Working Paper

Land health surveillance for identifying land constraints and targeting land management options in smallholder farming systems in Western Cameroon

Bertin Takoutsing, Ermias Ayenkulu, Zacharie Tchoundjeu,
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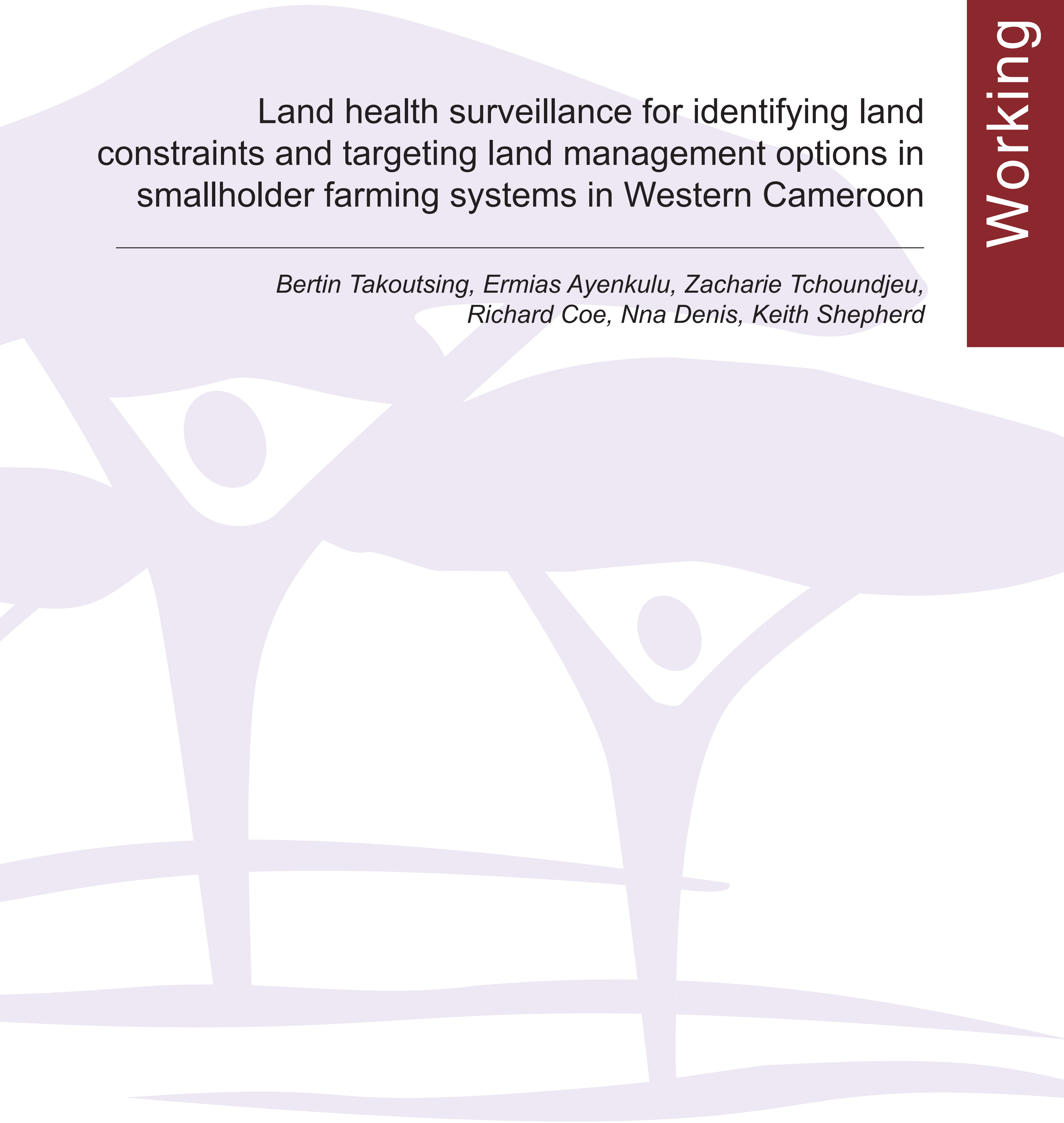

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Abstract

Quantitative and up-to-date information on ecosystem characteristics and land health constraints are needed to understand land degradation trends and patterns, as well as formulating appropriate and specific interventions. A study was carried out in the Western Highlands of Cameroon using the Land Degradation Surveillance Framework (LDSF) to: 1) establish baseline measurements to monitor and assess land management impact and ecosystem health over time, 2) describe land health patterns in land uses and associated degradation and 3) deduce implications and propose targets to engage with stakeholders to develop site-specific agroforestry and other sustainable land management interventions.

The LDSF is a spatially stratified, random sampling design framework use to characterise sentinel sites consisting of 10 km × 10 km blocks and clusters of 160 plots. This report provides preliminary analyses of the key factors that indicate the land and vegetation health of the Bamendjou sentinel site. These indicators provide a basis for assessing land degradation and productivity as well as the availability of key ecosystem services that are ecological functions and contribute to livelihoods improvement. The study identified and classified the indicators into ecological characteristics, soil physical and chemical indicators. We observed that the site is dominated by mountainous relief which is as inappropriate for intensive and continuous cropping without conservation practices. Over 88% of the site (8,800ha) was under cultivation at the time of the survey implying that nearly every hectare of the land including the steepest slopes is cultivated. Majority of land of the site (> 55%) has slope greater than 10% however, the soil erosion risk across the site was minimal. Trees and shrubs densities across the site were on average 143 tree ha^{-1} and 192 shrub ha^{-1} respectively.

Though not significant, both shrub and tree densities were higher in cultivated as compared to uncultivated. The herbaceous cover rate across the entire site was found to be annual and was estimated to be between 15-40% for cultivated and between 40 – 65% for uncultivated lands. Textural analysis of the samples indicated that the soils have a high content of Clay (75.64%). Infiltration was observed to be higher in cultivated than uncultivated lands. The estimated cluster-level frequencies of root depth restriction were 0.62% and 3.62% within the 0-20cm and 0-50cm depth respectively. We observed a wide range of values for SOC across the study site with significant differences in SOC concentration among land uses. The high proportions of lands of the study site are slightly acidic with pH ranging from 5.1-6.1 without any significant difference among land use.

The findings of this study provide a set of indicators and attributes of land degradation for smallholder farmers and decision makers and form a basis for targeting specific agroforestry and other land management interventions that help in reversing the trends of land degradation.

Keywords: Land degradation, soil improvement, ecosystem characterisation, soil health, vegetation health, Cameroon

Acknowledgements

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Acronyms

AfSIS	Africa Soil Information System
CGIAR	Consultative Group on International Agricultural Research
CRP	CGIAR Research Programme
FAO	Food and Agriculture Organization of the United Nations
HIDR	High Inherent Soil Degradation Risk
ICRAF	World Agroforestry Centre
ISFM	Integrated Soil Fertility Management
LCCS	Land Cover Classification System
LDSF	Land Degradation Surveillance Framework
LFA	Landscape Functional Analysis
MIR	Mid Infrared
PCA	Principal Component Analysis
PLSR	Partial Least Square Regression
RMSE	Root Mean Standard Errors
RMSEC	Root Mean Standard Errors of Calibration
SOC	Soil Organic Carbon
SWC	Soil and Water Conservation
TN	Total Nitrogen
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
UNESCO	United Nations
USDA	United States Department of Agriculture
VS-Fast	Visual Soil–Field Assessment Tool
WRB	World Reference Base

1. Introduction

Land degradation is increasing in severity and extent in many parts of the world. It is estimated that millions of hectares of land are being degraded annually (Bai et al., 2008). The impact of the phenomenon has now been recognized as a global issue by many international organizations and was highlighted at the United Nations Convention to Combat Desertification, the Convention on Biodiversity, the Kyoto Protocol on global climate change and the Millennium Development Goal (UNCED, 1992; UNEP, 2008). The decline in land quality has consistently been attributed to anthropogenic activities, mainly the incongruous land use that leads to degradation of soil, water, vegetative cover and biological diversity, therefore affecting ecosystem structure and functions (Snel and Bot, 2003).

