Land health surveillance in four agroecologies in Malawi

Tracy Beedy, Joyce Njoloma, Ermias Aynekulu, Richard Coe, Bertin Takoutsing, Keith Shepherd

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Abstract

Land health information across large areas is instrumental in understanding land degradation trends and patterns across the landscape, especially in those areas in Africa which support a growing population dependent on land-based resources. This study was carried out at four sites in Malawi, three containing important agricultural systems and one currently subject to great ecological disturbance. The Land Degradation Surveillance Framework was used to characterize land health and provide information needed to target areas at high risk for land degradation for management practices that provide increased soil cover and increased soil organic matter, so that these soils might become more resilient to environmental stresses. Among the four sites, the one in Ntchisi district (Visa) was the most heavily cultivated, followed by the sites in Kasungu (Kasu) and Salima (Sali) district. The site in Neno district (Mwan) was the least cultivated. The most prevalent HISD was root restriction at the 20-50cm depth, and was most prevalent at Mwan site. Kasu site contained the greatest cultivated area of soils with high inherent soil degradation risk (HISD). Soil analysis from Kasu site showed a deficit in soil organic carbon (SOC) in cultivated fine-textured soils, compared to semi-natural fine-textured soils, indicating nutrient mining from cultivation, and also indicating fallowing as a possible solution to the decline in soil fertility. The Mwan site contained the highest proportion of shrubs compared to trees, indicative of high current rates of wood harvesting from the landscape. These areas within these sites and surrounding districts should be targeted for education in soil protection practices appropriate to each farming system, and provision of incentives that bring these practices within reach of the farmers managing the landscape. As Malawi transitions from subsistence agriculture to production to meet the needs of growing urban and industrial populations, care must be taken to protect the health of the land for the benefit of both current and future populations.

Keywords

Land health, inherent soil degradation risk, LDSF, Malawi

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Acronyms

CGIAR	Consultative Group on International Agricultural Research
COP	Conference of the Parties
CRP	CGIAR Research Programme
FAO	Food and Agriculture Organization of the United Nations
GOM	Government of Malawi
HIDR	High Inherent Soil Degradation Risk
ICRAF	World Agroforestry Centre
Kasu	Site falling within Kasungu District, Malawi
LDSF	Land Degradation Surveillance Framework
Mwan	Site falling within Neno (formerly Mwanza) District, Malawi
Sali	Site falling within Salima District, Malawi
UNEP	United Nations Environment Programme
Visa	Site falling within Ntchisi (formerly Visanza) District, Malawi
WLE	Water, Land and Ecosystems

1. Introduction

Land health information across large areas is instrumental in understanding land degradation trends and patterns across the landscape. However, ecological processes in the landscape are difficult to observe in the field due to the complexity of ecosystems (Pellant et al., 2005), and the variability of land use. Of special concern are areas that can and will contribute to flows of ecosystem services improvement or degradation in the landscape (Chan et al., 2006). The information generated by monitoring systems are useful in understanding the extent of the problem, identifying and recommending to landscape planners and users appropriate measures to be taken, and evaluating effectiveness and efficiency of the measures for possible improvement; hence useful to decision makers at various levels (Chan et al., 2006).

In order to prevent land degradation, it is essential to first evaluate the current land degradation status and the underlying causes. So far, the main obstacle to achieving such evaluations has been the lack of a coherent and rigorous monitoring and surveillance framework that enables comparison of data across a wide range of environmental conditions and scales. This situation contrasts with that of the public health sector, where surveillance is the main source of information guiding decisions and actions in health policy and practice (Teutsch and Churchill, 2000). Land management problems definitely share many of the complex features of public health problems, especially those of non-communicable diseases and thus similar scientific approaches may be applicable. Therefore, principles of surveillance frameworks used in public health can equally be applied to landscape health surveillance in sustainable land management systems.

One such framework was developed by the World Agroforestry Centre (ICRAF) and is referred to as the Land Health Surveillance. Land health surveillance has been defined as an ongoing, systematic collection, analysis, and interpretation of data essential to the planning, implementation and evaluation of land management policy and practice, and application of these data to promote, protect, and restore land and ecosystem health (UNEP, 2012). Its concepts are put into operation and field implementation is achieved through the Land Degradation Surveillance Framework (LDSF) (Vagen et al., 2010). The LDSF is designed to provide a biophysical baseline for assessing land and vegetation 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 (Vagen et al., 2006; Kapalanga, 2008).

In addition, there is a high demand for improved land use/land cover data sets because of an increasing need to be able to precisely describe and classify land cover in order to develop sustainable land use systems. There is also a growing need for standardization and compatibility between data sets and for the possibility to map, evaluate and monitor wide areas (Di Gregorio, 1991; Reichert and Di Gregorio, 1995; Thompson, 1996; FAO, 1997). Technical advances, such as the vast amount of remote sensing data that has become available from earth observation satellites, makes this framework user friendly (Di Gregorio, 1995). Mapping and monitoring a sub-continent-wide area will facilitate identification of land health trends, and hotspots where land health is changing quickly. Including representative soil types and cropping systems at the national scale will facilitate linking large-scale land health trends with threats to environment and food security affecting policy at the national level.

In this study, four districts (Kasungu, Ntchisi, Salima and Neno) were chosen to represent four distinct soil type/cropping-practice combinations which are important food production and livelihoods systems in Malawi. Kasu site in Kasungu represents maize production in the central region of Malawi on the Central African Plateau, which is the breadbasket for Malawi. Sali site in Salima is part of the mixed maize/root crop system prevalent at low elevations along the south-west lakeshore. Visa site in Ntchisi represents mixed maize-groundnut-soybean production in the cooler high-elevation areas in the central and northern regions of the country. Mwan site in Neno lies in the southern region in a district known for environmental degradation as a result of charcoal production which is a major source of household energy for the southern cities of Blantyre and Zomba.

All these sites are subject to considerable alteration by the populations that depend on them for livelihoods, and many would benefit from landscape-level knowledge of land health and of land degradation processes that are active in the sites. Risks of land degradation are higher for soils with rooting depth restrictions and abrupt textural changes, and for landscapes that are cultivated, have steep slopes, and have sparse woody and vegetative cover. Areas with multiple risk factors will be in urgent need of intervention to improve surface cover and prevent further degradation. These areas can then be prioritized as interventions are planned.

Therefore the overall objective of the study was to assess current land health of the four study sites in Malawi. The objectives of the four targeted sites in this study were to conduct a baseline assessment of soil physical and vegetation characteristics and condition (health) at a landscape level; to identify where land health may be particularly at risk; and to characterize land health risk in the three sites representative of major soils and food production systems in Malawi, and one site that is currently undergoing rapid deforestation.

2. Methodology

2.1 Description of study sites

Vegetation type and biophysical characteristics

Among Africa's eco-regions, Malawi falls within the Miombo woodland region (Fig. 1), which are seasonally dry, deciduous, relatively open woodlands which support a fast-growing population depending primarily on subsistence farming (Williams et al., 2007).

