13.11	19.35	12.31	19.99	13.11	17.20
17	15.19	21.15	17.92	1 7.98	17.46	19.03	16.40	19.67	17.46	16.92
18	15.18	21.15	17.92	17.98	17.46	19.03	16.40	19.67	17.46	16.92
19	13.5	21.15	15.93	1 7.98	15.53	19.03	14.58	19.67	15.53	16.92
20	8.28	21.7	9.77	18.44	9.52	19.53	8.94	20.18	9.52	17.36
21	9.98	21.12	11.77	17.95	11.48	19.01	10.78	19.64	11.48	16.90
22	15.18	21.15	17.91	1 7.98	17.46	19.03	16.40	19.67	17.46	16.92
23	9.99	21.12	11.78	17.95	11.48	19.01	10.78	19.64	11.48	16.90
24	9.98	21.12	11.78	17.95	11.48	19.01	10.78	19.64	11.48	16.90
25	10.01	21.12	11.81	17.95	11.51	19.01	10.81	19.64	11.51	16.90
26	6.3	21.12	7.43	17.95	7.24	19.01	6.80	19.64	7.24	16.90
27	14.62	21.15	1 7.25	1 7.98	16.81	19.03	15.79	19.67	16.81	16.92
28	9.98	21.12	11.78	17.95	11.48	19.01	10.78	19.64	11.48	16.90
29	9.98	21.12	11.78	17.95	11.48	19.01	10.78	19.64	11.48	16.90
30	18.88	21.15	2.2.28	1 7.98	21.71	19.03	20.39	19.67	21.71	16.92
31	9.98	21.12	11.78	17.95	11.48	19.01	10.78	19.64	11.48	16.90
32	6.3	21.12	7.43	17.95	7.24	19.01	6.80	19.64	7.24	16.90
33	9.97	21.12	11.77	17.95	11.47	19.01	10.77	19.64	11.47	16.90

Based on both SWAT and SWAT-APEX assessments, a subwatershed within the Houet province that showed high erosion risk was selected and analyzed from sub-watershed level down to the lower farm levels. The integrated assessment for multi-scale analyses of the impact of introducing new interventions at the sub-watershed and sub-areas (farm) levels was quite informative from a management point of view. Based on the "What-if" scenarios conducted, the results of the interventions were positive and demonstrated that when implemented would enhance the sustainable agricultural production. As shown in Table 14, Figures 23 and 24, the proposed interventions reduce sediment loads and increase water yields. In order for these interventions to have impact, it will require both commitment and resources allocation in order for the options to be effectively disseminated on a broader scale. Additionally, the successful implementation of the proposed interventions will need supportive policy environments.

