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Soil nutrient loss assessment in Malawi

Technical Report

GLOBAL SOIL PARTNERSHIP

Soil nutrient loss assessment in Malawi

Technical Report

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Executive Summary

Introduction

Soil degradation and the consequent decline in plant available nutrients negatively affect agricultural productivity of the soil. In Malawi, soil degradation has been variously reported in the literature as an enemy of economic growth because Malawi is a largely agrarian economy. Soil degradation results in a decline in soil nutrient content and to the eventual deterioration of national food production and agricultural productivity. The government of Malawi and its development partners have called for an evaluation of the cost of soil loss in the country and its associated economic impacts. The aim of the present soil nutrient assessment study in Malawi was to quantify soil nutrient losses throughout the country for an economic assessment of overall national soil loss.

Soil resource information in Malawi

Although Malawi recognizes the importance of soil to its economic growth, the country does not seem to have an organized and easily accessible national inventory of its national soil resources. Consequently, users of soil information rely on soil research outputs of the international research agenda and outputs from foreign academic research programs in order to make decisions on domestic soil management. Some work is needed to assemble already existing pieces of soil information and support the development of national soil information service for Malawi. Analysis of available soil information shows that the soil nutrient content has suffered a lot of mismanagement over the years. Currently, the soil cannot sustain adequate agricultural productivity without application of fertilizers. However, the continuous application of inorganic fertilizers has created the threat of soil acidification, a process that lowers the capacity of soils to readily release its essential nutrient content to plants. Together with the current estimated soil loss rate of over 20 ton/ha/years, soil acidification has brought added impacts to the agrarian economy of Malawi. There is a need for targeted actions and research to support the well-intentioned agricultural policies in the country

Assessment of available information on critical soil nutrient limits and fertilizer application rates in Malawi shows that for adequate agricultural production (and especially maize) the following soil nutrient limits are key: pH 5.2 – 7; Exchangeable Ca^{2+} ≥ 0.2 cmol/kg; Exchangeable K^{+} ≥ 0.2 cmol/kg; available P – 15 mg/Kg; for total N > 0.1%; Organic Carbon ≥ 1.72%; Exchangeable Zn^{2+} ≥ 0.7 mg/kg. Presently, the majority of soils do not meet most of these nutrient levels. Consequently, inorganic fertilizer application has been widely campaigned for and backed with adequate agricultural policies. According to the Government of Malawi (GoM), there are about 25 types and brands of fertilizers used in the country. The most popular ones are: Urea, CAN, Ammonium Sulphate, 23:21:0+4S (also known as Chitowe), and Compound D (a local term that refers to an NPK blend of 7-14-7). The application rates for these fertilizers vary a lot throughout the country. For example, some places report using 87 kg of Di-ammonium Phosphate (DAP) fertilizer and 175 kg of urea fertilizer per hectare for hybrid maize. Reports demonstrate an average of 160 kg/ha total fertilizer spread across all crops, with 35 or 69 kg/ha of N fertilizers. Most of these recommendations are based on plant nutrient requirements and the need to boost crop yield. These recommendations often fail to consider soil conditions and abilities.

Study approach

The following approaches were used to quantify national levels of soil nutrients, nutrient losses, and mitigation measures:

- Field survey of soil nutrient indicators, soil erosion rates, and agronomic practices
- Digital soil mapping techniques
- Spatial modelling of nutrient levels, nutrient loss rates, and nutrient requirements

The first approach was used to obtain the actual nutrient measurements in farms and in deposited sediments in the bottomlands of farmer fields, agronomic practices, and farmer nutrient application and perceptions on soil nutrients and soil loss. The focus was to measure soil chemical properties (nutrient indicators that are key for crop production and which are often supplemented by farmers the form of inorganic fertilizers). The second approach was used to derive spatial information on soil properties, nutrient status, and to estimate soil deficiencies at both macro and micro-levels. The third approach was used to describe and relate soil characteristics, nutrient decline, fertilizer application characteristics, and agronomic practices in the entire country. The study employed various tools and techniques including: mobile tablet-based data collection, mobile soil testing and in-situ measurements, farmer interview using structured questionnaires, application of Digital Soil Mapping (DSM) techniques, and the use of GIS and remote sensing methods. Data collection was performed by a dedicated staff from LRCD and the collected information was centrally coordinated and stored in a server. Some aspects of capacity building were also carried out to ensure that the government receives the requisite support to continue with the activities of national soil resources inventory, assessment, and monitoring in future.

Study findings

1. Threat of soil acidification

A comparative analysis of soil nutrients between 2010 and 2017 of the same sampled locations showed that there is a general decline in soil pH in most Districts in Malawi. On average, soil pH was 6.29 in 2010 and dropped to 5.61 in 2017. In 2010, more than 77% of all the Agriculture Development Divisions (ADD) had pH levels above the critical topsoil pH (for maize production) except in Kasungu in which only 39% of the ADD was above the critical soil pH. In 2017, all the ADDs declined in the proportionate areas with topsoil pH ≥ 5.2, except Kasungu that nearly remained constant with 40% of the ADD still above the critical soil pH. Decline in soil pH is generally an indication of acidification. This study uncovered that the soils affected by acidification are the Lixisols in the northern region, Luvisols in central region, and Luvisols, Cambisols and pockets of Lixisols in the southern region. Acidic soils such as Acrisols and Ferralsols in the north and Alisols in the south may also be slightly affected by a decline in soil pH. One of the potential causes of acidification in these soils was found to be inappropriate fertilizer application in the agriculture areas. As pointed out by various researchers in Malawi, the long-term use of blanket fertilizer recommendations in these soils is a potential contributor to the issue of soil acidification.

2. Soil nutrient status

Spatial distribution of the NPK-soil nutrients in 2017 showed that thecontent of exchangeable potassium may not be a significant problem in Malawian topsoil except in Kasungu, Thyolo, Zomba, and Machinga Districts. In these areas, exchangeable potassium was below the critical level for both 2010 and 2017. Previous reports also indicate that the majority of soils in the country seem to have sufficient levels of exchangeable potassium. This implies that, over the years, exchangeable potassium may be sufficiently available in Malawian soils. For available organic phosphorous and total nitrogen, there seems to be some deficiency in certain parts of the country. The areas that were identified with acidification problems also had low available P; perhaps due to the oxidation of soil P. Oxidation of the soil P can lead to unavailable forms of phosphorous and result in the decline of bioavailable P. In general, this study demonstrated that the soils in the country seem to have significant deficiency in certain key soil nutrients for plant growth and development. These nutrients include nitrogen, phosphorous, calcium and zinc. This implies that the harvested crops are also likely to be lacking in these essential elements unless appropriate fertilizers are used to supplement these nutrients during plant development.

3. Soil and nutrient loss

During the study, it was found that nearly half of the Districts in Malawi had more than 40% observable signs of soil degradation in the farmlands. This portrays a significant level of prevalence of soil degradation in the country. The most prevalent degradation types are: a decline in soil fertility and an increase in erosion (sheet, rill, and gully). Interviews with farmers from sampled locations demonstrate widespread belief that the soil has lost a great deal of its fertility over the years. The factors contributing to this prevalence of soil degradation include: poor maintenance of existing erosion control structure, inadequate soil fertility management, dominant fragile soils, steep slopes, limited extension services, poor adoption of soil conservation technologies, low levels of awareness on soil degradation and conservation technologies, low level of farmer-investment in soil conservation, erratic and high rainfall intensities, and reduction of protective soil cover.

In addition to farmer opinion, this study also measured soil loss rates throughout farmlands. The results show that between 2010 and 2017, topsoil loss rates slightly increased by over 10%. In 2010, the mean soil loss rate was estimated at 26 ton/ha/yr, which rose to 29 ton/ha/yr in 2014 and to 30 ton/ha/yr in 2017. The areas dominated by Cambisols on the steep slopes were found to have the highest risk for topsoil loss in the country. These soils are largely in the Rift Valley. The study also noted that the average annual loss rate of the main plant nutrients due to topsoil loss was 108 g/ha of total N, 350 g/ha of available P, and 16.6 g/ha of exchangeable K in 2017. This is equivalent to a loss of 3% of a 50kg-bag of Chitowe fertilizer per hectare annually through, soil erosion. This translates to over 2,000 metric tons of Chitowe fertilizers annually lost in the country due to soil erosion.