In the Western Highlands of Cameroon, land degradation processes result mainly from human activities (UNEP, 2008). The area, which is characterized by steep mountainous terrain, is an agrarian area subjugated by subsistence agricultural systems where farmers grow a range of food and perennial crops with limited soil improvement practices. If the current land management practices continue, there will be continued reduction in crop yields, decrease in the availability of goods and services, as well as the loss of other benefits produced from the ecological functional ecosystem (FAO, 2011). Quantitative and up-to-date information on ecosystem physical characteristics and land health constraints of the area is needed to understand land degradation trends and patterns, formulate appropriate and specific interventions, and support policy development for food and water security, environmental integrity and economic development (Shepherd et al., 2014). However, land degradation is a contentious subject and ecological processes in landscape are difficult to understand from cross-sectional (one time) data due to the complexity of ecosystems (Pellant et al., 2005).

To address this problem, land degradation assessment frameworks have been developed, not only to help understanding the processes, but also to determine the status, the extent and its impact so as to design appropriate conservation activities. Examples of such frameworks include the Landscape Function Analysis (LFA) (Tongway and Hindley, 2004; Tongway, 2010), Visual Soil–Field Assessment Tool (VS–Fast) designed to support and enhance the Land Degradation Assessment in Drylands (LADA) (Waswa et al., 2013) project of the Food and Agriculture Organization (McGarry, 2004) and the Land Health Surveillance (Vågen et al., 2010) designed to support the African Soil Information Service (AfSIS) Project.

Each of the frameworks is based on standard scientific principles and made up of a set of tools and methods that guide the field operations. Attempts have been made to make these frameworks user-friendly and based on visual assessment of soil condition and health, with particular emphasis on simple, repeatable methods using low cost methods and tools (Kapalanga, 2008; Waswa et al., 2013).

These frameworks have been successfully applied and proven to be simple yet robust, ensuring immediate data availability, farmer acceptance and rapid update of the descriptive and measurement tools, leading to rapid assessment of the current condition with a potential for longer-term monitoring comparison of data across a wide range of environmental conditions and scales (Kapalanga, 2008; Vagen et al., 2010; Waswa et al., 2013). The information generated by these frameworks are useful to understand the extent of the problem, identify and recommend to landscape planners and users appropriate measures to be taken, and evaluate effectiveness and efficiency of the measures for possible improvement; hence useful to decision makers at various levels (McGarry, 2004).

The potential of the land health surveillance to assess land degradation trends and patterns formed the basis for this work. Unlike other frameworks, the land health surveillance provide a systematic biophysical assessment at the landscape level using low cost sampling and analysis methods (Vagen et al., 2010).

The concept is put into operation through the combined application of a set of science and technology methods and tools and the field implementation is achieved through the Land Degradation Surveillance Framework (LDSF) (Vagen et al., 2010). The LDSF is designed to provide a biophysical and socio-economic baseline for assessing land characteristics and condition (or health) at landscape level, and a monitoring and evaluation framework for assessing processes of ecosystem services degradation and the effectiveness of rehabilitation measures (recovery) over time (Vågen et al., 2012).

The objectives of this study were therefore to 1) establish baseline measurements to monitor and assess land management impact and ecosystem health over time, 2) describe land health patterns in land uses and associated degradation and 3) deduce implications and propose targets to engage with stakeholders to develop site-specific agroforestry and other sustainable land management interventions.

2. Method

2.1 Study site

The study site is located in the West and North West regions of Cameroon, that make up the “Western Highlands” owing to similarities in physical, human, economic and cultural features (Figure 1). The area lies between latitudes $5^o20'$ and 7^o North, and longitudes $9^o40'$ and $11^o10'$ East, and covers an area estimated at 31,400 sq. km (3.1 million ha).

It is largely an agrarian area subjugated by subsistence agricultural systems where farmers grow a range of food and perennial crops. Traditional land tenure laws make for unequal rights of access to landed property based on gender. This inequality has far-reaching consequences for access to other agricultural development resources for women (Yengoh, 2012). As a common practice in the area, the land is divided by the head of the family and distributed to male children who will in turn repeat the same process from one generation to the other.

Most of the soils of the area are classified as Cambisols, Acrisols and Ferralsols in the FAO/UNESCO Legend (FAO-UNESCO, 1977) corresponding to Inceptisols, Utisols and Oxisols in Soil Taxonomy (USDA, 1998). The topography is undulating and the vegetation is predominantly savannah with patches of gallery and montane forests. The western highland is host to a variety of tree species that are either retained or planted for a range of products and services. The area is host to low (300–500 masl) and high plateaux (1000–1800 masl), and very high altitude mountains (2500–3000 masl). Annual average rainfall varies from 1,600 to 2,300 mm. The mean daily minimum and maximum temperatures are 18^oC and 28^oC, respectively.

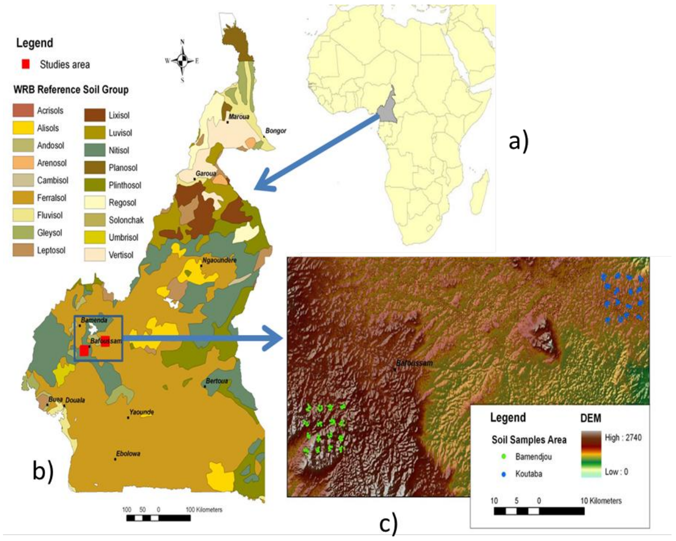


Figure 1: a) Map of Africa, b) Map of Cameroon WRB Reference Soil Group and c) Bamendjou and Koutaba sentinel sites (elevation background map).

2.2 Sampling framework

The framework used in the study was the Land Health Surveillance, drawn from the scientific principles used in public health surveillance to measure and monitor land health indicators (UNEP, 2012). The Land Degradation Surveillance Framework (LDSF), which is the field implementation of land health surveillance, was used to characterize the study area (Vågen et al., 2010; Aynekulu et al., 2011; Vågen et al., 2012). The LDSF is a spatially stratified, random sampling design framework built around a hierarchical field survey and sampling protocol using the concept of sentinel site. In the study, a sentinel site of 100 km^2 each (10km × 10km) was established (Figure 2a) and surveyed to capture land health indicators among land uses in the study area.

The sentinel site was further subdivided into 16 tiles (2.5 km × 2.5 km) in which a "cluster" of 10 plots (1000m^2 each) were randomly allocated and sampled in each tile (Figure 2b), given a total of 160 stratified random sampling plots. Within each of these plots, four sub-plots 100m^2) were established, one at the centre of the plot and the three others surrounding the centre plot, disposed at 120 degrees (Figure 2c).

This form of stratified cluster sampling allows the assessment of variability of soil properties at different spatial scales (sub-plot, plot, cluster, site) by applying models incorporating random effects that represent different groups, including spatial nested scales (Raudenbush and Bryk, 2002).

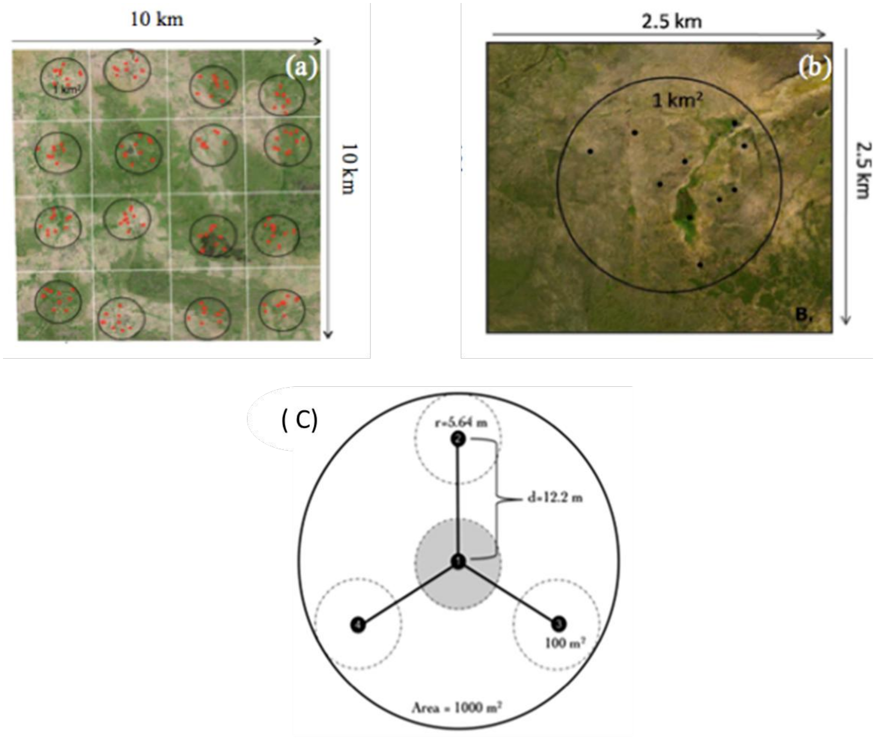


Figure 2: a) Illustration of the sentinel site of 100 km^2 block divided into 16 clusters. b) Illustration of the 1 km^2 clusters with 10 plots of 1000 m^2 each. c) Sub-plots (dotted circles) have a radius of 5.64 m (area 100 m^2), and the distance along the radial