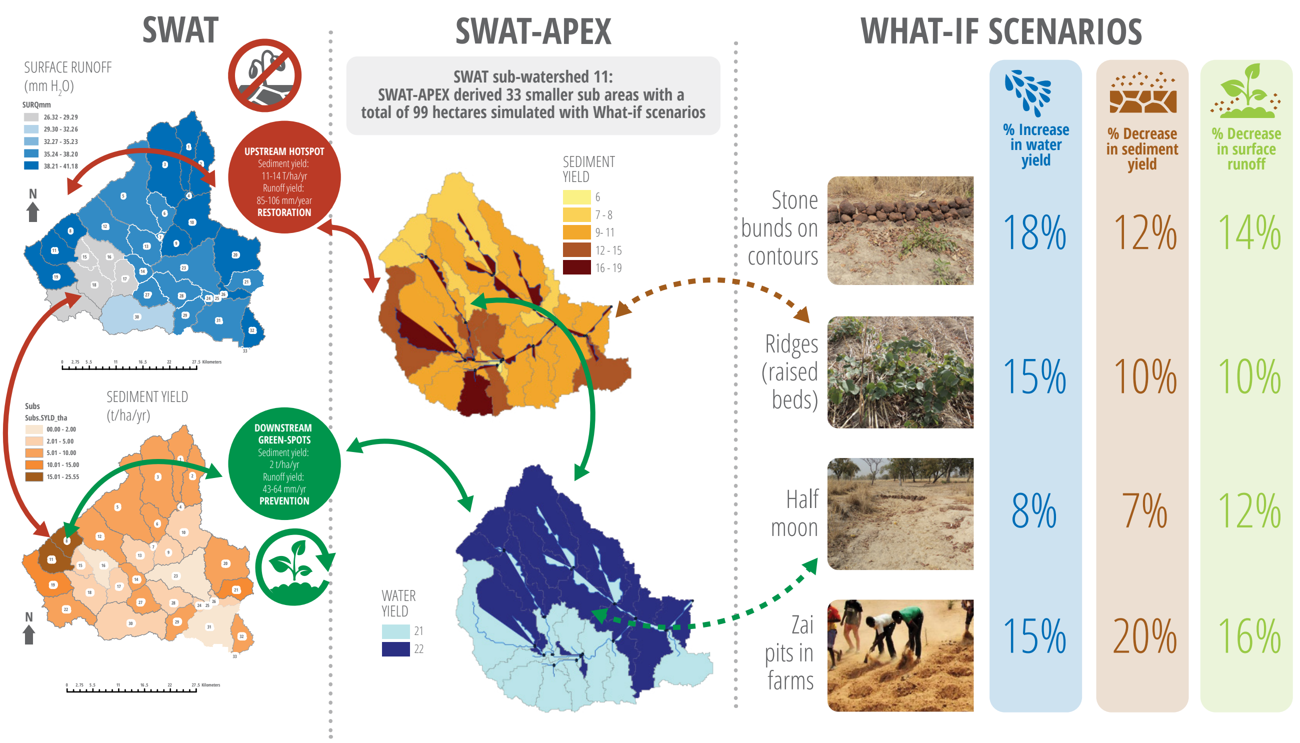


Fig. 23: *What if scenarios derived from a selected subwatershed (Subwater 11 from SWAT) for restoration and prevention interventions into various subareas (33 sub-areas from SWAT-APEX) for water yield and sediment yields.*

As depicted in Figure 24, context-based approaches that consider the problem at hand, the resources available and the willingness for stakeholders to implement will be critical. For example, there can't be blanket recommendations that Zai or stonebunds work in a given area unless stakeholder consultations and mapping of various relevant actors is conducted. The message we portray here is that biophysical approaches are very useful in identifying feasible solutions but they require inclusive, participatory approaches that are multidisciplinary in order to have impact. These considerations will prioritize community collective action, gender relations and resources (economics of implementation) supported by an enabling environment.

The health of many dryland ecosystems has declined dramatically over recent decades, largely due to unsustainable farming methods, increasing drought, deforestation and clearance of natural grasslands. Burkina Faso is hardest hit of all of Western Africa, with 40% of its soils severely degraded. Desertification is costing the country 9% of national agricultural GDP annually (IUCN, 2017). More attention is also required from national policy makers to encourage farmers to protect and increase soil health (As depicted in Table 8) specifically soil organic carbon which serves as a principle indicator of land degradation. It contributes to the fertility of the soil and to its capacity to hold water, determining the soil's capacity to produce food and to support other biodiversity. Most countries in Africa lack the facilities to routinely monitor soil organic carbon and it tends to be treated as a useful by-product, rather than an explicit objective, of sustainable land management. At the same time, some agricultural practices lead to large losses in soil organic matter that are not monitored or regulated, despite the major cost they represent to society. The benefits of sustainable land management, and of land restoration are felt across multiple sectors, hence policies are needed to guide investments that provide multiple benefits and these benefits need to be monitored and rewarded.

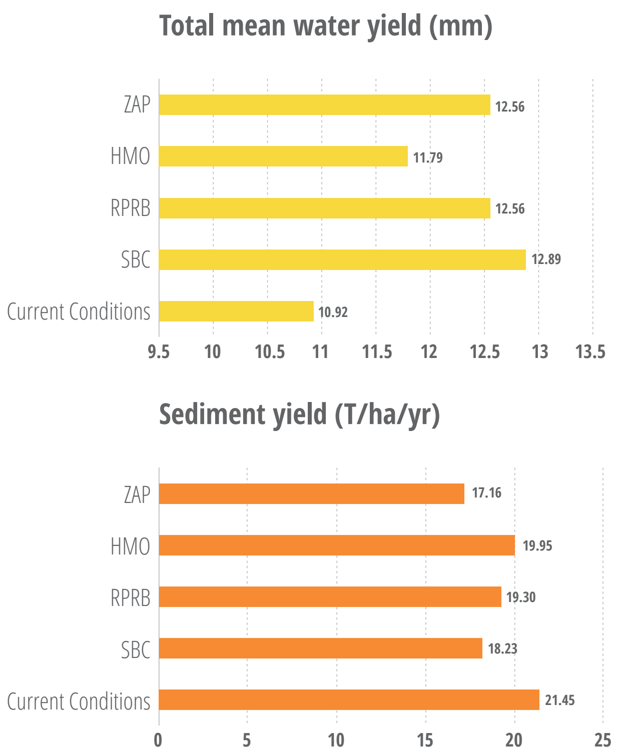
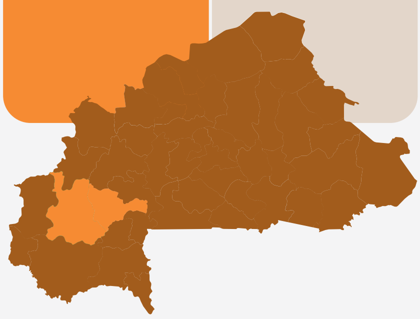


Fig. 24: *What if scenarios with graphical representation of water and sediment yields for the different basket of intervention options in Houet Province of Burkina Faso.*