4. Nutrient management options

In order to compensate for nutrient loss through soil erosion, plant uptake and tillage practices, some form of nutrient supplementation is necessary. The sustainable management practices for supplementing nutrient loss in the soil include: crop rotations, conservation agriculture, soil and water conservation practices, cover cropping, manure management and application, fertilizer application, etc. Presently, the use of inorganic fertilizers is widespread in the country owing to the increased support from government policies in the past few decades. The use of organic fertilizers is, however, still not as widespread as the use of inorganic fertilizers. This may be partly due to lack of knowledge, lack of sustained efforts and policy backing as is done for inorganic fertilizer use, and competitive use of input materials for organic fertilizers. If organic fertilizers were to be used to supplement soil nutrients, 50 kg/ha of manure can be as a starting campaign to restore the nutrients lost through soil erosion. According to the current inorganic fertilizer application rate in the country and the threat of soil acidification and subsequent decline of some soil nutrients, it is important that a critical assessment of the use of inorganic fertilizer be done. This may entail long-term research on impacts of acidification on nutrient availability in Malawi, soil testing and calculation of requisite acidity amelioration strategies, and matching fertilizer application with soil properties and crop needs. This procedure was not taken during this study owing to the scope and other logistical limitations.

Conclusions and recommendations

This study established that there has been a consistent decline in soil pH in the country over the last 7 years. This decline, an indication of soil acidification, was found in at least 40% of each district in Malawi. Consequently, it was flagged as an important soil problem for the country to address. In addition to soil acidification and risk of bio-unavailability of certain soil nutrients, the country faces increasing soil loss. A high prevalence of observable signs of soil loss was found in virtually all districts in Malawi. Analysis of soil loss rates revealed that the rate of soil loss was 26 ton/ha/yr in 2010, 29 ton/ha/yr in 2014 and that the current soil loss rate is 30 ton/ha/yr. This trend portrays an increasing problem of soil loss in the country. Some of the potential drivers of this high rate of soil loss were identified. In terms of nutrient loss, the current soil loss rate was found to remove, on average, 108 g/ha of total N, 350 g/ha of available P, and 16.6 g/ha of exchangeable K in 2017. This is equivalent to 3% of a 50kg-bag of Chitowe fertilizer per hectare lost through soil erosion annually. In order to overcome soil loss and nutrient loss, this study found that integrated soil fertility management (ISFM) is the best option for Malawi. ISFM focuses on the combined use of inorganic fertilizers, soil amendments (e.g. lime, rock phosphate, etc.), and organic matter (e.g. crop residues, manure, legumes, etc.) to replenish lost soil nutrients. Although there are practical examples of ISFM in Malawi, widespread adoption of ISFM may need further research and trials on optimal alternatives. In addition, ISFM needs policy support backed with widespread campaign throughout the country. These efforts should be blended with awareness raising, technology transfer, and farmer trainings supported by adequate extension services.

Although significant strides were made during this study, there are gaps identified that need further work. For example, the study noted a clear lack of an organized, easily accessible national inventory of soil resources. It is recommended that work be done to support the establishment of a national soil information system for Malawi. Such a system will provide an overview of the national status of soil resources, soil conservation efforts and the monitoring of soil health in the long term. In the realm of wholesome soil nutrient dynamics quantification, this study recommends that a detailed study on the loss of soil nutrients due to acidification and nutrient mining be established. Afterwards, appropriate quantification of nutrient dynamics in the country may be established. Furthermore, opportunities should be considered on how to integrate ISFM options in agricultural and fertilizer policies in the country. Finally, the study developed data collection strategies that can be exhaustively used by the GoM to update its current database. It's recommended that the strategy be replicated in each ADD. The ADDs need to be supported with soil testing kits, mobile tablets, and mirror servers that are controlled at the headquarters.

List of abbreviations and acronyms

AfSIS	Africa Soil Information Service
ADD	Agricultural Development Divisions
ARET	Agricultural Research and Extension Trust (ARET)
ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
CAN	Calcium Ammonium Nitrate
DEM	Digital Elevation Model
DAP	Di-ammonium Phosphate
DSM	Digital Soil Mapping
EPA	Extension Planning Area
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FISP	Farm Input Subsidy Program
GDP	Gross Domestic Product
GoM	Government of Malawi
GSP	Global Soil Partnership
IFDC	International Fertiliser Development Centre
ISFM	Integrated Soil Fertility Management
ISRIC	International Soil Reference and Information Centre
ISSS	International Society of Soil Science
LRCD	Land Resource Conservation Department of the Government of Malawi
MPTF	Maize Productivity Task Force
MK	Malawian Kwacha
NPK	Nitrogen Phosphorous and Potassium
OC	Organic Carbon
OM	Organic Matter
PEI	Poverty Environment Initiative
SCORPAN	Soil Climate Relief Parent Material Age and Space factors of soil formation
UNDP	United Nations Development Programme
USDA	United States Department of Agriculture
WRB	World Reference Base

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1 Introduction

1.1 Background

Soil degradation and the consequent decline of plant-available nutrients negatively affect agricultural productivity of the land. Soil erosion (and especially topsoil loss) is one of the degradation processes that deteriorates plant available nutrients in the soil and contributes to the decline of the soil's productive potential. In countries throughout the world, soil loss has been identified as a major cause of deterioration of soil fertility and a contributor of declining per capita food production (El-Swaify et al., 1985[1]). In Africa, it was estimated in 1990 that soil loss caused the annual depletion of plant available nutrients of more than 30 Kg of total nitrogen and more than 20 Kg of potassium per hectare of agricultural land (Stoorvogel and Smaling, 1990[2]). This might be an over-estimation, owing to the scale of the assessment, but nonetheless is a pointer to the potential negative impacts of soil loss in the continent.

In Malawi, evidence of persistent soil loss problems has been variously reported (see for example World Bank (1990) and Vargas and Omuto (2015[3])). The reports also point to widespread soil loss as a problem that is increasingly becoming a national concern. Alongside this problem is also the threat of soil nutrient decline and eventual deterioration of national food production and economic growth (Matchaya *et al.*, 2010). Recent discussions suggested an evaluation of the cost of soil loss in the country in order to estimate its economic impacts (Yargon *et al.*, 2011[4]).

The cost of soil loss can be divided into on-site costs (direct or internal for the farmer) consisting of losses incurred on the farmland and off-site costs (indirect or external effects for society) occurring away from the farmland. Some studies have been attempted in the literature on evaluating the cost of soil loss using soil nutrient losses and decreases in yield (Bennett, 1933[5]; Telles *et al.*, 2011). The aim of the present soil nutrient assessment study in Malawi was to quantify nutrient losses for the sake of informing economic assessment of soil loss in the country. Specifically, this study endeavoured to:

1 El Swaify, S.A., Moldenhauer and A Lo. Editors (1985). Soil Erosion and Conservation. Ankeny, Iowa: Soil Conservation of America

2 Stoorvogel, J.J. and Smaling, E.M.A. (1990). Assessment of soil nutrient depletion in sub-Saharan Africa. 1983-2000. Volume 1: Main report. The Winard staring centre. Wagenigen, 137pp

3 Vargas RR, Omuto CT. 2015. Soil loss assessment in Malawi. FAO. http://www.fao.org/3/a-i6387e.pdf

4 Yaron, G, Mangani, R, Mlava, J, Kambewa, P, Makungwa, S, Mtethiwa, A, Munthali, S, Mgoola, W and Kazembe, J. 2011. Economic Study: Economic Analysis of Sustainable Natural Resource Use in Malawi. UNDP-PEI, Malawi

5 Bennett H.H. 1933. The cost of soil erosion. The Ohio Journal of Science 33: 271-279.

1. Determine the topsoil nutrient levels at the national scale
2. Determine the soil nutrient losses and trends due to topsoil loss
3. Assess the impacts of fertilizer application and provide recommendations on optimal rates
4. Determine the importance of a soil nutrient assessment in Malawi

Soil nutrients are required by plants for growth development, and the production of the harvestable crop itself (seeds, fruit, leaves and stem, roots, etc.). The three main nutrients are nitrogen (N), phosphorus (P) and potassium (K); more commonly known as NPK. Other important nutrients are calcium, magnesium and sulphur. Plants also need small quantities of iron, manganese, zinc, copper, boron and molybdenum, known as trace elements because only small amounts are needed by plants. Plant availability of these nutrients in the soil is affected by land use practices, soil types, climate, relief, soil pH, among others (Sims, 1985[6]; Mishima *et al.*, 2013[7]).