2.3 Field data collection

2.3.1 Plot level measurements

Samples were taken from each of the 160 plots in the sentinel site and basic characteristics of the entire plot were observed and recorded in the LDSF data entry sheets. Data collected include slope, the major landform of the plot (level, sloping, steep, and composite), the position of the plot along the topographic sequence (upland, ridge/crest, mid-slope, foot-slope or bottom land), the presence or absence of soil and water conservation structures and primary current use of the plot. In addition, ecosystem impact factors such as agriculture, grazing, fire and tree cutting were scored for each plot, based on methods adapted from Moat and Smith (2007).

2.3.2 Sub-plot level measurements

At sub-plot level, another suite of attributes and indicators were identified, assessed visually and coded on either categorical or ordinal rating scales. The term 'attribute' is used in this context to describe an ecosystem component that cannot be directly measured, but can be approximated by a set of observable indicators of the component (Pyke et al., 2002). Three overlapping subsets of indicators are used to assess three attributes of the site: soil and site stability, hydrologic function, and biotic integrity (Pyke et al., 2002).

Soil or Site Stability attributes refer to the indicators of the plot to limit redistribution and loss of soil resources by water such as proportion of bare ground, and erosion severity and typology (sheet, rill and gully).

Hydrologic Function refers to the indicators of the plot to capture, store and safely release water from rainfall and run-on such as ground cover and soil stability indicators.

Integrity of the Biotic Community refers to indicators of the site to support characteristic functional and structural communities in the context of normal variability and to resist loss of this function and structure caused by disturbance, and to recover following each disturbance. The indicators assessed included woody, herbaceous and rock cover rate, and soil texture.

2.3.3 Vegetation measurement

All trees (height > 3 m) and shrubs (1.5 < shrub < 3m) within each sub-plot were counted to obtain density estimates.

2.3.4 Root depth restriction

Root depth restrictions were recorded by measuring the depth (in cm) from the soil surface to the auger depth where the auger could no longer penetrate the soil. The presence of root depth restriction was assessed in the upper 50 cm of the soil profile within each sub-plot by scoring the occurrence from 0 (none) to 4 (all sub-plots had restriction).

2.3.5 Land cover

Land cover of the plot was recorded using a simplified version of the FAO Land Cover Classification System (LCCS) (http://www.africover.org). Using the 'binary phase' of this classification, the following broad classes were identified: i) cultivated or managed terrestrial areas, ii) natural or semi-natural vegetation, iii) cultivated aquatic or regularly flooded areas, iv) natural or semi-natural aquatic or regularly flooded vegetation, and, v) bare areas.

2.4 Soil sampling and analysis

2.4.1 Collection of soil samples

Soil samples were collected for each plot from two depths top soil (0-20 cm) and sub-soil (20-50 cm) at the centre of each sub-plot using an auger. Samples from each depth were pooled together to obtain a composite sample. Using the LDSF framework, 160 plots (16 clusters x 10 plots) randomly allocated were sampled. A total of 320 samples (160 top soil and 160 sub-soil) were collected, processed and analysed for selected chemical properties.

2.4.2 Soil spectral reflectance analysis

Soil samples collected were air-dried, crushed using a wooden rolling pin and passed through a 2-mm sieve. It was then finely ground to powder and loaded into micro-cups for Mid Infrared (MIR) analysis. All the samples were scanned using a Bruker Alpha Drift FT MIR Spectrometer and analysed by MIR diffuse reflectance spectroscopy using the OPUS Laboratory software 6.5 version as described by Terhoeven-Urselmans et al. (2010). The soil spectral data was analysed by conducting a principal component analysis of the first derivative spectra and computing the Euclidean distance based on the scores of the significant principal components. Samples collected from the first plots of each cluster were selected and used as reference samples to constitute 10% of the total samples that had undergone conventional wet chemistry analysis for calibration and validation of the MIR data (Shepherd and Walsh, 2002, 2007).

2.4.3 Laboratory analysis

The selected reference soil samples (n=32) were then analysed for particular properties following conventional wet chemistry methods. The analyses were conducted at the Crop Nutrition (Cropnut) Laboratory in Nairobi. Soil pH was determined in 1:2.5 (w/v) suspensions, exchangeable acidity by NaOH titration using a 1:10 soil/solution ratio. Samples with $pH > 5.5$ were assumed to have zero exchangeable acidity and samples with $pH < 7.5$, zero exchangeable Na. Exchangeable Ca and Mg was determined by 1 M KCl extraction, and exchangeable K and available P by 0.5 M $NaHCO_3$ and 0.01 M EDTA (pH=8.5) using 1:10 soil/solution ratio extraction method. Soil texture was determined using a Bouyoucos hydrometer after pre-treatment with H_2O_2 to remove organic matter (Gee and Bauder, 1986). Total carbon and nitrogen were analysed at ICRAF laboratory using thermal oxidation method (Skjemstad and Baldock, 2008).

2.4.4 Spectral prediction of soil properties

Values obtained from the chemical analysis of reference soil samples were calibrated to the first derivative of the reflectance spectra using partial least squares regression (PLSR). For each selected soil property, a calibration model, with the equations developed using PCA and PLSR, was developed on the samples for which chemical properties were obtained from the laboratory. The known properties were then used to predict the values for the independent spectra in the remaining samples under investigation. The correlation coefficient and the root mean standard errors of calibration (RMSEC) between the wet chemistry and the MIR results are presented in Table 1.

Table 1: Calibration results for selected soil chemical properties

Property (n = 32)	r-squared	rmse
Clay	0.51	0.14
Silt	0.44	0.51
Sand	0.29	1.06
ExCa	0.76	1.03
ExK	0.43	0.78
ExMg	0.75	0.87
Al	0.58	0.11
Mn	0.60	0.90
P	0.53	0.55
Zn	0.12	0.49
pH	0.52	0.07
Total.Nitrogen	0.88	0.30
Total.Carbon	0.90	0.26
Acidified.Nitrogen	0.87	0.29
Acidified.Carbon	0.87	0.25

rmse: root mean standard error

The best correlations ($R^2 > 50$) obtained for clay, pH, Ca, Mg, Mn, Al, P, C and N suggest that there is quite a strong relationship between the results of the laboratory analysis and the MIR analysis procedures (Table 1). Medium and low correlation ($R^2 < 50$) was obtained for sand, silt, K and Zn. The results obtained from model development and prediction by MIR-

PLSR are closer to previous prediction reported by Shepherd and Walsh (2002), Terhoeven-Urselmans et al., (2010), Vågen et al., (2006) and Waswa et al., (2013).

2.5 Statistical analysis

Linear mixed models were used to compare differences in soil and vegetation results by land use/land cover, elevation and slope classification using cluster as a random effect. We also used a linear mixed model to compare tree/shrub density categories and all the data related to tree and shrub attributes were aggregated to plot level. Partial least squares (PLS) regression, was used to predict soil properties for each spectrum based on the laboratory analysis. All statistical analyses were conducted using the open source software R version 3.0.2 (R Development Core Team, 2008). Descriptive statistics (mean, standard deviation, minimum–maximum values, coefficient of variation and skewness) were calculated for measured soil properties. Pearson correlation and regression analyses were performed to understand the relationships among the soil properties.