Figure 1. White's (1983) map of African vegetation. Miombo woodlands are shown in dark green. (School of Geosciences, University of Edinburgh, used with permission)

Miombo woodlands in Malawi outside of national parks and reserves have been largely converted to smallholder farmland. Although the four sites are considerably diverse in their biotic potential and current land use, they all fall largely within the Wetter Zambezian Miombo Woodlands vegetation zone (Lillesø et al. 2011). Kasu, Sali, and Mwan lie entirely within this zone. Most of the Visa sites also lie within the same zone, except the southeastern corner which falls within the Undifferentiated Afromontain Forest zone. The vegetation density of the original Miombo woodland in these sites would have varied, given the differences in temperature and rainfall, with the Visa site expected to support the greatest vegetation density while the Mwan site the least (Table 1). Over the past several decades vegetation in Kasu, Sali, and Visa has been cleared for smallholder agriculture and fuel wood, and Mwan site has been mostly deforested for charcoal production, so current vegetation

structure reveals more about the external effects of human activity in as far as land management is concerned other than the original conditions.

Malawi can be divided into six major physiographic zones, the High-elevation Plateaux, the High-altitude Hills, the Central African Plateau, the Rift Valley Escarpment, the Lakeshore Plain, and the Shire Valley (Saka, 1995). The sites chosen for LDSF represent a cross-section of Malawi's agro-ecology. Kasu is on the Central African Plateau in the north of Kasungu district. Mwan is in the newly created district of Neno (formerly Mwanza) in the southern portion of the Rift Valley Escarpment in Malawi. Sali is on the lakeshore plain north of Salima, and Visa is at the north-western foot of the High Altitude Hills stretching south from Ntchisi district (Table 1). The latitude and longitude given in Table 1 are the centre points of the 10km by 10km study sites.

Table 1. Malawi's sentinel sites described in relation to their climatic and biophysical conditions

Site	Latitude/ Longitude†	Landform‡	Elevation† (m)	Mean Temp* (C)	Rainfall* (mm)
Kasu	12.8135 S 33.3464 E	Central African Plain	1000-1200	20.1-22.0	1000-1200
Mwan	15.5199 S 34.6864 E	Rift Valley Escarpment	300-750	24.5-26.4	1000-1200
Sali	13.6744 S 23.3011 E	Lakeshore Plain	500-650	23.1-24.4	1200-1400
Visa	13.2680 S 33.8008 E	High Altitude Hills	1100-1250	15.1-20.0	1200-1400

† LDSF ‡ Saka, 1995 *Nyabenge, 2010

Cropping practices

The majority of cropped area in Malawi is classified as sub-humid, having 600-1200 mm of precipitation annually and a four to six-months cropping season. The Kasu and Mwan sites both fall in under the dry sub-humid category with less than 1200 mm of annual precipitation (Table 1), but the high mean temperatures and the rolling, sometimes undulating mountainous topography at the Mwan site results in dry, rocky, thinly-wooded hills, with maize and citrus grown in low-lying areas with sufficient soil depth (Table 1). Because the Kasu site is on the Central African Plain, it is higher, cooler, and a prime agricultural area for Malawi. The Sali and Visa sites are located in the moist sub-humid zone near the western lakeshore. The high elevation and cool temperatures at the Visa site

allow for lush growth of maize, soybeans and groundnuts, while the combination of relatively high precipitation and high temperatures at the Sali site is better suited to the production of maize, cassava, and cotton.

Many of these smallholders are subsistence producers, and due to population densities and poverty, maize is continuously grown on the small fields with little or no opportunity to rotate crops or leave land fallow to recover nutrients. Some, however, are able to produce a surplus of maize, and engage in crop rotation and intercropping practices that help to maintain soil fertility (Table 2). Population density and poverty (from district data) are highest in the Sali and Visa sites. Population is lowest at the Neno site, and poverty is lowest at the Kasu site.

Table 2. Malawi's sentinel sites described in relation to the corresponding districts' population, poverty level and cropping systems

District and site	Population*	Population density* (km ²)	Poverty** (%)	Cropping practice
Kasungu-Kasu	616,085	78	30-40	Maize/tobacco/groundnut or soybean rotation or continuous maize
Neno-Mwan	94,476	41	40-60	Continuous maize, also citrus and melons
Ntchisi-Visa	224,098	135	50-60	Maize/soybean/groundnut rotation or continuous maize
Salima-Sali	340,327	155	50-60	Maize/cassava/cotton rotation or continuous maize

*GOM, 2009

**GOM, 2006

The four sentinel sites fall within the central and southern regions of Malawi. Three sites are in Central Malawi in a sub-humid mixed-maize farming region. The Kasu site is on the central African plain, while Sali and Visa sites are near the western shore of Lake Malawi (Fig 2). Maize is rotated with either groundnuts or soybeans and tobacco in Kasu for households producing a surplus, while subsistence farmers mainly produce maize (Table 2). The major rotation in Visa site is maize with soybean and groundnut, while the Sali site produces maize and cassava with some cotton. Mwanza site is located in southern Malawi in a region known for charcoal production with very limited crop production, most often meant for subsistence. Soils are rocky and unproductive on the hillsides, which are deforested for charcoal. Maize and citrus are produced in low-lying areas where soil depth is

adequate. Citrus production forms a major viable complementary economic activity to charcoal production.

Figure 2. Map of the four sentinel sites with a background map showing the mean annual rainfall for Malawi (Nyabenge, 2010)

Soil types

The soils in the four sites vary both within and among the sites. Soils at the Kasu site are classified as Lixisols, with Fluvisols at the Sali site, according to the Soil Atlas of Africa (Jones et al. 2013) which has represented the data from the Harmonized World Soil Database (FAO, 2009) in traditional map form for sub-Saharan Africa. The scale of the atlas was appropriate for these two sites, which were relatively homogenous, but the Mwan and Visa sites had more heterogeneous soil-types. The Mwan site lay at the boundary between Ferralsols and Lixisols in the atlas, but more detailed Malawian maps classified the area as mixed ferruginous and lithosols (Saka, 1995). The Visa site lay at the boundary between the typical Lixisols of the plain land and lithic Leptisols of the hills in the atlas. Most of the site lay below the lithic hillsides, but receives much runoff/erosion from the hills. Saka (1995) classified the area as having calcimorphic alluvial soils. Thus the site may contain inclusions from Fluvisols, Lixisols, and Leptisols. Lixisols and Ferralsols correspond to Alfisols and Oxisols in Soil Taxonomy, and Fluvisols may correspond to Fluvents, and while Leptisols may correspond to soils with lithic sub-groups (USDA/NRCS 1999).

2.2 Sampling framework

The Framework that was used in the study to measure and monitor land health indicators is based on the scientific principles described in the public health surveillance (UNEP, 2012). The Land Degradation Surveillance Framework (LDSF), which is employed in the field implementation of land health surveillance, was used to characterize the study areas (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 sites.