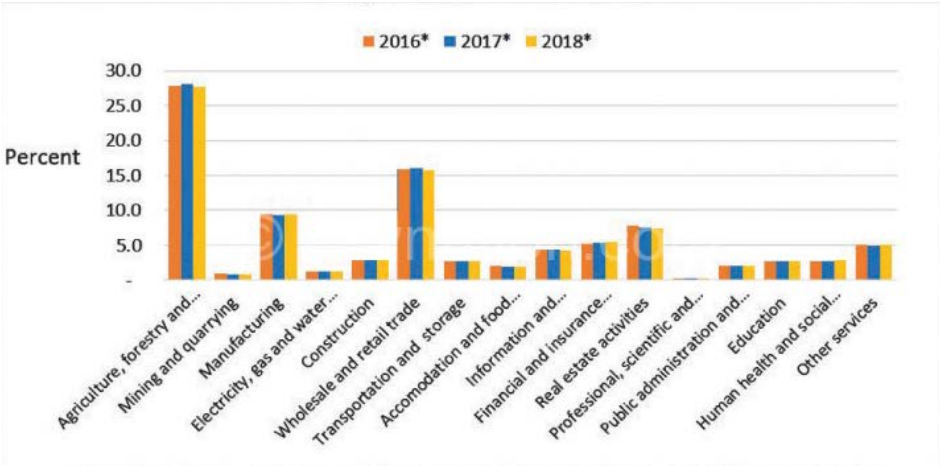
In Malawi, agriculture is central to the economic performance as well as for the provision of food and contributes to approximately 30% to the Gross Domestic Product (GDP) (Figure 1.1). Consequently, soil nutrient content is of utmost importance to the GoM. Most of the agricultural policies developed by the GoM that aim at improving/sustaining land productivity invariably address issues of soil nutrient dynamics (GoM, 2016[8]). The GoM and its development partners have had to intervene in soil fertilization and farm inputs whenever they observed declines in soil nutrient dynamics, which imminently threaten agricultural productivity. Consequently, programs such as the Farm Input Subsidy Program (FISP) have been tried at various times as a show of the Government's concern and the priority they give to the agricultural sector (FAO, 2015[9]).

6 Sims J.T. 1985. Soil pH Effects on the Distribution and Plant Availability of Manganese, Copper, and Zinc. Soil Science Society of America Journal, 50(2):367-373.

7 Mishima S.I., Kimura D.S., Eguchi S., Shirato Y. 2013. Changes in soil available-nutrient stores and relationships with nutrient balance and crop productivity in Japan. Soil Science and Plant Nutrition, 59: 371-379.

8 GoM, 2016. The National Agriculture Policy. Ministry of Agriculture, Irrigation, and Water Development. Lilongwe

9 FAO. 2015. FAO 2015. Review of food and agricultural policies in Malawi. MAFAP Country Report Series, Rome



Source: National Statistics Office, Reserve Bank, Ministry of Finance and Ministry of Economic Planning and Development

Figure 1.1: Relative position of agricultural contribution to GDP performance in Malawi

Owing to the strategic importance of soil and its nutrient status, the government of Malawi and its development partners have placed some interest in assessing soil nutrient levels, nutrient requirements, and in developing strategies to improve agricultural productivity in the country. This is evident from the many commissioned studies to document soil status in agriculture and potential areas; the number of donor supported projects in the agricultural sector; and the proportion of budgetary allocation by the Malawi government to the benefit of the agricultural sector.

2 Soil loss and soil nutrient information in Malawi

2.1 Agricultural production performance and soil nutrient conditions

Agriculture in Malawi is dominated by maize and tobacco cultivation. Hence, the performance of the sector is mostly correlated with the performance of these two crops. According to Chirwa *et al.* (2008[10]), the performance of the sector had mixed growth rates since the 1960s and erratic growth rates since the 1990s (Figure 2.1).

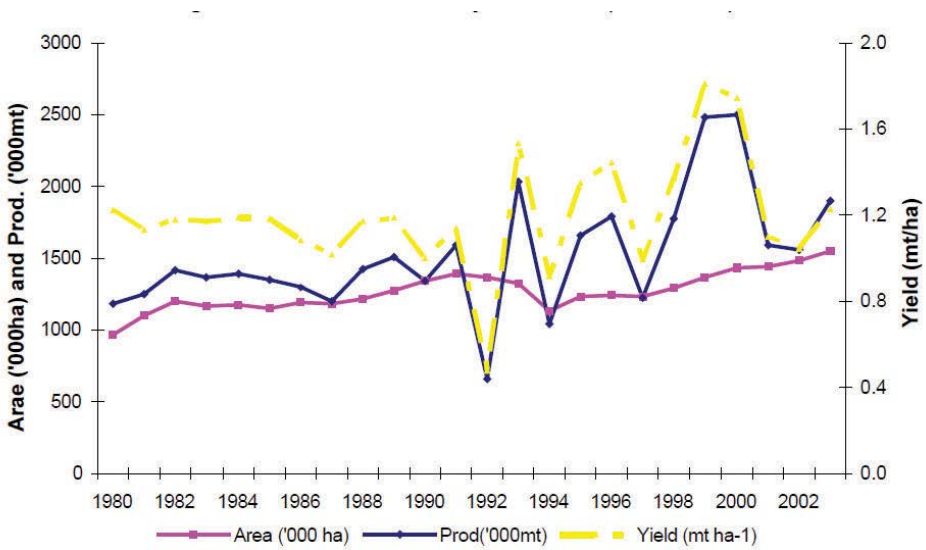


Figure 2.1: Performance of maize production in Malawi (Source: Sauer and Tchale, 2006[11])

Some of the factors that were found to influence the overall performance of the agricultural sector of Malawi include declining land productivity, the rain-fed nature of cultivation and associated exogenous shocks, thin agricultural markets, policy reversals and associated uncertainties, and declining public investments in the agricultural sector. According to Phiri

10 W. Chirwa W. E., Kumwenda I., Jumbe C., Chilonda P. and Minde, I. 2008. Agricultural Growth and Poverty Reduction in Malawi: Past Performance and Recent Trends. ReSAKSS Working Paper No.8. ICRISAT-IFPRI-IMWI, SA

11 Sauer J. and Tchale H. 2006. Alternative soil fertility management options in Malawi – An economic analysis. International Association of Agricultural Economists Conference, Gold Coast, Australia. August 12-18, 2006.

et al. (2012[12]), the dwindling agricultural performance in the country is also largely affected by the poor service provision and policy challenges related to quality and quantity of input supply, soil resource management, marketing, production costs, among others. FAO (2015[13]), in outlining the sector's performance, suggested that the low performance of the agricultural sector is both caused and reinforced by the high levels of poverty among farmers. This assessment noted a vicious cycle between low agricultural productivity, declining soil nutrient levels, malnutrition, and rural poverty in the country. This argument is plausible since soil health normally influences crop nutrient content and eventual dietary intake of the agrarian population. In fact, according to Joy *et al*. (2015[14]), soil nutrient deficiency is a direct result of low agricultural investment in Malawi, and is the cause of the country's prevalent malnutrition and poverty rates.

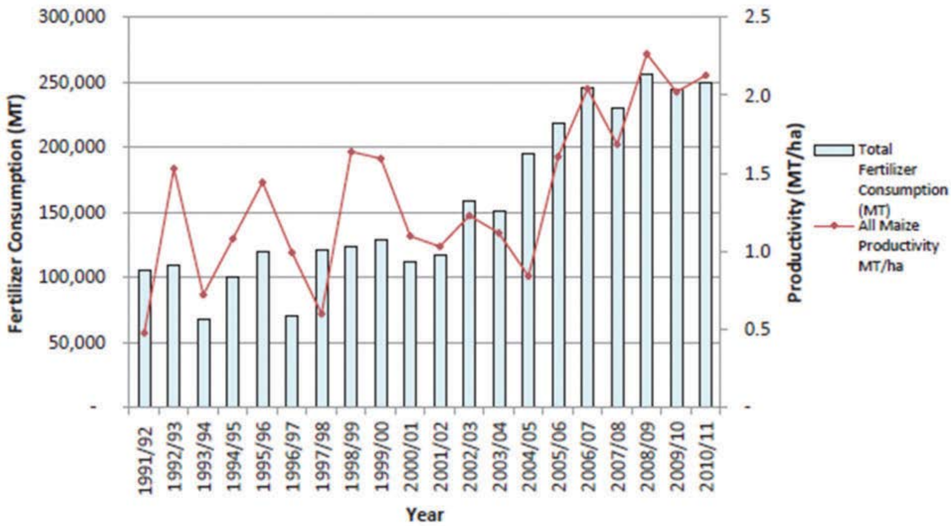


Figure 2.2: Example of maize production trend versus fertilizer use (source: Matchaya *et al.*, 2010[15])

A shocking feature of the agricultural sector of Malawi is its dependency on fertilizer application. The trend of agricultural productivity often closely mirrors the trend of fertilizer application (Figure 2.2). This implies that the quality and quantity of agricultural productivity is influenced by the amount and quality of fertilizers used by farmers in their plots. From another perspective, it can be said that the soil in Malawi currently lacks the natural nutrient balance needed to support agricultural productivity without adequate fertilizer application. This fact is corroborated by nutrient response trials which have reported declining maize yields in unfertilized plots (Hardy, 1998[16]).