3 Results and discussion

3.1 Ecological characterisation of the study

3.1.1 Land use

The distribution of land use across the entire site illustrates a critical challenge for the long-term sustainability for smallholder farmers who rely heavily on the ecosystem products and services provided by the landscape of the study site for their daily livelihoods. The moderate to steep slope lands that dominate the site are largely inappropriate for intensive and continuous cropping that is by far the most prevalent management practice (Table 4). While some farmers have made considerable efforts to engage in soil improvement and conservation practices, majority still continue to use unsustainable practices that could lead to the deterioration of the quality of the soils.

Land use spatial and temporal changes in land use were quite evident across the site as the land use depicted patterns closely related to rural settlements, located mostly where soil conditions were favourable for agricultural activities and year-round water supply was ensured. Settlements were therefore most abundant in the lowlands and at the foot of mountains.

Distribution of land use/ cover classes as estimated based on the observations on LDSF plots illustrate that the vast majority of the site is used for agricultural activities and six types of land uses were observed (Table 2). At the time of the sampling, farmers were using 48% of the area for croplands, while 41% were under fallow (1-8 years). Only 2.3% were uncultivated and distributed between forest, grassland, grazing and shrub land (Figure 4). This distribution illustrates a critical challenge for the sustainability of those who rely on the ecosystem services provide by the landscape of the study site for their livelihoods. The areas of the study site with a slope up between 0% to 20% are all cultivated (Figure 5).

Table 2: Land use/land cover classes determined by field data and definitions

Classification	Definitions
Cropland	Cultivated land or being prepared for cultivation with annual or perennial crops
Forest	A continuous stand of trees (and shrubs) with > 40% canopy cover
Fallow	A piece of land that has been previously used for farming but is currently left with no agricultural activities for 1–8 years in order to allow it to recover its fertility
Grassland	Land covered with grasses and other herbs with woody cover <10 %
Shrub land	Land with woody cover > 65% made up principally of shrubs (<3m)
Grazing	A field covered with grass or herbage and suitable for grazing by livestock

The under-storey vegetation of the site is dominated by a diverse assemblage of grass and herbs, most of which are palatable for animals. The cropping systems can best be described as multiple cropping systems with mixed inter-cropping, that is, two or more crops are grown simultaneously with no distinct row arrangement or row inter-cropping. Crop yields vary greatly depending on specific plot nutrient management practices, land use and the location of the cultivated plot along the topographic sequence. According to the Ministry of Agriculture and Rural Development, the average land holding is 0.25-0.75 ha per household for mixed cropping system and between 0.75-1.2 per household for perennial crops.

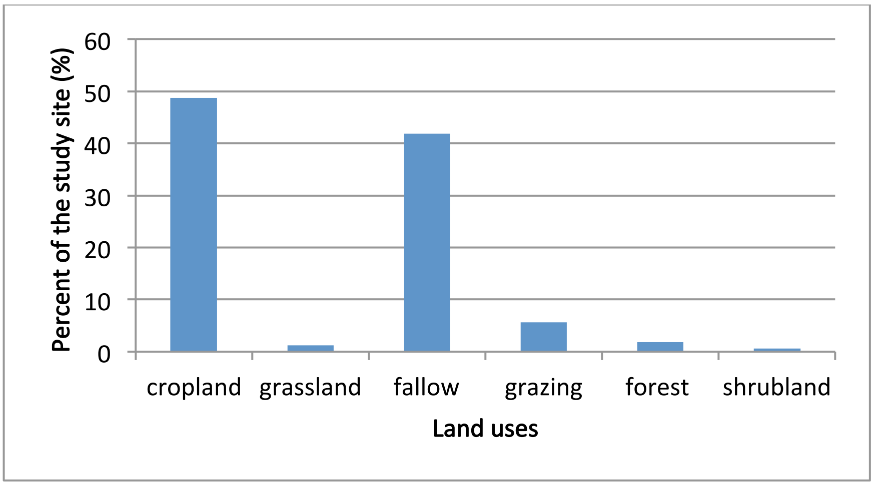


Figure 3: Distribution of land uses classes as estimated by the LDSF plot observations

3.1.2 Slope classification and terrain analysis

The analyses of the LDSF data revealed that over 88% of the study area (8,800 ha) is cultivated (Table 3; Figure 3), implying that the site is under intensive agricultural production and the farmers exploit nearly every hectare of the land, including those with steep slopes. This could be attributed, on the one hand, to high population density that prevails in the area (120-300 inhabitants per sq. km) and on the other, to the traditional land tenure system that favour land fragmentation. As a customary practice in many communities of the study area, the family land is redistributed to male heads of households from one generation to the other. Later, each male head will in turn divide his own portion of the family land to his male children, who will do same in for future generations.

Table 3: Estimated area under cultivation or management, tree and shrub densities in each cluster of the sentinel site

Cluster	**Percent cultivated area**	**Tree density (Trees ha-1)**	**Shrub density (Shrubs ha-1)**
1	70	150	280
2	0	190	200
3	70	320	290
4	100	80	133
5	100	100	120
6	100	200	122
7	100	170	104
8	100	150	120
9	100	130	164
10	100	110	155
11	90	80	120
12	80	60	107
13	100	100	231
14	100	180	233
15	100	130	327
16	100	140	380
Average	**88**	140	190

From the slope perspective, the land favourable for agricultural production (slope >10%) is very limited in the study area. Most of the area (> 55%) has slope greater than 10% (Table 4, Figure 4). Agricultural activities on sloping lands may expose the site to depletion and rapid nutrient losses, if proper conservation measures are not taken. Level lands which are less exposed to risk and favourable for agricultural production account for only 44% of total area against 42% for moderate slopes and 14% for steep slopes (Table 4; Figure 4). In addition, level lands are under more pressure as it mainly comprises settlements areas which further restrict agricultural activities.

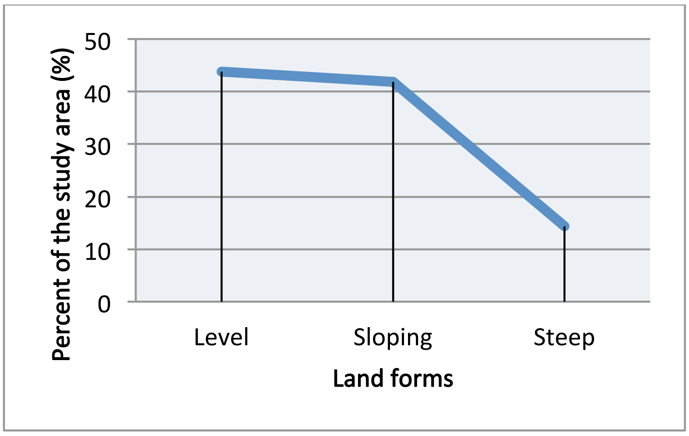


Figure 4: Distribution of land forms as estimated by the LDSF plot observations

Nearly all the plots with slope < 10% are cultivated, but as we progress to 20% slope, the percentage of cultivated land goes down to 50%. Above slope of 20%, we still found a number of cultivated plots ,meaning that even part of the steep slopes lands are under pressure. The uncultivated plots are either unsuitable for agriculture, located in steep slopes or are not easily accessible to farmers (Figure 5). The few forest plots found across the site have slopes of less than 20% and are made up of watershed, “sacred forests” and protected areas. These areas are governed by customary laws and thus cannot be utilized for agricultural activities.

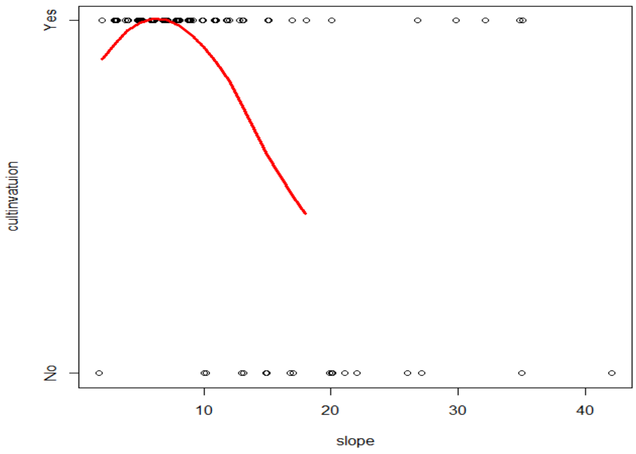


Figure 5: Cultivated/uncultivated against Slope classes

Table 4: Slope classification for the sites based on composited FAO slope classes and FAO recommendations for cropping based on slope classes

Slope percent	Slope classification	Percent of entire site
< 10	Level	44
10 - 20	Moderate	42
› 20	Steep	14

In addition, we observed that 60% of the plots are placed at mid-slope along the toposequence and only 10% are considered bottom-lands (Figure 6).