In the study, four sentinel sites of 100km² each (10km × 10km) were established: Kasu, Mwan, Sali, and Visa. The sites were surveyed to capture ecosystem health indicators and various land use patterns prevalent in the study area. The districts containing these four sites were purposefully chosen to give a cross-section of agroecologies, soils, and cropping systems. The study sites were randomized within each district.

Each of the sentinel sites was further subdivided into 16 tiles in a four by four arrangement (Fig. 3). Each tile was 2.5km × 2.5km in size and contained a randomly allocated cluster of 10 plots. Each plot covered an area of 1000m². Thus, for each sentinel site, 160 stratified random sampling plots were established.

Figure 3. Each sentinel site is a 10×10 km square divided into a grid composed of 16 clusters. Each cluster is located randomly within the individual grid square, and contains ten randomly selected sampling plots.

Within each of the 160 plots, four sub-plots of 100 m^2 each were established, one in the centre of the plot and the three others surrounding the centre plot, disposed at 120 degrees (Fig. 4). Each plot comprised an area of 0.1 ha and each sub-plot an area of 0.01 ha with its centre 12.2 m away from the plot's centre. This form of stratified cluster sampling allows the assessment of variability of soil properties at different spatial scales (sub-plot, plot, cluster, site, between sites) by applying hierarchical statistical models incorporating random effects that represent different groups, including spatial nested scales (Raudenbush and Bryk, 2002). Assessing and understanding spatial variability is essential for developing accurate predictive models and understanding landscape dynamics in ecoregions (Vagen et al., 2013).

Figure 4. Each 1000 m^2 plot contained four 100 m^2 sub-plots.

2.3 Field data collection

Observations were taken from each of the 160 plots per site. Basic characteristics of the entire plot were observed and recorded: landscape position, major landform, slope, current land management practices, land management history, evidence of flooding, existence of soil conservation practices, information about the type and structure of vegetation present and the primary impact to the site were evaluated. 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). At the sub-plot level another suite of observations were made, the severity and typology of soil erosion (sheet, rill and

gully) were recorded. Vegetation as well as percentage of woody, herbaceous and rock cover was estimated at the sub-plot level as: absent; <4; 4–15; 15–40; 40–65 and >65%.

All trees (height > 3 m) and shrubs ($1.5 < \text{shrub} < 3\text{m}$) within each sub-plot were counted to obtain density and bio-volume estimates. Prevalence and typology of soil erosion (sheet, rill and gully) were recorded for each sub-plot, while root depth restrictions were recorded by measuring the depth (in cm) from the soil surface to the depth where the auger could not penetrate the soil. The presence of root depth restriction was assessed in the upper 50cm of the soil profile within each sub-plot by scoring the occurrence from 0 (none) to 4 (all sub-plots had restriction). Soil samples were taken from 0-20 cm and 20-50 cm depths from each sub-plot, and the texture of each depth estimated manually. The soil sample depths were then consolidated from the four sub-plots, mixed well and sub-sampled. The soils were analysed for total carbon and nitrogen using infrared spectrometry (Shepherd and Walsh, 2007).

3. Results and discussions

3.1 Vegetation health and land use

Ecological characterization of sites

Forest and vegetation land cover has been observed to decline over time mostly due to agricultural activities and energy for cooking as well as curing tobacco among the other household uses. Malawi's economy is generally described as agricultural-based; a concept that has conditioned land use patterns across the country. Land use is driven by the need to produce adequate quantities of food crops to satisfy food security needs while ensuring surplus production for cash generation. About 60% of the landscape is dominated by crop mixtures involving maize, legumes and root and tuber crops while the rest of the land is covered by forests, hills and water bodies. Most of the land area deemed adequate for agricultural production is currently in production (Saka et al., 1995), and the population density continues to increase. The majority of Malawians engage in smallholder farming, and are dependent on the productive capacity of the soil for their livelihoods. It is important to generate more precise knowledge of the land and the risk of degradation to encourage targeted land conservation, preserve land health, and safeguard the well-being of those dependent on it into the future.

Higher population densities were evident in Sali and Visa sites than in the Kasu and Mwan sites. Compared to the 1980s, the population of Malawi has increased three-fold. With the current population of about 15 million, Malawi has a considerable population density, especially in some parts of the central and southern regions. The increased densities have undoubtedly resulted in the need for more land to be opened for agriculture and food production, disappearance of forest cover due to increased demand for fuelwood and charcoal, and increasing erosion of soil from unprotected soil. The liberalization of burley tobacco production in the 1990s resulted in wanton clearing of land by smallholder farmers for tobacco production and elimination of shrubs for barn construction and leaf curing needs in the Kasu site. This has exerted pressure on land cover and vegetation thereby leading to an increased risk of nutrient mining and soil erosion. Efforts on reforestation has not yielded much vegetation cover such that most land is still left bare and exposed to the effects of erosion.

Cultivation

The proportion of cultivated plots (Fig. 5) generally follows the population density in the districts (Table 2) though cultivation in Kasu exceeds the population trend. The disproportionate trend of area under cultivation and population in the Kasu site could be explained by the dominance of estate farming where large tracts of land are involved in production of either tobacco, groundnuts or soybean. A combination of favourable soils, mainly Lixisols, with moderate temperature and precipitation has made the Kasu site a centre of attraction for many Malawians who are interested in estate farming. This has resulted in more farmland cultivated by non-residents than in the other sites. The plain-lands of the Visa site are heavily cultivated, while the rocky and shallow soils predominant in the Mwan site have greatly restricted land use to forests and shrubs growth. Proportionately, the Sali and Kasu sites have experienced a similar degree of exposure to cultivation.

Figure 5. Percentage of sub-plots cultivated in each cluster in the four sites in Malawi.

On average, three-quarters (76%) of Visa site was cultivated, while more than half of Kasu (58%) and Sali (58%) were cultivated and only 18% of Mwan was cultivated. Four of the clusters within the Mwan site were not sampled, as the terrain was too mountainous and rocky for the safety of the team. The Kasu, Sali and Visa sites had generally mild slopes which ranged from 0 to slightly below 6%

(Table 3) while slopes of over 6% were not evident. It is worth noting that the three sites largely fall on the plain-lands of the central region which constitute the bread basket of the country characterized by diverse cultivation practices. The growing need to increase food production has resulted in encroachment of both forest and sloping areas otherwise not suited for cultivation without appropriate land use planning, thereby increasing risk of soil erosion. Slopes measured in Mwan site ranged up to 10%, however, greater slopes would be expected in the four sites not characterized due to mountainous terrain.