12 Phiri1 M.A.R., Chilonda P., Manyamba, C. 2012. Challenges and opportunities for raising agricultural productivity in Malawi. International Journal of Agriculture and Forestry, 2(5): 210-224.

13 FAO. 2015. Country fact sheet on food and agriculture policy trends: Socio-economic context and role of agriculture. FAO-Malawi.

14 Joy E.J.M., Broadley R.M., Young S.D., Black R.C., Chilimba A.D.C., Ander E.L., Barlow T.S., Watts M.J. 2015. Soil type influences crop mineral composition in Malawi. Science of the Total Environment 505: 587–595.

15 Matchaya G., Nhlengethwa S., Chilonda P. 2014. Agriculture sector performance in Malawi. Regional and Sectoral Economic Studies 14: 141-156

16 Hardy T. 1998. Malawi: soil fertility issues and options. Unpublished discussion paper.

2.2 National inventory of soil resources in Malawi

Although the government of Malawi recognizes the importance of soils to its economic growth, the country has no established, easily accessible national inventory of soil resources nor a soil information system. In spite of having dedicated government departments to soil surveying and soil conservation, data on the status of soil resources on the national level are limited. Consequently, users of soil information are only able to rely on isolated soil research outputs, the content of which is determined by the international research agenda, and from academia, etc. in order to make decisions on soil management. Relevant pieces of Malawian soil information in government offices are shared in hardcopy format and are rarely available in synthesized forms for soil users, such as farmers, investors, etc. Presently, the majority of online downloadable documents on soil information are archived in repositories of international organizations, in academic theses outputs, and in online journal articles. This presents an advantage to possible efforts to inventory soil resource information in the country since the data is freely downloadable.

The EU soil data centre for Africa (https://esdac.jrc.ec.europa.eu) provides downloadable soil maps of Malawi. These maps were once hardcopy maps which were collected from government offices, the international community, and universities and colleges. They were then scanned, georeferenced, and archived in online repositories for the benefit of users of soil information of Malawi. Old maps of other soil forming factors such as vegetation, land use, are available as well at this site for various parts of the country. The ISRIC soil maps and databases (http://data.isric.org/geonetwork/) also provide downloadable soil and terrain databases for Malawi. Data is freely accessible for both maps and soil profile information of selected sites in the country. At the Africa Soil Information Service (AfSIS, http://africasoils.net/), there are soil profiles for Malawi which are complete with soil properties at different depths. In general, a lot of information exists for starting the development of a national soil inventory for Malawi. Besides the online soil data, there is a rich archive of legacy information in form of technical reports, journal articles, and academic theses for various aspects of soil resources in Malawi. These reports and publications can be accessed as hardcopies or as downloadable documents from local and international universities, local research stations, and from government offices in Malawi.

During this study, some of the soil datasets and reports mentioned above were assembled into a collection. The collection can be useful in initiating the development of a soil information system for Malawi.

2.3 Soil loss in Malawi

Soil loss is a major threat to the agricultural development of Malawi. Not only does soil loss reduce the cultivable soil depth but it also remove the fertile soils from the farmlands. The net effect is loss of agricultural productivity, increased expenditure on fertilizers, and a general decline in profitability of crop production. Incidences of soil loss have been variously reported in the literature since the 1970s to date. Over 80% of these reports indicate soil loss rates between 0 and 20 ton/ha/yr. Khonje and Machira (1987[17]) reported national average soil loss rate at 33 ton/ha/year, while the World Bank (1992) reported a rate of 20 ton/ha/year. Recently, Vargas and Omuto (2015[18]) carried out a national assessment of topsoil loss in the country and reported an average loss of 29 t/ha/yr (Figure 2.2). Although not entirely cross-compared, these soil loss reports point to a relatively high rate of soil loss in the country.

Soil loss carries away plant nutrients, and in addition causes off-site effects such as pollution, siltation of water storage, and more. In Sub-Saharan Africa, the annual net nutrient depletion due to soil loss is reportedly exceeding 30 kg N and 20 kg K per ha of arable land (Stoorvogel and Smaling, 1990[19]). This impacts many aspects of agricultural productivity and food production in the region. In Malawi, farmers apply 20 kg/ha of fertilizer on average during maize production (FAO, 1998[20]). This is still below the soil and crop nutrient maintenance requirements (Heisey and Mwangi, 1995[21]); which implies a net negative nutrient balance throughout many croplands in the country.

Soil loss and soil nutrient depletion in Malawi poses potential economic loss in the country. A study by Yaron *et al.* (2011[22]) put a conservative estimate of the annual on-site loss of agricultural productivity as a result of soil loss to cost as much as MK 7.5 billion (US$54 million or 1.6% of GDP). A detailed economic analysis of the impacts of soil loss in the country is necessary to underscore the extent of soil loss in the country or quantify positive gains that could be realized if soil loss was controlled.

17 Khonje C.S., Machira S.K. 1987. Erosion hazard mapping of Malawi. Land Husbandry Branch, MOGA, Lilongwe

18 Vargas RR, Omuto CT. 2015. Soil loss assessment in Malawi. FAO. http://www.fao.org/3/a-i6387e.pdf

19 Stoorvogel, J.J. and Smaling, E.M.A. (1990). Assessment of soil nutrient depletion in sub-Saharan Africa. 1983-2000. Volume 1: Main report. The Winard staring centre. Wagenigen, 137pp

20 FAO. (1998). Malawi Soil Fertility Initiative, Concept Paper. Food and Agriculture Organization of the United Nations, Rome. Investment Centre Division FAOlWorld Bank Cooperative Programme

21 Heisey, P.W and Mwangi, W (1997) Fertiliser Use and Maize Production in Sub- Saharan Africa in Byerlee, D and Eicher, C.K, (eds) Africa's Emerging Maize Revolution, Rienner, London.

22 Yaron, G, Mangani, R, Mlava, J, Kambewa, P, Makungwa, S, Mtethiwa, A, Munthali, S, Mgoola, W and Kazembe, J. 2011. Economic Study: Economic Analysis of Sustainable Natural Resource Use in Malawi. UNDP-PEI, Malawi

2.4 Soil information in Malawi

A scanned old soil map of Malawi is available at the scale of 1:1 million. This map was done in 1965 and re-traced in 1983 to show the general information of major soil types in the country (Lowole, 1983[23]). Recently, a detailed soil map of the country was produced in 2010 by the government of Malawi and its development partners. This map has over 4,500 sample locations with the following soil properties: organic matter (OM), organic carbon (OC), nitrogen (N), potassium (K), phosphorous (P), calcium (Ca), magnesium (Mg), copper (Cu), iron (Fe), Zinc (Zn), and manganese (Mn). The data also include observations for both topsoil and sub-soil horizons. Table 2.1 shows a summary of these attributes aggregated by the Agricultural Development Divisions (ADD). In 1998, Snapp (1998[24]) carried out a soil nutrient analysis from 1,130 samples across the country. The summary is shown in Table 2.3. In 2013, Lakudzala (2013[25]) carried out an assessment of the soil nutrient status of selected sites within the country while studying potassium response in Malawian soils (Table 2.2). These results are more comparable to the 2010 soil study by the GoM than the study by Snapp (1998).

Table 2.1: Key soil attributes in Malawi

ADD	2010						1998				
	pH	C (%)	N (%)	P (mg/kg)	K (cmol/kg)	Ca (cmol/kg)	pH	C %	Ca (cmol/kg)	K (cmol/kg)	P (mg/kg)
Blantyre	6.04	0.88	0.08	82.54	0.46	1.60	6.9	1.2	3	1.1	45.5
Karonga	6.17	0.73	0.06	34.90	-	-	8.3	1.3	3.1	0.7	30.1
Kasungu	6.00	0.95	0.08	6.11	0.32	0.02	7.2	1.7	1.9	0.5	24.2
Lilongwe	5.69	1.01	0.09	35.00	0.79	3.21	6.8	1.6	4.1	0.4	31.3
Machinga	6.20	1.28	0.07	23.89	0.14	8.50	-	-	-	-	-
Mzuzu	5.66	0.83	0.07	137.72	0.00	0.80	7.7	1.2	2.3	0.5	21.7
Salima	5.93	0.68	0.06	10.78	0.00	0.01	-	-	-	-	-
Shire Valley	6.78	0.97	0.07	31.03	0.28	5.99	-	-	-	-	-

23 Lowole, M. 1983. Soil Map of Malawi (at a scale of 1:1:000,000). Lilongwe, Malawi: Soil Survey Section Kasungu, Dept. of Agtricultural Research

24 Snapp SS. 1998. Soil nutrient status of smallholder farms in Malawi. Communications in Soil Science and Plant Analysis, 29(17):2571-2588

25 Lakudzala DD. 2013. Potassium response in some Malawi soils. International Letters of Chemistry, Physics and Astronomy 8(2): 175-181.