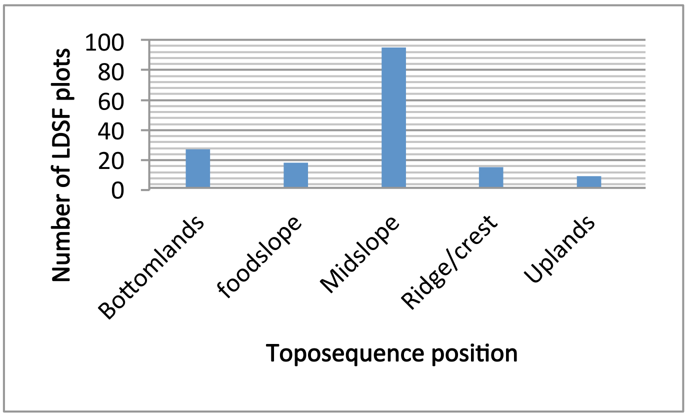


Figure 6: Toposequence position of the LDSF plots

3.1.3 Vegetation cover and structure

Anthropogenic activities have forced the forest back to areas along the waterways, watershed and galleries of community forests, and have allowed wooded grasslands to expand into the area. The vegetation of the study area varies with elevation with sub-mountain forests extending from 900m to 2,000m elevation. Above 2,000m, are distinct mountain grasslands, subalpine grasslands and shrub lands. The vegetation of the site is dominated by a variety of tree and shrub species that are either retained, or planted and managed by the farmers, for the provision of a range of tree products and services that impact the livelihood of the population. Trees and shrubs densities across the entire site were on average of 140 tree ha^{-1} and 190 shrub ha^{-1}, respectively (Table 3). The median where however lower, 134 tree ha^{-1} and 159 shrub ha^{-1}, indicating that there is a great variation in the distribution of trees and shrubs not only within clusters, but across the entire site. A detail analysis reveals that high densities of both trees and shrubs were surprisingly found in cultivated areas (Figure 8). These densities were found to decrease in uncultivated lands made up of (forest, wooded grassland and shrub lands) to a minimum of 62 tree ha^{-1} and 103 ha^{-1} shrub ha^{-1}, respectively (Figure 8). The presence of trees and shrubs even in cultivated plots can be justified by the fact that agroforestry has been a common practice in the area for many decades. In addition to tree products and services, farmers maintain or plant trees in the landscape for farm demarcation, as a legacy and proof of land ownership as applied by the traditional land tenure system.

Based on the LDSF field plots, we estimated that the site is still covered by woody plant species determined as the percentage of canopy of the trees and shrubs (Table 3). Area of the study site under dense woody cover was averagely estimated at about 2.5 ha.

As majority of the land is continuously changing depending on the period of the year and also from year to year, the land uses, particularly cropland in the area, should be assumed to be dynamic. Though we did not capture crop rotation during the study, it is possible that some of the plots change their uses during various times of the year, e.g. from fallow to cropland and vice-versa. Land-use dynamic should be incorporated in the LDSF framework so as to account for land use changes that influence land degradation indicators.

The herbaceous cover rate across the entire site is annual and was estimated at between 15–40% for cultivated and 40–65% for uncultivated lands (Figure 7). This could explain the low risk to erosion observed in the area despite having cultivated plots with slopes greater than 15%. The permanent herbaceous cover could be attributed to soil and climate conditions such as rainfall and temperatures that prevail in the area.

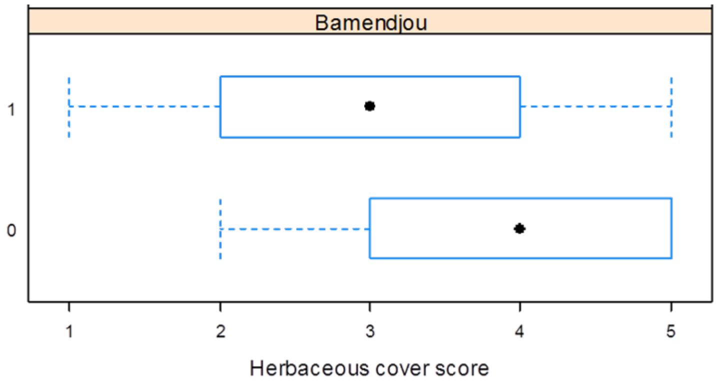
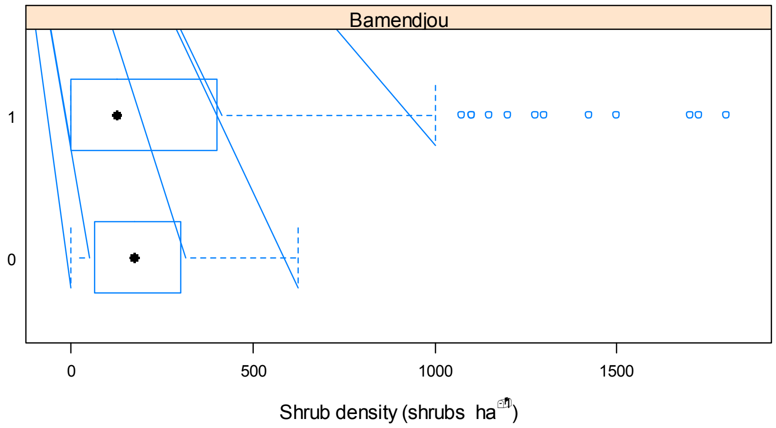


Figure 7: Estimates of herbaceous cover rate in cultivated (1) and semi-natural (0) areas based on estimates for each cluster



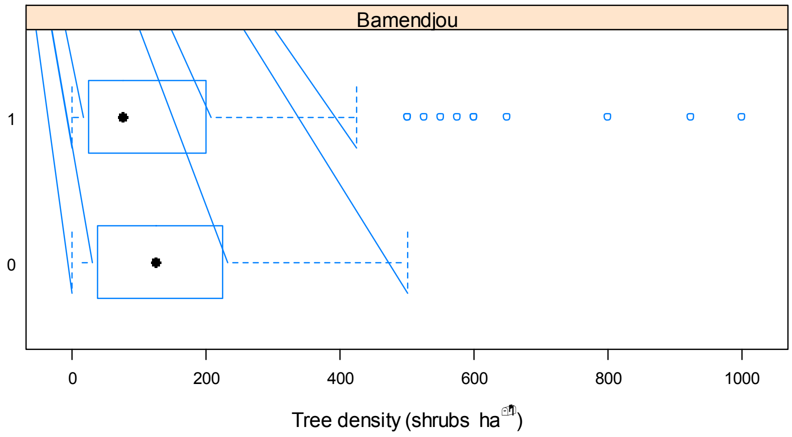


Figure 8: a) Estimates of shrub density (shrubs ha-1) in cultivated (1) and semi-natural (0) areas based on estimates for each cluster. (b): Estimates of tree density (trees ha-1) in cultivated (1) and semi-natural (0) areas based on estimates for each cluster

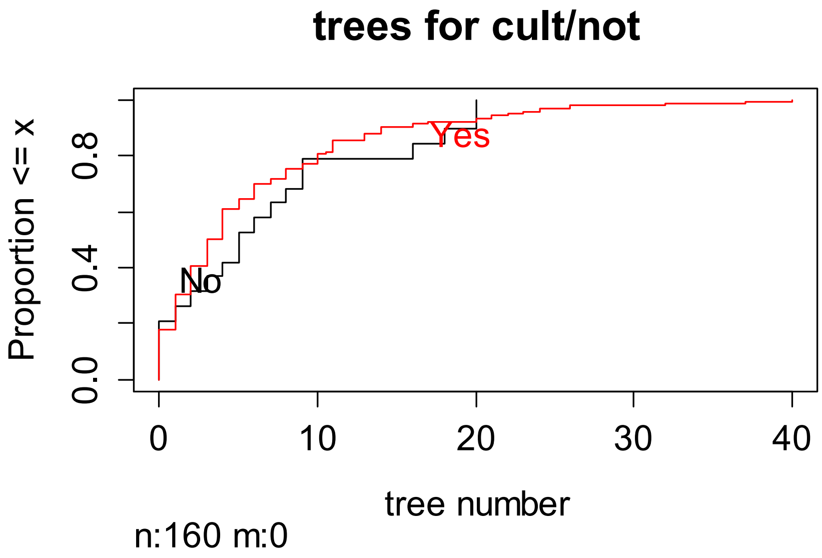


Figure 9: Distribution of plot-level tree numbers for cultivated (yes) and uncultivated (no) plots

The plots with less trees are made up of few cultivated, grassland and grazing land and could be targeted for agroforestry interventions. We expected the curve for non-cultivated plots to be at the right of that for cultivated plots, but instead we observed the opposite, although the difference is not significant (Figure 9). About 10% of the cultivated plots have very high tree and shrub densities (Figure 9). These are mostly fruit trees that are well maintained in the agricultural landscape for the characteristics of their fruits. Dominant species are *dacryodes edulis, cola acuminata* and *persea americana*. On the other hand, the very high tree and shrub densities in cultivated plots could be attributed to the fact that most of these plots are demarcated with live fences that surround the plots. The fences are made up of a variety of species planted with very short inter-tree distances and are regularly maintained and pruned. The vegetative materials obtained after the pruning are either use as fuelwood or as organic materials buried to improve the fertility of the soils.