Table 3. Estimated means by cluster of slope within each site

Cluster	Kasu	Mwan	Sali	Visa
	(degrees)			
1	1.4 ¹	2.4 ²	0.8 ⁴	0.9 ⁵
2	2.2	ND ³	2.5	0.7
3	1.6	3.7	1.9	1.1
4	2.0	2.6	3.1	0.9
5	1.3	2.1	0.7	2.2
6	1.6	ND	0.9	0.9
7	1.2	5.5	1.4	0.9
8	1.7	3.4	1.6	1.1
9	1.5	0.4	1.5	1.9
10	1.4	4.0	1.8	1.3
11	1.0	3.8	0.9	2.5
12	1.7	3.8	0.9	1.7
13	1.0	1.0	1.1	1.9
14	1.2	1.8	0.9	1.8
15	1.5	ND	1.5	1.6
16	1.4	ND	1.1	0.7
Average ²	1.48	2.87	1.41	1.38

¹ Range of SE: 0.07-0.38 ² Range of SE: 0.11-0.84 ³ No Data ⁴ Range of SE: 0.07-0.61 ⁵ Range of SE: 0.20-0.43

As the slopes measured for the four sites fall below 16%, all fall within the first FAO slope class, or 'level' slopes. However, based on observation Mwan site may contain some areas that would fall into the moderate class with 16-30% slopes, especially from the hilly and rocky site clusters that were not sampled. In Kasu site, slopes were similar in cultivated and semi-natural plots, most falling under 2.5%. Slopes were slightly more variable in cultivated plots. In Sali site, slopes were greater in semi-natural plots while slopes clustered near 1% in cultivated plots. Slopes in Mwan site were similar in cultivated and semi-natural plots, with mean slopes near 3% and greater variability than in the other sites. Mean slopes in Visa were also similar in cultivated and semi-natural sites, with mean slopes slightly higher in cultivated plots.

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. Loamy soils may have sufficient clay content to hold the particles together, while the sandy soils have high permeability that limit the amount of surface runoff that can wash soil particles away. Their larger particle size makes them too heavy to be easily entrained (transported) in flowing water. Loamy soils on the other hand, exhibit the less 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. Mkanda (2000) estimated that soil loss in six districts in Malawi ranged from 13-29 t ha⁻¹ yr⁻¹. However, as the agricultural areas are largely level, much of this sediment is moved slowly across the landscape, and the average rate of sediment deposition into Lake Malawi has been reported to be nearly 12 t ha⁻¹ yr⁻¹ (Mkanda, 2000).

Herbaceous and woody cover

Originally, the four sentinel sites should have been covered by open, dry forest and shrubs typical of Miombo woodlands. However, the density of the forests varied based on the differences in rainfall and temperature patterns (Table 1). Over the years most of this vegetation has been removed and replaced by various land uses dominated by agricultural production. However, manual cultivation practices have allowed some shrub and tree growth within cultivated sites. Some valuable shrubs and trees that naturally regenerate are managed by smallholders, especially those used for fruit production, soil fertility maintenance, dry season forage and medicinal purposes.

Shrub density was found to be highest at the Mwan site, seconded by Kasu while both Visa and Sali recorded lesser densities (Table 4). High shrub densities at the two sites may result from the divergent land use patterns prevalent in the sites. Mwan is characterized by rocky soils with a high frequency of root restriction within 20-50cm, which has over the years discouraged cultivation thereby promoting shrub growth. Unlike in Mwan, the need for stakes for tobacco curing on most of the farmlands in Kasu has resulted in extensive reforestation using agroforestry species. This has resulted in regenerative forestry in most of the clusters.

Table 4. Estimated shrub density (shrubs ha⁻¹) within each site

Cluster	Kasu	Mwan	Sali	Visa
Shrubs ha ⁻¹				
1	620	1073	118	470
2	250	ND ¹	183	93
3	340	133	310	253
4	223	1395	828	50
5	473	855	65	55
6	263	ND	33	115
7	813	1333	100	530
8	380	1418	388	333
9	1040	963	138	230
10	1108	1310	178	153
11	693	823	83	160
12	173	875	395	400
13	1520	533	263	175
14	388	680	115	245
15	818	ND	150	70
16	288	ND	623	695
Average ²	281 587 ⁸¹⁴	847 1032 ¹³¹⁶	111 248 ³²⁹	109 252 ³⁴⁹

¹ No Data ² Estimated sentinel site average, with estimated sentinel site quartiles

Tree density followed the same general pattern as shrub density, with the highest densities found in Mwan site, a lower density in Kasu, and similar densities in Sali and Visa (Table 5). The same land management issues influencing shrub densities similarly affected tree densities. Since many trees are coppiced for use as building material for tobacco drying sheds in Kasu, a high shrubs/tree ratio of about 5 to 1 was determined. The ratio is almost 10 to 1 in Mwan site, probably due to tree clearing for the charcoal trade. The average of 5 to 1 ratio holds for Sali and Visa. Species of trees in these plots are mixed, except at Sali site, where there is a preponderance of mango (*Mangifera indica*) for fruit, and *Faidherbia albida* locally known as ‘msangu’ for soil improvement and animal fodder.

Table 5. Estimated tree density (trees ha⁻¹) within each site

Cluster	Kasu	Mwan	Sali	Visa
Trees ha ⁻¹				
1	110	263	63	8
2	95	ND	43	13
3	103	118	135	40
4	40	13	253	40
5	143	293	13	13
6	38	ND	35	30
7	38	18	40	43
8	63	78	93	75
9	130	110	3	113
10	135	78	28	43
11	40	265	20	168
12	25	288	28	80
13	293	95	18	63
14	28	135	30	85
15	118	ND	30	18
16	13	ND	28	203
Average ²	₃₈ 88 ¹²¹	₇₈ 145 ²⁶³	₂₄ 53 ⁴⁸	₂₇ 64 ⁸¹

¹ No Data ² Estimated sentinel site average, with estimated sentinel site quartiles

Herbaceous cover for Kasu ranged from 4% to 65% with most sentinel sites having about 4-15% (Table 6). On the other hand, for Sali and Visa the results showed that most of the sentinel sites had >65% herbaceous cover. Herbaceous cover in Mwan was intermediate between Kasu on one hand, and Sali and Visa on the lower end. Some of the disparity in herbaceous cover may be explained by sampling periods, which fell during the dry season for Kasu and Mwan and during the rainy season for Sali and Visa. Many cultivated areas of Kasu were clean-tilled in anticipation of planting, while cultivated fields in Sali and Visa sites contained lush crops of maize, soyabean, groundnut, and cotton.

Table 6. Estimated proportions of five ratings of herbaceous and woody cover at the four sites.

Ratings: 0=none, 1= <4%, 2=4-15%, 3=15-40%, 4=40-65%, 5=>65%

Rating	Kasu	Mwan	Sali	Visa
%				
Herbaceous Cover Rating				
0	18	0	0	1
1	22	4	1	0
2	51	14	7	0
3	8	17	6	1
4	1	18	15	6
5	0	47	71	92
Woody Cover Rating				
0	42	6	50	51
1	22	9	28	28
2	25	58	21	18
3	9	24	1	2
4	2	2	0	0
5	0	1	0	1
Dense Woody Cover (3 or greater)				
	11	27	1	3

Woody cover ratings indicate that very few sites had woody cover of >65% and that in most sentinel sites there was no woody cover (Table 6). Most the sites are under cultivation of agricultural crops which would explain the lack of woody cover. Thus, dense woody cover is less on heavily cultivated farmland, but higher than expected at Mwanza, which was much less cultivated.