Table 2.2: Summary results of soil nutrient status according to Lakudzala (2013)

Location of site		pH	S	Ca	Mg	K	CEC	P	Mn	Fe	Cu	Zn
District	Village		meq/100 cm³					mg/100cm³				
Nkhotakota	Mphonde	7.76	>6	>5	>1.8	0.015	18.3	27.5	3.1	0.9	3.5	2.2
Salima	Nsuwadzi	4.49	> 6	2.775	0.37	0.029	3.29	> 40	55.3	75.35	4.85	6.45
Kasungu	Kasungu	5.03	> 6	> 6.38	> 2.30	0.054	7.1	> 40	42.8	239.6	3	8.8
Thyolo	Bvumbwe	4.74	> 6	2.36	0.42	0.056	4.17	> 40	75.3	191.5	46	8.3
Lilongwe	Chitedze	5.37	> 6	3.16	1.14	0.022	7.53	> 40	83.1	83.3	3.9	7.5

The existing soil information portrays the country as slowly developing acidic soils. This is especially occurring in the central regions, which are more agriculturally productive and are therefore experiencing a general trend of increasing soil acidity. Acidity in the soil limits availability of certain plant available soil nutrients (Rorison, 1980[26]). There are studies which allege that continuous fertilization of soil with nitrogenous inorganic fertilizers could contribute to soil acidification (Tian and Niu, 2015[27]). It can be assumed that as agricultural productivity deteriorates in the bread-basket areas of Malawi, fertilizer use leads to an increase in acidic soil conditions.

Other soil related information such as landscape relief, climate, and land use/cover types, can also be found in various government departments. Literature is also available on soil management, fertilizer application methods and rates, isolated soil conservation efforts, and cropping areas of major crops (FAO; UNDP-PEI, LRCD, GoM[28]).

According to the soil map of Malawi, the major soil types in the country are Luvisols, Lixisols, and Cambisols. Lixisols are dominant in the northern region, Luvisols in the central, and Cambisols along the Rift Valley and largely in the southern regions. Cambisols and Luvisols are naturally endowed with good chemical properties that can be exploited for agricultural purposes. They can sustain good crop production especially if they are properly managed. Their vast majority implies that they can benefit the country in supporting crop production programs. Lixisols have relatively higher silt and organic matter content. However, they need appropriate fertilizer application in order to guarantee good performance in crop production. Furthermore, they may also take a long time to regenerate if excessively exploited through continuous nutrient mining.

26 Rorison I.H. (1980) The Effects of Soil Acidity on Nutrient Availability and Plant Response. In: Hutchinson T.C., Havas M. (eds) Effects of Acid Precipitation on Terrestrial Ecosystems. NATO Conference Series (I: Ecology), vol 4. Springer, Boston, MA

27 Tian D., Niu S. 2015. A global analysis of soil acidification caused by nitrogen addition. Environmental Research Letters, 10: 024019. doi:10.1088/1748-9326/10/2/024019.

28 Land Resource and Conservation Department of the Government of Malawi (LRCD)

2.5 Critical nutrient limits for crop production

Soils are important for crop growth and development and therefore for good agricultural productivity. Soils possess the reservoir of relevant nutrients for agricultural productivity. Healthy soils should retain, cycle, and supply the essential nutrients for plant growth over many years. However, owing to continuous nutrient mining (crop harvesting without nutrient replacement), many areas of the world are experiencing a decline in soil nutrient content, slowly losing their ability to sustain good agricultural productivity. In Africa, the role of soil in agriculture is fast waning due to nutrient content decline and loss of fertility (Sanchez *et al.*, 1997[29]). Primary drivers of this phenomenon are: soil loss, soil acidification, and soil nutrient mismanagement.

Soil pH is one of the major factors affecting nutrient availability in the soil. In the literature, soil pH between 5.5 and 6.5 is preferred by most plants. Acidification results when soil pH decreases. Soil acidity affects the mobilization and availability of major nutrients such as N, P, S, and basic cations. It also regulates the rate of organic matter mineralization, reducing the number of simple organic molecules available for further decomposition and eventually rendering N and other constituent elements (P and S) soluble (Curtin *et al.*, 1998[30]). In Malawi, research studies on maize production have shown that the critical pH is 5.2 for most soils in the country (Snapp, 1998). Similarly, the critical levels of other soil nutrients were observed as follows: Exchangeable Ca^{2+} - 0.2 cmol/kg; Exchangeable K^{+} - 0.2 cmol/kg; and Extractable P – 15 mg/Kg. In 1999, Chilimba *et al.* (1999[31]) also made similar observations on critical levels for extractable P and exchangeable Zn^{2+}.

According to Sys *et al.* (1991), critical value for total N> 0.1% is adequate for both ground nut and maize production. They also suggested a critical value for Extractable P as 10 mg/Kg for ground nut production. A similar observation was made by Chirwa *et al.* (2016[32]) in Zambia. Chirwa *et al.* (2016) observed that OC>1.72% stabilises the soil structure, decreases bulk density and promotes heightened nutrient cycling. The study suggested 1.72% as the critical limit for no capital letters needed here. (SOC) for crop production. In Malawi, Snapp (1998) indicated SOC levels of > 0.8% as the critical limit for soil organic carbon.

29 Sanchez, P.A., Shepherd, J.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.M.N., Mokwunye ,A.U., Kwesiga, F.R., Ndiritu, C.G., and Woomer, P.L. (1997). Soils fertility replenishment in Africa: An investment in natural resource capital. In Buresh RJ, Sanchez PA, Calhoun F (eds), Replenishing Soil Fertility in Africa, Soil Science Society of America Special Publication 51. SSSA and ASA, Madison, WI, USA, pp 1–46

30 Curtin, D., Campbell, C.A., Jalil, A., 1998. Effects of acidity on mineralization: pH-dependence of organic matter mineralization in weakly acidic soils. Soil Biol. Biochem. 30, 57–64

31 Chilimba ADC, Mughogho SK, Wendt J. 1999. Mehlich 3 or Modified Olsen for soil testing in Malawi. Communications in Soil Science and Plant Analysis 30(7-8):1231-1250

32 Chirwa M, Lungu OI, Kaaya AK. 2016. Evaluation of Soil Fertility Status and Land Suitability for Smallholder Farmers' Groundnut and Maize Production in Chisamba District, Zambia. International Journal of Plant & Soil Science. 10(4): 1-18.

According to Alloway (2008[33]), the levels of DTPA extractable Zn varies with soil types. Nonetheless, a critical value of 0.7 mg/kg is often used. In Malawi, Snapp (1998) used a critical value of 0.5 mg/kg for all the major soil types in the country.

2.6 Fertilizer application rates

Agriculture in Malawi is dominated by maize, pulses, ground nuts, cassava and potato (Table 2.3). The yields of these crops are reported to have stagnated at less than 50% of the actual attainable yields, leading to declining per-capita food production as the population grows (IFDC, 2013[34]). For example, on average, smallholder farmers produce about 2 t/ha of maize against attainable yields of between 6 to 10 t/ha for the maize varieties in the country. The large gaps between actual and attainable yields can be attributed, in part, to declining soil fertility due to low and inappropriate fertilizer application in the crop lands (Snapp, 1995[35]).

Table 2.3: Productivity of common crops in Malawi (source: IFDC, 2013)

Smallholder farms - 5year (2007-11) averages				Estate farms - 5 year (2007-11) averages			
Crop	Area (ha)	Total production (tons)	Average yield (tons/ha)	Area (ha)	Total production (tons)	Average yield (tons/ha)	Cumulative production (tons)
Maize	1,628,306	3,224,070	2.0	56,929	182,497	3.21	3,406,567
Sorghum	78,456	61,533	0.8	0	0	0	61,533
Rice	60,884	116,914	1.9	0	0	0	116,914
Millet	44,891	29,736	0.7	0	0	0	29,736
Wheat	1,610	2,736	1.7	25	52	0.82	2,817
Pulses	636,691	462,145	0.7	13,097	10,698	0.81	472,843
Groundnuts	281,560	281,302	1.0	14,354	17,467	1.21	298,769
Cassava	188,909	3,817,081	20.1	2,431	52,675	21.60	3,869,755
S Potatoes	169,777	2,716,523	15.9	2,601	50,654	19.35	2,767,176

33 Alloway BJ. Zinc in soils and crop nutrition. IZA and IFA, Brussels. https://www.fertilizer.org/

34 IFDC. 2013. Malawi fertilizer assessment: In support of The African Fertilizer and Agribusiness partnership (AFAP), www.Ifdc.org

35 Snapp, S.S. (1995). Improving fertilizer efficiency with small additions of high quality organic inputs. In S.R. Waddington (ed.), Report on the First Meeting of the Network Working Group. Soil Fertility Research Network for Maize-Based Farming Systems in Selected Countries of Southern Africa. Lilongwe, Malawi, and Harare, Zimbabwe: The Rockefeller Foundation Southern Africa Agricultural Sciences Programme and CIMMYT. Pp. 60-65

Other studies have shown that the country experiences net negative annual nutrient balance due to soil loss and nutrient mining (Table 2.4) (IFDC 1999[36]). The indicative negative NPK nutrient balance could be a signal of low application of appropriate fertilizers and/or inadequate soil fertility management.