3.1.4 Visible signs of soil erosion

Erosion assessment based on LDSF field plots data revealed a low risk of soil erosion across the entire site despite the fact that 88% of the site is cultivated including the steep slopes. We also observed that less than 5% of the site showed some obvious signs of erosion even on sloping lands. We expected steep and moderate slopes to be more susceptible to erosion than the level land as reported in previous studies due to accelerated flow of surface runoff (Garrison, 2013), but erosion risk was generally low. In addition, we did not observe any significant soil conservation measures across the entire study site.

The low erosion risk observed could be attributed to the soil types that prevail in the area. The textural analysis of the soils classified them as clay-rich soils which are known to be moderately resistant to erosion. The ability of soils to resist water erosion depends on their texture and topographic characteristics. Clay-rich soils resist erosion well because of strong cohesive forces between particles and the glue-like characteristics of humus. The soils of the study area have sufficient clay content to hold the particles together. On the other hand, sandy soils have high permeability that limit the amount of surface runoff that can wash soil particles away. Silty soils on their part, exhibit the least resistance to erosion because their permeability is low (resulting in more surface runoff), and their particle size is neither small enough to promote cohesion nor large enough to prevent entrainment.

In addition to the types of soils, and in the absence of soil conservation structure, the low erosion risk could also be explained by the slope stabilization that is contingent on the minimal tree and shrub cover, herbaceous cover and extensive annual cropping. Nevertheless, preventing soil erosion should still be included in the priority actions related to soil management if the site sustainability objectives are to be met. Unabated soil erosion despite the low magnitude not only results in the loss of the growth medium for plants, but also results in loss of nutrients that the plants need for productivity. Promoting a transition from annual cropping to agroforestry on moderate to steep slopes, better planning and control of grazing to reduce impact and soil conservation practices could help maintain the low soil erosion risk of the study site and ensure sustainable productivity of the land.

3.2 Soil properties

Physical and chemical soil properties varied greatly across the entire site and in some cases could be differentiated by land use/cover. While it is challenging to determine what factors caused this variation, the large differences across the site indicate that there is need for site-specific management recommendations and activities. Overall the major challenges presented by soil properties are related to topographic factors and ineffective nutrient cycling or replacement of nutrients lost from leaching or export by crop during harvesting.

3.2.1 Soil physical properties

a) Soil texture

Textural analysis of the top soil using the textural triangle indicated that clay was the most dominant proportion (75.64%) followed by silt (16%) and then sand (8.36%). In addition, majority of sampling plots have ribbon lengths greater than 50mm (Figure 10). The soil of the study area can therefore be classified as clay soil. Clay content was observed to decrease with slope along the toposequence and was observed to be higher in the bottom-land and foot-slope as compare to mid-slope and uplands (Figure 7). It was also observed to increase with tree and shrub cover and was higher in uncultivated, compared to the cultivated sections, though detail data are not presented here.

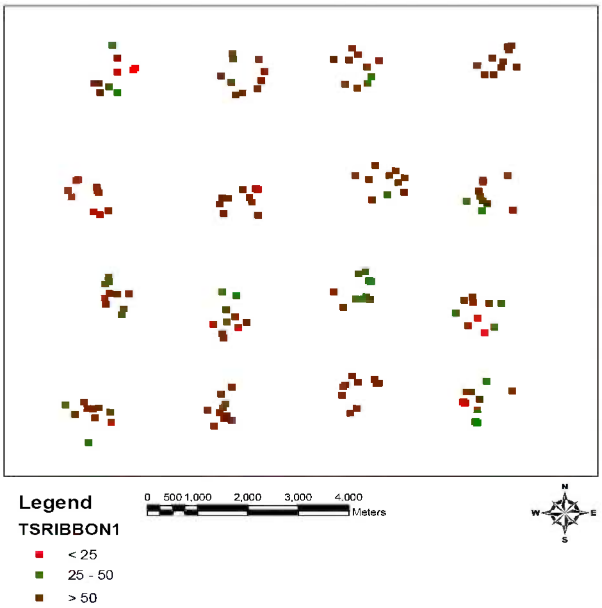


Figure 10: Length of top soil ribbon for the 160 plots

b) Infiltration rate

The analysis of the infiltration data revealed high infiltration rates at the beginning of the water infiltration events, followed by a relatively rapid decline that transitions towards near-constant values. The average saturated infiltration capacity for the study site was 711mm hr^{-1} (Figure 11). Infiltration rates were found to be higher in cultivated than uncultivated lands. The high infiltration capacities observed may be explained by the fact that the majority of the LDSF plots (88%) are cultivated. A critical analysis of the data revealed that as common land preparation practices in the area, lands are tilled to a depth of between 20cm and 30cm, then ridges are formed on top, and crops planted. The infiltration rates in the cultivated lands are therefore influenced by the tillage practice that loosen the top soil and increase permeability. Infiltration rates were lower in uncultivated lands probably due to compaction as a result of grazing, the effects of vegetation in forest plots and generally, the high clay content in the soil.

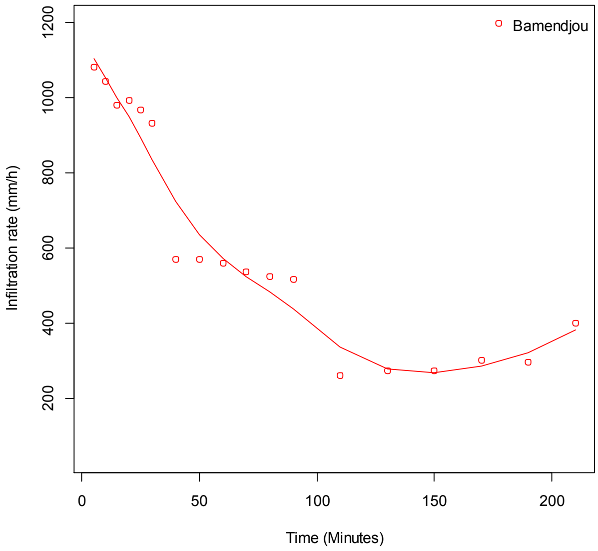


Figure 11: Infiltration curves showing average for the Bamendjou site

c) Root depth restriction

The estimated cluster-level frequencies of root depth restriction were estimated at 0.62% and 3.62% within the 0-20cm and 0-50cm depth, respectively (Table 5). The average soil depths were observed at 31cm for cultivated and 25cm for uncultivated lands (Figure 12). These average depths observed are unlikely to impede crop production, but there was substantial variation within plots that may be indicative of areas that have severe restrictions. In many cases, plots were found to have two to three sub-plots with no restrictions and then one or two that had only a few centimetres of soil. This was particularly apparent on the steepest slopes.

In general, the frequency of severe root depth restriction is highest in uncultivated lands implying that either the soil depth is too shallow and rocky and farmers do not farm them, they are simply of very low quality and not suitable for cultivation, or they are physically inaccessible due to slope or depression.