Figure 6. Percentage of sub-plots with woody cover rating of 3 or greater. Ratings: 0=none, 1= <4%, 2=4-15%, 3=15-40%, 4=40-65%, 5=>65%

In Kasu site, 89% of the sub-plots had a woody cover rating of less than 3 (Table 6). The highest proportions of woody cover were concentrated in the central and southeast areas (Fig. 6). In Mwan site, a quarter of the clusters had greater than 30% of plots with woody cover rating of 3 or greater. As cultivation was concentrated in the three northeastern clusters in Mwan, the low proportion of woody cover in the remaining clusters should have been due to natural low densities attributable to relatively low rainfall and high temperatures, and also due to cutting of larger trees for the charcoal trade. Sali and Visa sites have virtually all plots with woody cover rating of less than 3. Kasu and Sali woody cover ratings indicate that very few plots had woody cover of >65% and that in most sentinel sites there was no woody cover (Table 6). Most of these are under cultivation of agricultural crops which should explain the lack of woody cover. Thus, dense woody cover is less on heavily cultivated farmland, but higher than expected at Mwanza, which was much less cultivated. Smallholders at Kasu site maintain relatively more woody cover at a given proportion of cultivation. The parkland agroforestry system at Sali site maintains widely spaced trees over a highly cultivated land surface and the lowest tree and shrub density of the four sites (Tables 4, 5, 6).

4 60%	8 30%	12 70%	16 78%
3 35%	7 58%	11 40%	15 28%
2 53%	6 48%	10 25%	14 55%
1 35%	5 30%	9 10%	13 13%
KASU			
4 10%	8 15%	12 8%	16 ND
3 5%	7 8%	11 0%	15 ND
2 ND	6 ND	10 5%	14 10%
1 3%	5 0%	9 5%	13 5%
MWAN			
8 18%	12 60%	16 30%	20 30%
7 38%	11 48%	15 73%	19 63%
6 58%	10 55%	14 55%	18 58%
5 55%	9 70%	13 58%	17 38%
SALI			
8 43%	12 45%	16 63%	20 40%
7 45%	11 33%	15 35%	19 65%
6 68%	10 48%	14 58%	18 45%
5 40%	9 78%	13 50%	17 43%
VISA			

Figure 7. Percentage of sub-plots with woody cover rating of 0. Ratings: 0=none, 1=<4%, 2=4-15%, 3=15-40%, 4=40-65%, 5=>65%

The proportion of sub-plots with no woody cover was 42% for Kasu site, 6% for Mwan, 50% for Sali and 51% for Visa. These proportions follow roughly the cultivation patterns (Fig. 7) in Fig 5.

However, Kasu clusters 3 and 8, Sali clusters 1 and 6, and Visa clusters 4, 6, 10, and 14 combine relatively high proportions of cultivation and moderate to low proportions of sub-plots bare of woody cover. When devising interventions for high-risk areas at each site, these clusters may yield locally acceptable methods of increasing woody cover.

Figure 8. Distribution of woody cover ratings with associated slopes in (a) Kasu site and (b) Mwan site. Ratings: 0=none, 1=<4%, 2=4-15%, 3=15-40%, 4=40-65%, 5=>65%

Woody cover was associated with lesser slopes in Kasu site, than in Sali and Visa sites, consistent with the greater need for accessible wood for tobacco drying sheds (Figs 8, 9). The range of slopes

under woody cover increased from Kasu to Sali to Visa to Mwan sites. Dense woody cover (Table 6) was most common in Mwan site. All densities of woody cover were distributed across a greater range slopes in Mwan site than in the other three, and associated with a much lower general level of cultivation (Fig. 5).

Figure 9. Distribution of woody cover ratings with associated slopes in (a) Sali site and (b) Visa site. Ratings: 0=none, 1=<4%, 2=4-15%, 3=15-40%, 4=40-65%, 5=>65%

All the sites were characterized by extensive human management. More than 50% of plots in Kasu, Sali, and Visa sites were cultivated, and many trees from the uncultivated portion of Mwan had been

cleared for charcoal production. Herbaceous cover ratings in Kasu were quite low during the dry season, and were quite high in Visa and Sali during the cropping season, suggesting a cropping cycle that leaves soil surfaces vulnerable during the beginning of the rainy season in cultivated plots. Thus, soil exposure to erosion because of cultivation should be greatest within Visa site, intermediate in Kasu and Sali, and least in Mwan. In addition, Mwan site has a higher overall woody cover rating, which lessens soil exposure. However, most of Mwan site is considered only useful for wood production, as the soils are rocky. Kasu site has intermediate woody cover ratings, while woody cover in Visa and Sali sites is very sparse.

3.2 Soil health

Root depth restrictions

In three of the four Malawi sentinel sites no root depth restriction was recorded in the 0-20cm depth (Table 7). About one-third of the clusters in Mwan site showed root restriction of up to 5%. On the contrary, in the 20-50 cm depth, root depth restriction was determined in 37% of the Kasu sites ranging from 2.5% to 12.5%. In Mwan, 75% of the sites had root restriction ranging from 2.5% to 37.5%. Whereas in Sali, root restriction was determined in two clusters only, no root restriction was determined in Visa sites (Table 8).

Table 7. Estimated cluster-level proportion of root depth restriction within 0-20 cm soil depth

Cluster	Kasu	Mwan	Sali	Visa
	%			
1	0	5	0	0
2	0	ND ¹	0	0
3	0	0	0	0
4	0	5	0	0
5	0	2.5	0	0
6	0	ND	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	5	0	0
15	0	ND	0	0
16	0	ND	0	0
Average ²	0	1.5	0	0

¹ No Data ² Estimated cluster average

Thus there is increased risk of erosion due to restricted plant growth and lack of rainfall infiltration in 2.5% of one cluster and 5% of three clusters. However, less grave risk of root depth restriction below 20cm depth averaged 14% in Mwan, with much lower averages in Kasu, and were virtually non-existent in Sali and Visa sites.

Table 8. Estimated cluster-level proportion of root depth restriction within 20-50 cm soil depth

Cluster	Kasu	Mwan	Sali	Visa
%				
1	0	32.5	0	0
2	12.5	ND ¹	2.5	0
3	0	0	2.5	0
4	5	0	0	0
5	0	27.5	0	0
6	7.5	ND	0	0
7	7.5	27.5	0	0
8	0	37.5	0	0
9	0	0	0	0
10	0	7.5	0	0
11	0	25	0	0
12	2.5	2.5	0	0
13	0	2.5	0	0
14	0	10	0	0
15	2.5	ND	0	0
16	0	ND	0	0
Average ²	2.3	14.4	0.3	0

¹ No Data ² Estimated cluster average

Root depth restrictions at greater than 20 cm were found in 14% of plots at Mwan sites, at slopes ranging from one to seven degrees and averaging four degrees. These pose some increased risk of soil erosion if rainfall events saturate the soil overlying the depth restriction, and if the soil is of medium texture, and easily eroded. Root restrictions were found in 2.3% of plots in Kasu site, were rare at Sali site and non-existent at Visa site.