Other studies have shown that the country experiences net negative annual nutrient balance due to soil loss and nutrient mining (Table 2.4) (IFDC 1999[37]). The indicative negative NPK nutrient balance could be a signal of low application of appropriate fertilizers and/or inadequate soil fertility management.

Table 2.4: Annual nutrient balance in Malawi (1993-1995) (Source: IFDC, 1999)

	Area	NPK	N	P2O5	K2O	NPK
	('000 ha)	('000 MT)	kg/ha			
Annual nutrient requirement	2029	263.8	38.9	37	54.1	138.8
Annual nutrient consumption	2029	61.4	18.9	8.4	3	30
Nutrient balance	2029	-202.4	-47.5	-16	-45.3	-108.8

The GoM has made notable achievements to support smallholder farmers to increase productivity through fertilizer subsidy programs. The main fertilizer types used in Malawi are Urea, 23:21:0+4S, CAN, and Compound D. Urea and 23:21:0+4S are commonly applied to maize while CAN and Compound D are used in tobacco crops (GoM[38]). The fertilizer subsidy program implemented by the government has led to increased fertilizer supplies from 14,237 metric tons in 2005 to 216,553 metric tons in 2009 (IFDC, 2013). This translates to fertilizer application rates of less than 20 kg/ha in 2000 to 43 kg/ha in 2009 (IFDC, 2013). According to the GoM and WB (2007[39]), smallholder average fertilizer consumption is 34 kg/ha while estate farms consume an average of 150 kg/ha.

There have been varied reports of fertilizer recommendations used in the country. Snapp (1998) reported recommendation of 87 kg of Di-ammonium Phosphate (DAP) fertilizer and 175 kg of urea fertilizer per hectare for hybrid maize. This translates 96 kg of nitrogen and 40 kg of P_2O_5 per ha to the crops. This recommendation was adopted by the GoM based on practical considerations for extension officers to communicate uniform messages rather than based on site-specific needs or the socio-economic circumstances of poorly resourced farmers. It is important to note that the recommendations ignored differences between soils and were

36 IFDC, 1999. Estimating Rates of Nutrient Depletion in Soils of Agricultural lands of Africa. International Fertiliser Development Center, Alabama 35662, USA

37 IFDC, 1999. Estimating Rates of Nutrient Depletion in Soils of Agricultural lands of Africa. International Fertiliser Development Center, Alabama 35662, USA

38 GoM. The National Fertilizer Strategy. Unpublished and Undated Report.

39 The World Bank and Government of Malawi (2007). "Malawi – Poverty and Vulnerability Assessment: Investing in Our Future." Washington, D.C., USA

highly incompatible with smallholders' resources (Kumwenda *et al.*, 1996[40]). The GoM, through the National Fertilizer Strategy (NFS) put varied recommendations for different crops and for different fertilizers. On average, it has put a rate of 160 kg/ha across all crops regardless of the type of fertilizer (Table 2.5) (GoM). The Ministry of Agriculture of the GoM, through the Maize Productivity Task Force (MPTF) made area-specific fertilizer recommendation of 35 or 69 kg/ha of N fertilizers (urea or 23:21:0+4S) (Sauer and Tchale, 2006).

Table 2.5: Recommended fertilizer application rates (Source: National Fertilizer Strategy-GoM)

Input type	Crops	Application rate (kg/ha)	Estimated Area cultivated (ha)	Estimated required amounts (Mt)
Basal application				
23:21:0+4s	Hybrid Maize	200	354,921	70,984
DAP	Local Maize	22	912,751	20,081
UREA 46%N	Local Maize	44	912,751	40,161
23:21:0+4s	Sorghum	200	67,937	13,587
23:21:0+4s	Finger millet	200	35,165	7,033
23:21:0+4s	Wheat	100	2,483	248
23:21:0+4s	Phaseolus beans	200	171,663	34,333
DAP	Soybeans	100	40,829	4,083
compound s	Soybeans	200	40,829	8,166
23:21:0+4s	Sunflower	200	3,898	780
DAP	Cotton	100	45,023	4,502
D Compound	Tobacco	600	105,000	63,000
DAP	Sorghum	300	67,937	20,381
DAP	Rice	50	41,770	2,089
UREA 46%N	Rice	65	41,770	2,715
MOP 60%K20	Sugarcane	300	15,000	4,500
DAP	Sugarcane	300	15,000	4,500
Top dressing				
UREA 46%N	Hybrid Maize	150	354,921	53,238
CAN 27%N	Local Maize	150	912,751	136,913
UREA 46%N	Sorghum	50	67,937	3,397
UREA 46%N	Finger millet	50	35,165	1,758

40 Kumwenda, J.D.T., S.S. Snapp, V.H. Kabambe, A.R. Saka, and R.P. Ganunga. 1996. Effects of organic legume residues and inorganic fertilizers on maize yield in Malawi. Target Newsletter No. 7, Soil Fertility Network for Maize-Based Farming Systems, CIMMYT, Harare, Zimbabwe

CAN 27%N	Wheat	100	2,483	248
CAN 27%N	Sunflower	90	3,898	351
AS 21%N24%S	Cotton	100	45,023	4,502
CAN 27%N	Tobacco	400	105,000	42,000
AS 21%N24%S	Rice	45	41,770	1,880
AS 21%N24%S	Sugar cane	100	15,000	1,500

It is important to note that most of the fertilizer recommendations in Malawi are based on plant nutrient requirements and the need to boost crop yields. The majority of these recommendations disregard soil conditions and abilities, especially with respect to the impact of organic fertilizers to the overall nutrient exchange capacity of the soil (Ngwira et al., 2013[41]; Mutegi et al., 2015[42]).

3 Approach for studying soil nutrient decline in Malawi

The following approaches were used to quantify national levels of soil nutrients, nutrient losses, and mitigation measures:

- Field surveying of soil nutrient indicators and agronomic practices;
- Digital soil mapping; and
- Spatial modelling of nutrient levels and nutrient requirements.

The first approach aimed to obtain the actual nutrient indicators in farms and in deposited sediments in the bottomlands of farmer fields, agronomic practices, and farmer nutrient application and perceptions on soil nutrients and soil loss. The assessment focused on measuring soil chemical properties (nutrient indicators that are key for crop production and which are often supplemented by farmers in the form of inorganic fertilizers). The second approach was used to derive spatial information of soil properties, nutrient status, and to estimate soil nutrient deficiencies at both the macro- and micro nutrient levels. The third

41 Ngwira RA, Nyirenda M, Taylor D. 2013. Toward Sustainable Agriculture: An Evaluation of Compost and Inorganic Fertilizer on Soil Nutrient Status and Productivity of Three Maize Varieties Across Multiple Sites in Malawi, Agroecology and Sustainable Food Systems, 37:8, 859-881, DOI: 10.1080/21683565.2013.763889

42 Mutegi J, Kabambe V, Zingore S, Harawa R and Wairegi L (2015) The Fertilizer Recommendation Issues in Malawi: Gaps, Challenges, Opportunities and Guidelines: Soil Health Consortium of Malawi. CABI, Nairobi.

approach is to describe and relate soil characteristics, nutrient decline, fertilizer application characteristics, and agronomic practices in the entire country.

3.1 Field survey of soil nutrients and agronomic characteristics

3.1.1 Data requirements

Data needs for quantification of soil nutrients and agronomic practices are: 1) soil nutrient indicators which include N, P, K, OC, pH, Zn, Mg, Ca, S, Fe, Na, and Mn; 2) soil texture and soil loss rates; 3) types of fertilizers used and their application rates, soil conservation measures, crops grown and acreages, and farmer opinions with regard to soil loss, nutrient loss and soil management.