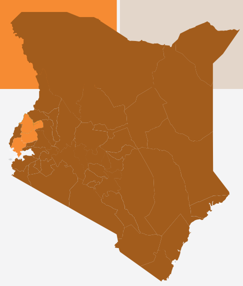
6. Conclusions and recommendations

Land degradation is a dynamic and constantly shifting challenge, energized by both biophysical and anthropogenic forces. In trying to combat it and preserve fertility of land, it is important to ascertain those areas that are at highest risk of being affected by land degradation. It is essential to get rapid information on the spatial distribution of hotspots for intervention prioritization. It is also important to develop frameworks and tools that can help to quickly designate those areas within a landscape where erosion is most likely to occur, based on what is known about those areas where it has already occurred. Based on this, timely interventions can be deployed allowing the threat of degradation to be kept in check even as it constantly changes. The analysis in this study explored approaches to identify and map land degradation hotspots at different scales that require priority intervention. The national level approach was based on time series satellite and rainfall data. The results showed land degradation trend hotspots across the two countries (Kenya and Burkina Faso). The results can guide planning and decision making at national level. The second approach used relatively fine resolution biophysical dataset (different erosion parameters) and weighting methods to produce erosion hazard maps at county and province levels. These maps were then integrated with key soil attributes such as texture and organic carbon to produce land degradation risk maps for three counties in Kenya and two provinces in Burkina Faso. The counties and provinces were identified to align with GIZ activities in the two countries. The results at these levels can be instrumental for planning and decision making at lower levels where regional governments and NGO will be more interested. Both maps (national and country level) were assessed by national and local stakeholders at a workshop. This approach was very instrumental as the local experts who have long-term experience were able to assess how far the maps were accurate and suggested what improvements should be made. Generally, the maps were perceived to be accurate and useful to guide planning at different levels. In order to see the possible correspondence between land degradation risk and food insecurity/vulnerability at county level, the participants of the workshop were asked to delineate potential food insecurity 'zones' within the three counties (Kenya). This exercise also generated additional information about the locations

	BURKINA FASO: AREA % area covered	BURKINA FASO: Average sediment yield (t ha^{-1} yr^{-1})	KENYA: AREA % area covered	KENYA: Average sediment yield (t ha^{-1} yr^{-1})
Cultivated	22%	6	68%	6
Grazing/grassland	71%	6	11%	5
Bush/shrub	1%	9	8%	4
Forest	6%	6	13%	3
Barren land	-	-	1%	5



BURKINA FASO



KENYA

where food insecure communities live and whether there was correspondence with the severity of land degradation. The third and more detailed analysis was focused on hotspot watersheds within the counties/provinces in the two countries. For this level, we used relatively high resolution dataset and more elaborated modelling approach. In this case, the SWAT model was used to model sediment and runoff yield at landscape/watershed levels and identify hotspots areas that experience soil loss beyond the tolerable (acceptable) limits in the respective countries. We also simulated the impacts of different management measures in reducing soil loss and expressed the results with respect to the tolerable limits. This step provided detailed information about the risk of land degradation and the benefits of different measures to tackle the problems. This was instrumental because such detailed level of analysis can support local level planning as the scale of analysis fits well with local level decision making.

Based on the scenarios of 'best management practices', it is generally possible to state that appropriate structures be built in hotspot areas especially focusing on factors/drivers that help to slow down the momentum of water during the rainy season. Interventions of that type currently exist in the form of structures such as rock bunds. However the density and spread of these need to be increased to a number capable of having sustainable impact during the rainy seasons. In addition, soil and water conservation measures are required to arrest soil being swept away by runoff. This is where the second factor of biomass comes in. Integrating biological options such as planting trees and grasses can help stabilize the soil erosion control structures and also help reduce the energy of runoff. Most critically it will remedy the big problem of low biomass/ground cover during the early period of the rainy season. This is the window period when the landscape is most vulnerable due to having gone through a dry spell that saw it lose most of its ground cover. The first rains are therefore the most devastating in terms of erosion and ways to increase biomass during this period should be explored. There are various short term herbs and shrubs that can withstand the dry season and provide essential cover to the soil at the critical time. It is recommended that future research explore the use of these indigenous species as biomass cover during the dry season.

It is also recommended that the "what-if" scenarios be executed periodically with updated data in order to form a mechanism by which threats can be identified early and appropriate mitigation measures deployed. In this manner the fertility of the land and its capacity for food production can be maintained sustainably. The sequential approach from national, sub-regional and landscape level results demonstrate the ability to predict the consequences/outcomes of interventions using quantitative methods to improve the livelihoods of subsistence farmers while evaluating the environmental consequences at multiple levels of scale, which adds unique value to the current knowledge in agricultural research.

The study shows how a multi-criteria approach can be applied to make rapid assessments of erosion vulnerability. Using publicly available datasets a rapid appraisal of the vulnerability of an area to erosion can be done. The use of field data and AHP for parameterization allows the localization of the model to the area of interest. This allows its wide scale of application in many different and diverse locations facing unique confluences of factors. It is recommended that future work focus on increasing the diversity of the primary data used for the modeling. Having more covariates particularly those representing anthropogenic forces could shine new light on the dynamics driving the observed degradation patterns.

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