Infiltration

Figure 10. Infiltration rates (mm hr⁻¹) over 2.5 hours in the four sites

Infiltration rates in Mwan and Kasu site were markedly higher than those in Sali and Visa sites (Fig. 10). The differences can largely be explained by differences in soil texture at the four sites (Table 9). Coarser soil texture at the Mwan and Kasu sites was associated with greater infiltration rates, while medium to heavy textures at the Sali and Visa sites were associated with slower infiltration. In the course of manually measuring textural classes, gravel and rock fragments were removed. Gravel and rock fragments were common in the Mwan site, and may have resulted in higher infiltration than in the Kasu site.

Table 9. Distribution of textural classes at the 0-20 cm depth in the four sites

Ribbon Length	Textural Classes	Kasu	Mwan	Sali	Visa
		%			
Bare	Sand	32	0	2	13
< 25 mm	Loamy sand, Sandy loam	37	63	9	14
25-50 mm	Loam, Clay loam	29	36	65	65
> 50 mm	Clay loam, Clay	2	1	24	8

Infiltration is also affected by development of soil structure, which typically increases macropore occurrence in the soil as clay and organic matter content increase. These macropores allow the higher rates of infiltration initially observed in Sali and Visa sites, decreasing gradually as the soil aggregates absorb water and swell, gradually closing many of the macropores. Macropores can also be left by

decomposing plant roots, and tunnelling by worms and other soil fauna. Large macropores may allow exceptional rates of infiltration. However, the influence of macropores on infiltration is often less than that of soil texture.

Infiltration was measured two to three times per cluster, from 32, 25, 37 and 38 plots in Kasu, Mwan, Sali and Visa, respectively. Infiltration rates were averaged over the 150-minute measurement periods, and the averages subjected to a mixed model analysis of variance (Littell, 2006). This indicated that soil textural class and cultivation were the two most important factors in explaining the differences in average infiltration rates, followed by surveillance site, cluster and root depth restriction in the 20-50 cm depth.

Figure 11. Averaged infiltration rates in cultivated and semi-natural soils. (Kasu=red, Sali=aqua, Mwan=green, Visa=pink)

Cultivated soils were more common in Kasu, Visa and Sali sites, whereas semi-natural soils were more common in Mwan (Fig. 11). Cultivated soils typically had average infiltration rates of less than 600mm per hour, while semi-natural soils had a wider range of infiltration rates. This is consistent with the results of Lal (1975), who found lower infiltration rates under tillage in maize cropping systems in western Nigeria. Increasing slopes should also decrease infiltration, but are not included here as our infiltration method prevents water from moving downslope.

Abrupt textural changes

Soils with a sandy surface texture underlain by clay soil horizons have the least resistance to erosion. These soils with abrupt textural changes support high infiltration in the surface horizon, which does

not penetrate the deeper clay horizons well, and with little vegetation and long or steep slopes can result in high erosion rates.

Table 10. Estimated area with abrupt soil textural change in the upper 50 cm of the soil profile.

Cluster	Kasu	Mwan	Sali	Visa
			%	
1	0	0	0	0
2	0	ND ¹	0	2.5
3	0	0	2.5	0
4	0	0	0	0
5	0	0	0	0
6	0	ND	0	0
7	0	0	0	0
8	0	0	0	2.5
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	2.5
13	0	0	0	0
14	0	0	0	10
15	2.5	ND	0	0
16	0	ND	5	0
Average	0.15	0	0.47	1.1

¹ No data

Among the four sites, Mwan had no soils with abrupt textural changes (Table 10), and generally had coarse soil textures, allowing for fairly high infiltration rates throughout the soil profile. This would offset, to some extent, the erosion risk from higher slopes in the site (Table 3). In Kasu site, only one cluster had abrupt textural changes, and in only 2.5% of plots, and much lower slopes than Mwan site (Tables 3 and 10). Soils with abrupt textural changes were also found in a few locations in Sali and Visa sites. However, slopes on cultivated Sali soils were almost 1% while slopes on both cultivated and uncultivated Visa soils were almost double those in Sali. Cultivation on slopes combined with abrupt textural changes in clusters 2, 8, 12 and 14 sets the stage for higher soil loss in Visa site than in Sali or Kasu.

3.3 Priority intervention areas

The greatest proportion of risk factors is found in Mwan site (Table 11), and the most prevalent risk factor is rooting depth restriction between 20cm and 50 cm soil depth. The Mwan site also contained

rooting depth restrictions between 0cm and 20cm depth in up to 5% of plots in four clusters. Mwan site is the least cultivated, as is appropriate, given the prevalence of risk factors for soil degradation.

Table 11. Estimated percentage of plots with high inherent soil degradation risk

Cluster	Kasu	Mwan	Sali	Visa
			%	
1	0 ¹	5.0, 32.5 ²	0	0
2	12.5	ND ³	2.5	2.5
3	0	5.0	2.5, 2.5	0
4	5	0	0	0
5	0	2.5, 27.5	0	0
6	7.5	ND	0	0
7	7.5	27.5	0	0
8	0	37.5	0	2.5
9	0	0	0	0
10	0	7.5	0	0
11	0	25.0	0	0
12	2.5,	2.5	0	2.5
13	0	2.5	0	0
14	0	5.0, 10.0	0	10.0
15	2.5, 2.5	ND	0	0
16	0	ND	5.0	0
Average	2.34, 0.16	1.46, 14.38	0.31, 0.47	1.1

¹ None of the clusters in any site had slopes greater than or equal to 30 degrees ²Root depth restriction from 0-20 cm are in red, root depth restriction from 20-50 cm in green, and abrupt textural changes in blue. None of the sampled plots contained more than one risk factor. ³No data

Kasu site has no rooting depth restrictions at less than 20cm depth, and a low incidence of rooting depth restrictions in the 20-50cm depth, with one occurrence of an abrupt textural change in the soil profile. Sali and Visa have yet lower occurrence of risk factors, with few occurrences of rooting depth restrictions and abrupt soil textural changes. Slopes greater than 30 degrees were not recorded in any site. However, the four un-sampled clusters in Mwan site may contain some of these.