3.1.2 Data collection

Soil nutrient data and agronomic practices were surveyed at the farm level throughout the country (Figure 3.1). A stratified random sampling of one in every 50 sample locations studied during 2010 soil mapping exercise and all locations studied during the 2014 soil loss study were visited for re-sampling during this study. In addition, the soil deposits at the bottomlands of each sampling points were sampled. About 700 samples were collected during the survey.

Data collection was carried out in the field and in the laboratory. In the field, the following data were collected: in situ soil loss rates, soil pH, and infiltration rates. Soil loss rates were determined using the methods outlined in Omuto and Vargas (2009[43]) and Stocking and Murnaghan (2000[44]). Infiltration rates and soil pH were determined using the soil testing kit (USDA, 1999[45]).

43 Omuto CT, Vargas RR. 2009. Combining pedometrics, remote sensing and field observations for assessing soil loss in challenging drylands: a case study of northwestern Somalia. Land Degradation & Development 20: 101-115

44 Stocking M, Murnaghan N. 2000. Handbook for the Field Assessment of Land Degradation. Earthscan Publication, London

45 USDA. 1999. Soil quality test kit. USDA.https://www.nrcs.usda.gov/

Figure 3.1: Field data collection

Soil samples were collected from the field for further laboratory analyses. The samples were: disturbed samples for analysis of plant available soil nutrients and undisturbed samples for bulk density. Sampling and in-situ testing were done for topsoil (0 cm - 30 cm) depths only.

In the laboratory, soil samples from the field were tested for chemical indicators of soil nutrients. The nutrient indicators were: N, P, K, OC, pH, Zn, Mg, Ca, S, Fe, Na, and Mn. The analyses were done at the Agricultural Research and Extension Trust (ARET) laboratory in Lilongwe (http://www.aret.org.mw/).

The data collection was done by dedicated staff split in three groups corresponding to the three regions of the country (north, central and south). The data collection was facilitated and monitored using a mobile application software containing data entry forms and checklists. The agronomic practices at each farm were collected using the pre-loaded interview questionnaires in the mobile application software. All data points were georeferenced and transmitted in real-time to a centrally located server (Figure 3.2).

Figure 3.2: Mobile application for real-time data collection and survey monitoring

3.2 Digital soil mapping

3.2.1 Data requirements

In terms of digital soil mapping (DSM), the needed data for spatial mapping of soil nutrient status are also known as SCORPAN factors (McBratney *et al.*, 2003[46]). They include:

- Soil map (representing S factor in the SCORPAN factors);
- Mean annual rainfall (representing C factor);
- Land use/cover maps (representing O factor);
- Altitude/DEM map (representing R); and
- Geological map (representing P).

3.2.2 Data collection

The SCORPAN factors were obtained as indicated in Table 3.1. The data was collected as GIS databases using portable hard drives.

46 McBratney A.B, Santus M.L.M., Minasny B. 2003. On digital soil mapping. Geoderma, 117, 3 – 52

Table 3.1: Sources of SCORPAN factors for DSM

SCORPAN factor	Source
Soil data and soil map	FAO and LRCD, field survey and laboratory analyses
Mean annual rainfall	The meteorology department of Malawi
Altitude map (ASTER DEM)	Downloaded from https://lty.usgs.gov
Land use/cover map	Survey Department and LRCD
Geology map	Survey Department
SCORPAN factor	**Data characteristics**
Soil data	Topsoil as described in section 3.1.2 of this report
Soil map	1:200,000 GIS vector map with over 4500 data points
Rainfall	Monthly mean rainfall amounts from 77 stations between 2010 and 2017
EM	30-m resolution GIS raster map
Land cover map	1:200,000 GIS vector map
Geology	1:1, 000, 000 GIS vector map

3.2.3 Data analysis and mapping

In the process of mapping the soil nutrient dynamics, laboratory data was first statistically analysed to obtain the representative nutrient content of the sampled locations. The statistics were then used to derive the nutrient availability of the topsoil in kg/m² for the sampled locations using the laboratory measurement units, soil bulk density, soil depth and conversion factors as follows:

$$Nutrient\left(\frac{kg}{m^2}\right) = soildepth\,(m) * bulkdensity\left(\frac{g}{cm^2}\right) * labnutrientcontent\,(units) * F \quad (1)$$

Where, F is the unit's conversion factor depending on the reported units of the laboratory analysis.

Once the nutrient levels were estimated, they were then subjected to DSM modelling to produce the spatial distribution of the nutrient indicator. In the DSM paradigm, the spatial modelling expression is as follows:

$$Nutrient\left(\frac{kg}{m^2}\right) = f\,(S, C, O, R, P, A, N\,) + \varepsilon \quad (2)$$

Where the terms in the bracket are the DSM predictors (Table 3.1), e is the prediction error term which is assumed as e @ IID (0, 1), and f is the prediction model. In this study, f was carefully chosen between the Random Forest (Breiman, 2001[47]) or Regression Kriging (Omuto

47 Breiman L. 2001. Random Forests. Machine Learning. 45 (1): 5–32. doi:10.1023/A:1010933404324

and Vargas, 2015[48]) depending on the level of accuracy with a quarter-sample holdout cross-validation (Figure 3.3).

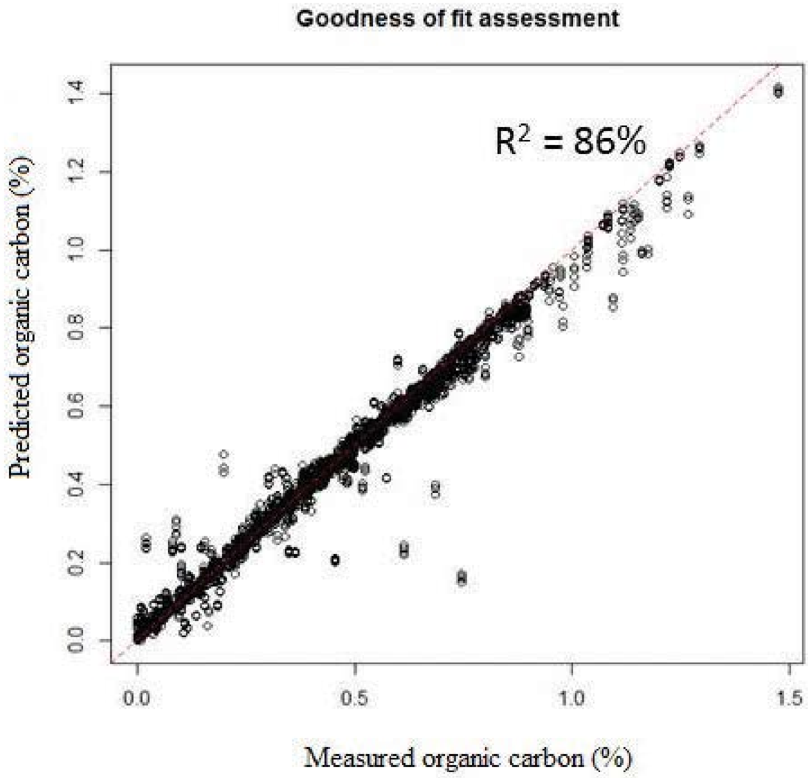


Figure 3.3: Example of goodness-of-fit diagnosis for spatial modelling of organic carbon

Topsoil loss rates were determined using the SLEMSA modelling approach and validated using the field-measured topsoil loss rates. The model, its input data, and implementation strategies were those reported in Vargas and Omuto (2016[49]). The topsoil loss rate map was used to determine the nutrient loss maps of Malawi.

$$Nutrientloss\left(\frac{kg}{m^2}\right) = Nutrientmap * soillossmap * H \quad (3)$$

Where, H is a conversion factor to account for the differences in measurement units of the input data. Equation (3) was repeated for 2010 to 2017 in order to estimate the trend of soil nutrient loss in the country. The trend was used to highlight areas that have consistently lost soil nutrients over the years and earmark them either as bright spots (low steady decline) or

48 Omuto CT, Vargas RR. 2015. Re-tooling of regression kriging in R for improved digital mapping of soil properties. Geosciences Journal, 19(1): 157-165.

49 Vargas RR, Omuto CT. 2015. Soil loss assessment in Malawi. FAO. http://www.fao.org/3/a-i6387e.pdf

hotspots (severe cases). In addition to the quantification of loss of soil nutrients, analysis was also done to determine the difference between nutrient requirement (for dominant crops) and nutrient availability (and the risk of nutrient loss) to establish sustainable options for nutrient management.