Table 5: Estimated cluster-level frequency of root depth restriction within 0-20 cm and 20-50 cm soil depth

	0 – 20 cm	20 – 50 cm
Cluster	%	
1	0	8
2	3	8
3	0	7
4	0	4
5	1	3
6	2	6
7	1	3
8	2	4
9	0	4
10	0	1
11	0	0
12	1	1
13	0	2
14	0	4
15	0	1
16	0	2
Average[1]	0.625	3.625

[1] **Estimated sentinel site average**

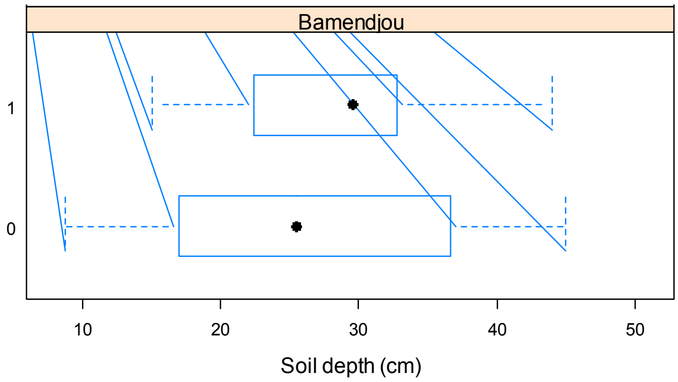


Figure 12: Estimated soil depth in cultivated (1) and uncultivated (0) lands

d) Inherent soil degradation risk

In the study, we considered high inherent soil degradation risk (HIDR) areas as those with physical degradation such as root-depth restriction at 0–50cm depth, abrupt textural gradients (e.g. sandy loam over clay), or areas with slopes greater than 30°. The analyses of the LDSF plots revealed that the entire site (100%) is under high inherent soil degradation risk (Table 6).

Table 6: Estimated cluster-level proportion of areas predicted to have high inherent soil degradation risk

Cluster	Bamendjou %
1	100
2	100
3	100
4	100
5	100
6	100
7	100
8	100
9	100
10	100
11	100
12	100
13	100
14	100
15	100
16	100
Average[1]	100

[1] **Estimated sentinel site average**

3.2.2 Soil chemical properties

Our analyses of chemical properties indicate that there are several properties that are of concern for soil management across the site. For a number of these parameters, there were significant differences in their values based on land use/cover, illustrating the need for specific interventions and development of management practices.

Descriptions below summarize the analysis of soil characteristics illustrating their distributions and differences across the land use (Table 7). These distributions are illustrated in the context of critical threshold values, which indicate potential constraints to production.

Table 7: Mean values of soil parameters in different land use

	cropland (78)	**grassland (2)**	**fallow (67)**	**grazing (9)**	**forest (3)**	**shrub land (1)**
Clay (%)	67.93	61.34	66.83	76.50	57.17	68.85
Silt (%)	20.88	28.22	22.55	14.77	36.01	19.05
Sand (%)	12.70	20.77	14.83	7.54	25.05	11.19
S.O.C (%)	3.79	4.48	3.90	1.63	5.79	3.58
N (%)	0.260	0.336	0.274	0.107	0.439	0.262
pH	5.905	6.191	5.903	5.559	6.181	5.818
P (mg kg^{-1})	5.385	8.036	5.707	2.753	9.721	4.451
Ca (mg kg^{-1})	7.753	17.494	8.819	2.353	24.349	5.231
K (mg kg^{-1})	0.399	0.685	0.446	0.242	0.934	0.397
Mg (mg kg^{-1})	3.652	5.500	3.929	1.467	8.386	6.205
Al (mg kg^{-1})	1420	1319	1421	1192	1393	1447
Mn (mg kg^{-1})	11.9	20.5	13.3	8.5	26.5	11.2
Zn (mg kg^{-1})	1.297	1.695	1.346	1.440	1.869	1.275

Total soil samples 160. SD, standard deviation; Q, quartile; S.O.C. Soil organic carbon (%).

a) Soil organic carbon (SOC)

We observed a wide range of values for SOC across the study site with significant differences in SOC concentration among land uses. The values ranged from 0.5% to 8.30%. A detail look at the SOC variation revealed that 16% of the plots had SOC values below the critical level of 2% (Figure 14). In general, we observed that the SOC concentration was higher in cultivated lands (Figure 15). This could be attributed to the high organic matter content in the land use. It could also be ascribed to the high densities of tree and shrubs in the cultivated lands. The lowest value observed in some plots can be attributed to the fact that they have not been receiving enough organic matter inputs to offset losses from leaching and decomposition.

The large variability of SOC concentrations within each of the land use suggests that there is potential to substantially increase the amount of SOC in the agricultural land that dominate the entire site. Even within croplands, the variability in SOC concentrations indicates that some of the agricultural practices may be contributing to the variations. Such practices include tillage, fertilization, removal of nutrients by plants, and the changes in soil/water balance. Some of the variability can be explained by the relationship that exists between soil carbon and clay content (Table 8).

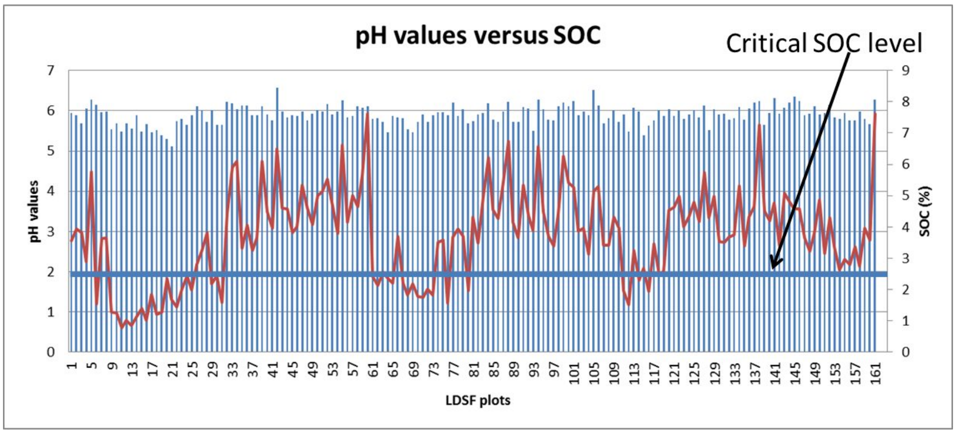


Figure 13: Soil organic carbon (SOC) and pH variation across the LDSF plots sampled

The results indicated that majority of the farms had SOC value above the critical thresholds (Figure 14). Below the 2% SOC critical level or 3.4 % SOM (van bemmelen factor 1.724) and irrespective of the types of the soils, we expect the deterioration of the quality of the soil (Kemper and Koch, 1966; Loveland and Webb, 2003; Pretty, 1998). The fact that very few plots have SOC below the critical level may be tricky, and one could be tempted to conclude that the threat of degradation is within the acceptable range. However, it is highly recommended that proper measures be taken to prevent further deterioration of SOM which improve soil structure, maintain tilth and minimize erosion (FAO, 2005). Soils with low SOM have low nutrient availability and poor water holding capacity and also exhibit poor responses to fertilizer application (Tittonell et al., 2005; Waswa et al., 2013).

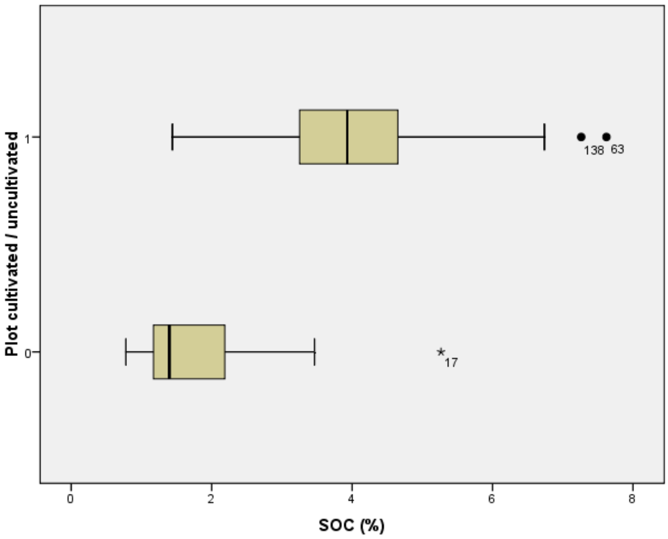


Figure 14: SOC concentration in cultivated (1) and uncultivated (0) plots

b) Total Nitrogen (N)

Nitrogen is another important key indicator for soil health. It is generally very critical for plant growth, but only available to plants in its mineral forms, either ammonium or nitrate. Total nitrogen (TN) does not necessary provide a direct correlation between the quantity of available nitrogen to plants, but does indicate the potential pool. We observed that the concentration of total N is very closely correlated to that of SOC (R2 = 0.98) (Table 8). We also observed that the distribution of total N across the land uses closely followed the same pattern as SOC.