Management options and interventions should be different in cultivated and semi-natural areas, so these are described separately. Many semi-natural areas in Kasu, Sali and Visa sites and in the cropped clusters of Mwan site are formerly cropped areas currently in grass fallow. These are often used as communal grazing and fuel-wood collection areas. Most of the trees in these areas appear to be naturally regenerated. The estimated priority area for reforestation is much higher in Mwan site (Table 12) because it is much less heavily cropped and demonstrates more soils with high inherent risks than the other sites (Fig. 5, Table 11). Mwan site contains almost 600 ha of priority area, compared to roughly one-tenth that amount in Kasu and Sali sites, and none in Visa site. The clusters

listed below should be prioritized, due to higher risk factors, however training and incentives should be provided to farmers to encourage adoption of these practices. In Kasu, the maximum tree density in any sub-plot of cluster two was 300 trees ha⁻¹, which may serve as a target density for that cluster. In clusters 12 and 15 the target would be 400 trees ha⁻¹ and 600 trees ha⁻¹. In Mwan site, target tree densities would be 1800, 700, 2000, 600, and 700 for clusters 5, 8, 11, 13 and 14, respectively. In Sali site, the tree densities targeted would have been 200 in cluster 2 and 100 in cluster 3. Preferences for tree species, and the extent that farmer-managed natural regeneration should play would vary greatly among the four sites.

Table 12. Priority reforestation intervention areas for each cluster (625 ha)

Cluster	Kasu	Mwan	Sali	Visa
Area (ha)				
1	0	0	0	0
2	31	ND ¹	16	0
3	0	0	31	0
4	0	0	0	0
5	0	188	0	0
6	0	ND	0	0
7	0	0	0	0
8	0	125	0	0
9	0	0	0	0
10	0	0	0	0
11	0	156	0	0
12	16	0	0	0
13	0	16	0	0
14	0	94	0	0
15	16	ND	0	0
16	0	ND	0	0
Total	63	579	47	0

¹ No data

One of the most urgent interventions needed for Mwan site is to reduce the prevalence of harvesting naturally-regenerating woody species for the charcoal trade and encourage the management of natural regeneration, both on farm and other landscapes. Over the years this has resulted in siltation in the Shire River and debris accumulation at the power generating turbines consequently leading to frequent power outages. Malawi's National Environmental Action Plans in 1992 and 2011 have provided planning for reducing such land degradation (GOM, 2011). However it has not been possible to fully implement these programs, and the charcoal industry has grown to harvest 6,000 ha yr⁻¹, from land with customary tenure, such as the Mwan site. These areas in Neno district are transitioning from dry Miombo woodland to savannah grasslands (Kambewa et al., 2007) Programs to improve the

efficiency of current charcoal use and to provide opportunity and incentives for adoption of alternative cooking fuels other than charcoal in the poorer sections of the two cities are also needed. In Kasu and Sali sites, fuel-wood is harvested for local use, and the quantities used are much less. However, of late observations show increasing charcoal outlets in some parts of Salima feeding into the Lilongwe city.

Table 13. Estimated means of soil organic carbon, nitrogen, sand fraction, and pH by cluster in Kasu soils at 0-20cm depth

Cluster	Soil Organic Carbon (%)	Nitrogen (%)	Sand Fraction (%)	pH
1	0.81, 0.10 ¹	0.054, 0.0049 ¹	49.8 ²	6.2 ³
2	1.57, 0.28	0.097, 0.0129	20.9	6.2
3	0.51, 0.04	0.040, 0.0025	61.9	6.2
4	0.99, 0.23	0.063, 0.0111	50.1	6.3
5	0.84, 0.11	0.056, 0.0055	46.8	6.1
6	0.95, 0.13	0.063, 0.0067	42.1	6.1
7	0.87, 0.21	0.058, 0.0097	42.6	5.9
8	0.47, 0.06	0.036, 0.0034	59.3	6.2
9	0.39, 0.07	0.032, 0.0041	68.7	6.4
10	0.54, 0.06	0.041, 0.0037	54.4	6.1
11	0.44, 0.07	0.035, 0.0040	55.8	6.1
12	0.41, 0.07	0.033, 0.0037	68.2	6.2
13	0.39, 0.04	0.032, 0.0025	60.8	6.2
14	0.96, 0.21	0.062, 0.0102	45.9	6.1
15	0.81, 0.12	0.056, 0.0063	42.5	6.1
16	0.58, 0.08	0.041, 0.0041	55.4	6.1

¹ Mean (%), SE

² SE range: 2.4 to 5.9

³ SE range: 0.021 to 0.066

Lixisols, which are most prevalent in Kasungu district (FAO, 2009), commonly have a relatively coarse surface texture, underlain by finer-textured sub-soils. The soils in the Kasu site demonstrate this coarse texture, with a mean sand content above 50% in over half of the clusters (Table 13). Sandy soils hold less carbon than clay soils, as the organic matter is more exposed to decomposition by soil organisms. These results are consistent, with cluster 2 having the lowest sand content, and also by far the highest soil carbon content, while cluster 9 has the greatest proportion of sand and only one-quarter the mean soil carbon in cluster 2.

Agricultural soils in Malawi are known to suffer from low and declining fertility due to long-term low-input agriculture (GOM, 2011), and the acidified soil carbon values shown for Kasu site are consistent with this view (Table 13). Soil carbon values are used in this discussion to exclude carbon

from wood ash commonly used as fertilizer in these fields, which is less biologically active than unburned biomass. Soil carbon was negatively correlated (-0.87) with sand content and positively correlated with clay content ($+0.70$). Soil carbon values were relatively high in the heavily cultivated areas along the western edge of the site (Fig. 5). Cluster 4 is 90% cultivated and has 50% sand content, but also has the second highest mean soil carbon content in the cluster. Cropping systems in this cluster may contain very useful local information in stabilizing soil health while also providing agricultural products to sustain the community. It is possible that the addition of cash crops to the district may be providing sufficient revenue to fertilize many of these soils, in addition to the government programs that supply urea to support agriculture.

A mixed-model analysis of variance (Littell, 2006) confirmed that SOC was inversely and very strongly related to sand content (Fig. 12) especially when sand content was high. Other possible factors such as cultivation and slope did not at first appear to be relevant in explaining SOC. However, in Figure 15, the SOC values in cultivated soils did appear to be lower than in semi-natural soils when sand content was low. When only the 50 observations with the lowest sand content were considered, sand content as well as cultivation and the interaction of sand content with cultivation were relevant in explaining SOC.

Figure 12. Soil organic carbon (%) and soil nitrogen (%) as a function of sand content (%)

It is reasonable that cultivation showed a greater effect in fine-textured soils, as cultivation exposes soil organic matter to decomposition that may have been protected inside soil aggregates prior to the turning of the soil. Cultivated soils with nearly 20% sand content appear to have 0.5% less SOC than the semi-natural soils of similar sand content. In the smaller dataset, sand content ranged from 7% to 46%, and SOC from 0.62% to 3.1%, and were taken from 13 of the 16 clusters. These finer-textured soils should recover soil fertility more quickly than the sandy soils, though very low sand content may also signal difficult tillage and some reduced plant-available soil water. The sandy soils should be managed to recover any lost food crop production capacity, and the coarse soils may also suffer from increased drought risk from reduced capacity to hold available water.

Nitrogen values generally followed the trend of carbon values (Table 13), but did not correspond precisely, which is not unusual, given the relative mobility of soil nitrogen, compared to soil carbon. Variations in the nutrient quality and carbon/nitrogen ratio of biomass added to the soil may also influence the variability nitrogen values. The pH of the soils ranged from 5.9 to 6.4 with very narrow standard deviations, and was surprisingly stable, given the range of soil nutrients and textures.

The mixed model analysis of variance for Soil N was very similar to SOC. However, the only variable with significant explanatory value for soil N values was the soil's sand content. When soil N was plotted against sand content (Fig. 12) soil N was more variable in the higher sand content range than SOC, and the gap between N content in cultivated and semi-natural plots was less. The higher variability of soil N is consistent with the higher mobility of soil N compared to SOC, variability of the carbon to nitrogen ratios of crop residues left on the soil and varying additions of N fertilizers. The relatively low levels of soil fertility demonstrated across this site combined with population pressure support the argument that interventions described below for the four sites should be made available across entire sites, even as the clusters with greatest number of risk factors are prioritized.

The area prioritized for interventions is less in cropped areas than in semi-natural areas and much more evenly distributed among the sites (Table 14). Soils with high inherent soil degradation risk (HIDR) are being more commonly cropped in Kasu than in Mwan and Visa sites, and only in one cluster of Sali site. In Kasu site clusters along the western and northern edges of the site (Fig. 5) share a high cultivation rate and moderate incidence of root depth restrictions. These should be targeted for agroforestry, conservation agriculture, reduced tillage and other cultivation practices that increase soil

cover and soil organic carbon. *Tephrosia vogelli* and *T. vogelli* (var. *Candida*) are being promoted in this district for soil improvement and provision of poles to support tobacco production.

Table 14. Priority agroforestry and conservation agriculture intervention areas for each cluster (100 ha)

Cluster	Kasu	Mwan	Sali	Visa
Area (ha)				
1	0	0	0	0
2	47	ND	0	16
3	0	0	0	0
4	31	0	0	0
5	0	0	0	0
6	47	ND	0	0
7	47	0	0	0
8	0	109	0	16
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	12	0	0	16
13	0	0	0	0
14	0	0	0	63
15	0	ND	0	0
16	0	ND	31	0
Total	189	109	31	111

¹ No data

In Mwan site, cluster 8 has a particularly high incidence of cropping with rooting depth restrictions. Whether this rooting depth restriction is due to shallow soils with rocky profiles, or to developing hardpans, the cluster needs targeted assistance to increase soil cover and soil organic matter.

Gliricidia sepium may be used to increase soil organic carbon, as well as to break up developing hardpans. Given the combination of relatively low rainfall and high temperatures in this site, the *Gliricidia* intercrop in Mwan may require lower planting densities than have been developed under cooler temperatures at the nearby Makoka Agricultural Research Station.

No restriction was found at Sali site in cropped areas except in cluster 16. Parklands with *Faidherbia albida* and mango (*Mangifera indica*) are well-accepted and accessible in this district, and should be promoted, with medium-term trees such as *Gliricidia sepium* providing a possible transition phase to the slower-growing *Faidherbia* and mango. This is especially important in soils with abrupt textural changes, to increase soil organic matter and resilience against erosion during intense rainfall events.

Visa site has HIDR combined with cultivation in clusters 2, 8, 12 and 14. Soils in the site are predominately medium-textured, and thus more mobile in erosion events than sands or clays, and thus more vulnerable. Because of extensive cultivation, there is less space for acceptably introducing agroforestry trees than in other sites. In similar settings in southern Malawi, *Gliricidia* has been successfully introduced, as it does not compete with annual crops for space. Conservation agriculture technologies would have potential to increase biomass additions more quickly to the soil in this site because of relatively high rainfall and low temperatures. Boundary plantings of fruit trees or of valuable timber trees, such as *Khaya anthotheca* have also been successfully promoted in this district.

We have documented sizable differences in land use and land cover across the four landscapes, likewise some land degradation risk due to deforestation and increased cropping intensity and nutrient mining. Poorer farmers in these areas can neither rotate crops nor afford fertilizer, and subsidized fertilizer is not available for all, thus land degradation in Malawi would result in increasing risk to food security of rural population. In the same vein, land renting for crop production has increased in recent times whereby salaried income earners rent out land from vulnerable households in exchange for food and socio-economic security. This practice has implications for sustainable land management as many of the rented-out fields tend to be subjected to ever-changing crop production practices, which reduces the use of sustainable land management over the long term. Increased efforts to spread sustainable land management practices over the long term will be important in sustaining both rural and urban populations into the future.

4. Conclusion

The results indicated considerable variation in various aspects of land health among the four sites, particularly with regard to the quality of area under cultivation or management, semi-natural vegetation, woody vegetation and soil characteristics. The major difference between the three heavily cultivated sites and the Mwan site in Neno district was apparent and the interventions required for the Mwan site include both planting of trees and protecting regenerating trees from current market forces for energy supply in this region.

Among the three heavily farmed sites, Visa site contained the most suitable soils for cropping and was the most heavily cultivated. While Kasu and Sali sites are roughly equal in cropping intensity, Kasu site contained almost twice the area of cropped sites with HIDR, compared to Sali or Visa sites. This increased pressure for cropping did not appear due to increasing population (Table 2), but may be connected to the tradition of growing cash crops such as tobacco, groundnuts and soybeans that has developed in this district. As more districts in Malawi transform into market-driven agriculture, emphasis must also be given to protecting and rehabilitating the land producing the crops. In addition, as the government develops smallholder irrigated agriculture in lowlands near Lake Malawi, emphasis should be given to maintaining and increasing the cropped area protected by parklands of *Faidherbia* and mango among the other naturally regenerating tree species that could be managed on the farmlands, which would then promote the health of both the people and land.

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6. Appendix

Glossary

Afromontane: pertaining to mountainous regions of Africa

Alfisols: soils that have an argillic (clay), kandic, or natric horizon and a base saturation of 35% or greater

Ferralsols: strongly weathered soils with low nutrient-holding capacity

Fluvisols: young soils in floodplains, lakes, deltas or marine deposits

Leptisols: shallow soils over hard rock or gravelly material

Lixisols: Slightly acid soils with a clay-enriched subsoil and low nutrient-holding capacity

Lithisols: rocky, stony, and sandy soils with extremely low inherent soil fertility

Miombo woodlands: seasonally dry, deciduous, relatively open woodlands common in central, eastern, and southern Africa

Oxisols: soils having an oxic (highly-weathered) horizon within 150cm of the soil surface

Soil texture: the proportion of different-sized mineral particles (sand, silt, clay) found in the soil

Zambeian: pertaining to the Zambezi River in southeastern Africa, which flows through Zambia, Zimbabwe, and Mozambique to the Indian Ocean

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