Since TN and SOC are highly correlated, they seem to be all depleted through the same processes such as erosion, crop harvest and leaching. The recommendation for conserving total nitrogen are similar to that of SOC: increase the amount of organic materials that are incorporated in the soil, encouraging the adoption of agroforestry practices, and promoting indigenous soil improvement and conservation practices.

c) pH

At a glance, acidity was noted to be a major problem and the entire site was found to be dominated by acidic soils. About 20% of plots sampled recorded very strong acidic (pH 4.82-5.5) soils, while 62% of the plots recorded moderate acidic (pH 5.6-6.5) soils. Forested plots recorded the highest pH value of 6.56, and the value was found to decline for other land uses (Table 4). Normally at low soil pH values (< 5.5 units), strong soil acidity constrains the availability of most nutrient elements and there is a high risk of aluminium and magnesium toxicity. The high intensity of agricultural activities in the study site however, suggests that soil pH on average is unlikely to have a negative impact on plant growth and agricultural productivity. Most crops produced in the area such as maize, seem to be acid-tolerant.

3.2.3 Variation among chemical properties and their correlation

The variability observed among chemical properties might be due to spatial differences in soil forming processes as well as plot management practices at the time of sampling. Plots were randomly assigned within the clusters and cover both managed and natural vegetation, different land forms (level, sloping, steep and composite) and different positions in topographic sequence (upland, ridge/crest, mid-slope, foot-slope and bottom-land). The distribution and variability of soil properties are scale dependent. That is, the bigger the scale the higher the variability and vice versa (Seyfried and Wilcox, 1995; Momtaz et al., 2009; Waswa et al., 2013). However, the variability helps in understanding the state of the soil and provides valuable information for future activities in the area.

Table 8 shows the Spearman's correlation coefficients among soil parameters correlation coefficients of soil properties of the study site. Significant correlations ($\alpha < 0.01$) were observed among soil parameters. Significant positive correlation was observed between SOC and N, P and K, K and Ca, Mg and Ca, pH and P and between pH and Ca. Clay was negatively correlated with all the parameters considered in the study (Table 8).

Table 8: Pearson product moment correlations between soil properties of the LDSF plots samples for the 0–20 cm depth

Variables	Clay	Silt	Sand	SOC	N	PH	P	Ca	K	Mg	Al	Mn	Zn
Clay	1												
Silt	-0.935	1											
Sand	-0.758	0.884	1										
SOC	-0.725	0.626	0.309	1									
N	-0.774	0.696	0.402	0.989	1								
PH	-0.768	0.608	0.441	0.664	0.705	1							
P	-0.937	0.907	0.744	0.775	0.838	0.842	1						
Ca	-0.765	0.731	0.536	0.723	0.798	0.811	0.908	1					
K	-0.851	0.861	0.675	0.739	0.822	0.723	0.919	0.930	1				
Mg	-0.606	0.587	0.421	0.622	0.704	0.596	0.679	0.802	0.851	1			
Al	-0.255	0.117	0.081	0.492	0.449	0.230	0.239	0.122	0.110	0.127	1		
Mn	-0.839	0.855	0.653	0.655	0.733	0.667	0.870	0.882	0.967	0.793	-0.017	1	
Zn	-0.591	0.684	0.494	0.384	0.457	0.380	0.592	0.616	0.751	0.614	-0.492	0.822	1

4. Land constraints, identification of priority intervention areas and key recommendations

4.1 Summary of land constraints

The land constraints identified during the study are summarized below:

- Over 88% of the site (8,800ha) is under cultivation, meaning that nearly every hectare of the land including the steepest slopes has been used for agriculture.
- About 100% of lands with slopes of less than 10% (level) are cultivated and the rate of cultivation decreases as the slope increases to about 50% for slopes above 20%. Only 45% of the entire site is suitable for sustainable agricultural production with slopes of less than 10%.
- Visible signs of erosion are observed on only 5% of the site and all the LDSF farms sampled completely lacked soil and water conservation (SWC) structures.
- Trees and shrubs densities were on average 143-tree ha^{-1} and 192-shrub ha^{-1} respectively, and were higher in cultivated when compared to uncultivated lands. Farmers integrate trees and shrubs in the farming systems as a strategy for diversification and intensification of production.
- The herbaceous cover rate was estimated to be between 15–40% for cultivated and between 40–65% for uncultivated lands.
- Textural analysis of the samples indicated high clay content (75.64%). The soils in the study site are classified as clay soils.
- The estimated cluster-level frequencies of root depth restriction were 0.62% and 3.62% within the 0-20cm and 0-50cm depth, respectively.
- The values of SOC concentration vary among land uses and ranged from 0.5% to 8.30%. About 16% of the top soil samples and 28% of the sub-soil samples had SOC

values below the critical level of 2%. The concentration of total N was very closely correlated to that of SOC.

- The study area was dominated by acidic soils with pH ranging from 5.10 to 6.56 for top soil (0–20 cm) and from 4.82 to 6.30 for sub-soil (20–50 cm). About 20% of the plots sampled recorded very strong acidic (pH 4.82–5.5) soils, while 62% of the plots recorded moderate acidic (pH 5.6–6.0) soils.

4.2 Identification of priority intervention areas and key recommendations

Based on LDSF data collected during the study, land management strategies can be elaborated to address some of the soil constraints that have been observed for specific crop or land management practices. What are therefore, the most appropriate soil management options for a recommended cropping system given the site's elevation, slope, low erosion risks and soil constraints? It is recommended that areas of the study site with soil constraints be targeted for soil amendments to help ameliorate the constraints.

a) Fertilizer application

The entire study site including areas with low soil erosion risk is suitable for fertilizer application. The application rate will depend on the cropping system in place, the slope and the management of the plot. However, fertilizer should be used with caution and in combination with organic inputs, particularly on moderate to steep slopes. Production constraints for specific priority crop in the area should be made available and accessible so as to help the farmers and extension services determine the fertilizer application rates.

b) Integrated Soil Fertility Management (ISFM)

The entire study site is suitable for integrated soil fertility management (ISFM), a practice that will be able to address the problem of low SOC and nitrogen. ISFM includes a wide range of practices that enable the farmers to better ensure nutrient use efficiency and improve soil quality. In general, these practices are designed to increase soil organic matter and can be used in combination with targeted fertilizer or manure application. ISFM practices include: growing and incorporating or mulching with green manure, usually nitrogen fixing species, either in rotation, intercropping or as hedgerows.

Problems related to low pH, affecting the entire site, can be addressed through the application and incorporation of lime, compost and green manure. Compost and green manure will be more appropriate taking into consideration the low cost of the composting processes, the availability of vegetative materials and the high volume of waste generated by some households.

In addition, soil constraints for the site can be prioritized for intercropping of rain-fed annual crops. There are currently number of intercropping combinations already being practised in the area that includes combining maize, beans, cassava, sweet potatoes, macabo and yam. Intercropping is designed to reduce the risk of crop losses as a result of disease or pests, as well as to maximize soil resources. When this production strategy is practised in slopy areas, soil conservation practices should be employed.

On areas of the study site with moderate to steep slopes, low erosion risk with soil constraints, strategies can be prioritized for perennial production. It is recommended that these areas be planted with trees and shrubs that are either coppicing or planned to be harvested for a longer period of time (e.g. 10 years) to maintain soil and slope stability.

Permanent crops may include perennials such as cocoa, coffee, banana and a range of fruit trees such *Mangifera indica, Persea americana* and *Dacryodes edulis*.

4.3 Policy recommendation

- Promote extension services to improve farmers' knowledge on fertilizer application and nutrient management.
- Information on fertilizers distributed across the study site should not be only based on crop requirements, but should also take into consideration soil constraints.

5. **Conclusion**

The study evaluated various indicators of soil and site stability, hydrologic function and biotic integrity and noted that the presence and magnitude of these indicators varied across the landscape. The current preliminary assessment is not a comprehensive analysis of the availability of ecosystem services, but does provide data to develop integrative indicators that can be used for monitoring changes relative to a baseline. The assessment provides an effective set of tools for stakeholders in the study site to better understand and managed the landscape for ecosystem services and improves livelihoods. It also provides some basis for developing targets that aid in planning and management, as well as providing a solid visual and quantitative basis of land degradation assessment for decision-makers and land users in regard to designing and implementing programmes for rehabilitation and restoration.

Further analysis and interpretation of the data, particularly in an iterative process with stakeholder consultation, will help in providing more detailed information on land constraints and soil characteristics, as well as prioritize interventions. It is clear that changes in land management would better enable communities to maintain or rehabilitate the environment and basic ecosystem services, and improve agricultural productivity.

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