3.2.4 Capacity development and soil mapping

The participatory-learning approach was used during capacity building and digital soil mapping in order to allow for equipment and knowledge transfer, to encourage participation, and to deliver some of the final output maps required for the soil nutrient assessment. The approach simultaneously mingled intellectual and technology transfer with equipment and software transfer, development of online system for data collection and management, and production of soil maps for uploading into the online system (Figure 3.4).

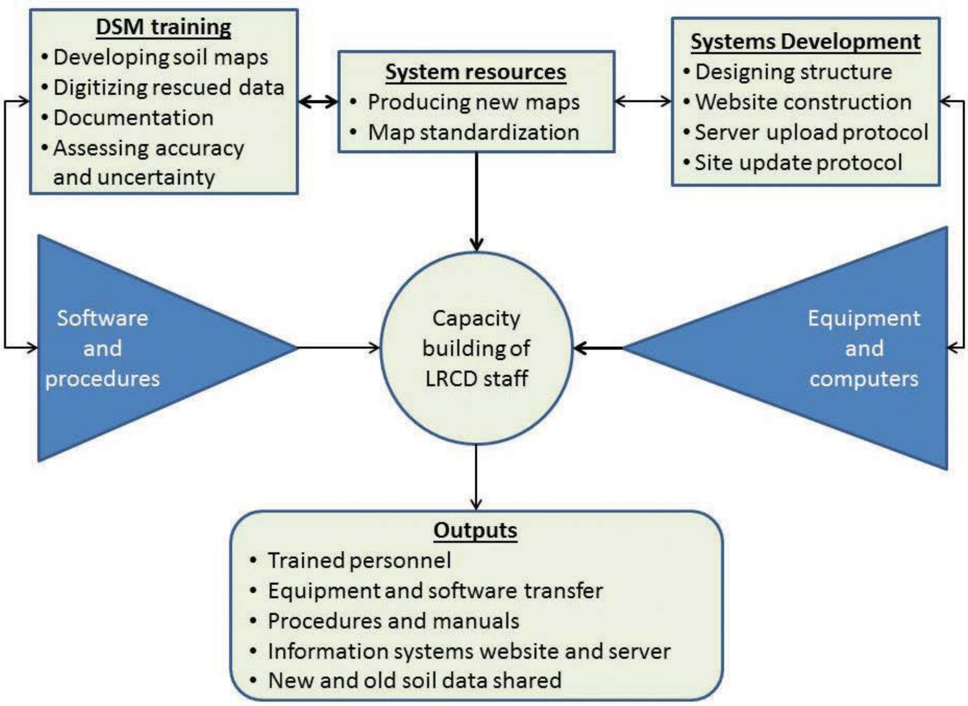


Figure 3.4: DSM capacity building framework

4 Soil nutrient dynamics

4.1 Nutrient level dynamics

4.1.1 Field and laboratory observations

The locations which were sampled in 2010 were sampled again in 2017 and similar soil nutrient indicators determined. In both years, the sampling was done after harvest but before land preparation for the next planting season. Table 4.1 gives the summary statistics of the results. It shows that, assuming that all factors remain unchanged, there is a general decline in soil pH in most districts (see Figure 4.1). These results corroborate the observation made in Section 2.3 indicating a general tendency of acidification of the soils in the country between 2010 and 1998. Most affected districts regarding soil acidification are: Lilongwe, Neno, Chiradzulu, Mulanje, Ntcheu and Nkhotakota (see Figure 4.1).

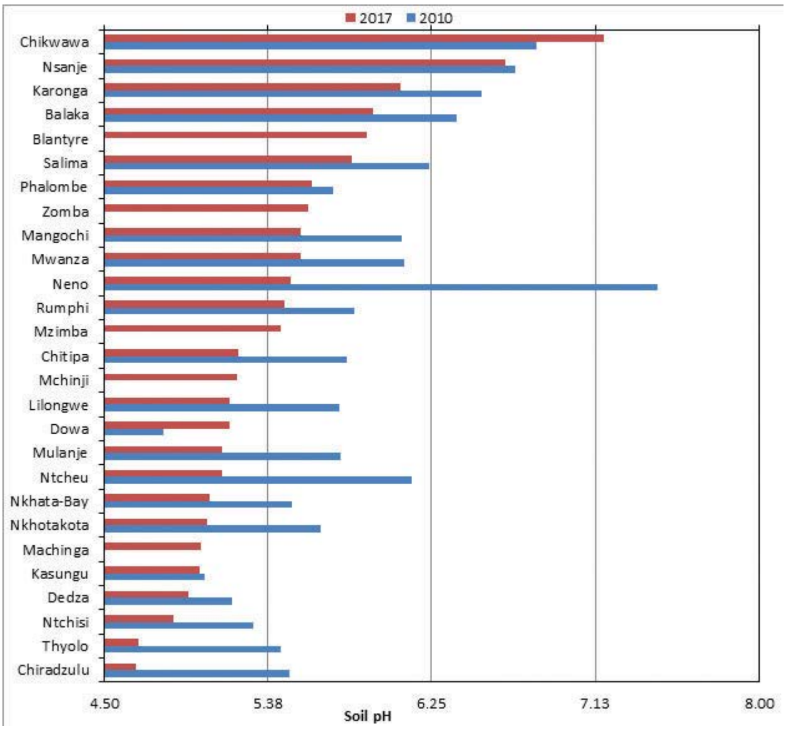


Figure 4.1: Changes in soil pH between 2010 and 2017

Kasungu, Thyolo, Ntchisi, Dedza and Dowa districts seem to have comparatively low topsoil pH while Chikwawa, Nsanje, and Karonga districts have relatively high (suitable) topsoil pH (Figure 4.1). It is important to note that the majority of sampled soils in Kasungu, Thyolo, Ntchisi, and Machinga, were Lixisols, Alisols, and Ferralsols, while in Dowa and Lilongwe Luvisols were the most commonly sampled soil types. Although some of these soil types are naturally acidic, application of (ammonium-based nitrogen) fertilizer can accelerate their soil acidification (van Raij, 1991[50]).

The trend of acidification of soils in Malawi will pose challenges to soil nutrient status. According to previous studies, low soil pH (< 5.4) can affect availability/plant uptake of certain nutrients, and consequently affect agricultural productivity (e.g. Janssen *et al*. 1990[51] and Landon, 1991[52]). In Malawi, the situation may be made worse given the progressive decline in soil pH as indicated in some Districts in Figure 4.1. In addition, there are imminent threats of aluminium toxicity with increasing soil acidity. Normally, Aluminium (Al) becomes available if the pH falls below a certain threshold and may cause toxicity problems in soils if exchangeable Al is high. Although there are scanty reports of aluminium toxicity in Malawi, some studies have signalled possibilities for the risk of aluminium toxicity in southern Malawi tea estates and in isolated high altitude areas in central regions (Aggarwal *et al.*, 1997[53]). There is a notable concern for soil acidification in the central region where the main grain production in Malawi is located. An alarm was raised by Snapp (1998) more than 20 years ago, implying strong evidence that the region is slowly losing its agricultural productivity due to acidification. With the central region being the most agriculturally productive area of the country, its increasing trend of acidification could be linked to the fertilizer-use efforts in Malawi.

One of the major consequences of soil acidification is the decline in basic cations such as Ca^{2+} and Mg^{2+} (Myers and De Pauw, 1995[54]). At low pH levels, exchangeable Ca^{2+} and Mg^{2+} decrease with falling soil pH, owing to their poor competition with Al^{3+} for the exchange sites. Consequently, these conditions often create deficiencies of these cations that are responsible for plant growth. As seen in Table 4.1, the majority of districts with declining soil pH also showed a corresponding decline of exchangeable Ca^{2+} and Mg^{2+}. Although the soil acidification may potentially lower the amount of exchangeable cations, soluble forms of the cations may increase but become liable to leaching. Nutrient leaching can be detected in effluent water or sediment plumes (and eutrophication) in the water bodies at the bottom of catchment areas.

50 Van Raij B. 1991. Fertility of acid soils. In: Wright R.J., Baligar V.C., Murrmann R.P. (eds) Plant-Soil Interactions at Low pH. Developments in Plant and Soil Sciences, vol 45. Springer, Dordrecht

51 Janssen, B.H., F.C.T. Guiking, D. van der Eijk, E.M.A. Smaling, J. Wolf, and H. van Reuler. 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46:299-318.

52 Landon, J.R. 1991. Booker Tropical Soil Manual. Longman Science and Technical, Essex, England

53 Aggarwal, V.D., S.K. Mughogho, R.M. Chirwa, and S.S. Snapp. 1997. Field-based screening methodology to improve tolerance of common bean to low-P soils. Communications in Soil Sci. Plant Anal. 28(17&18):1623-1632

54 Myers R.J.K., De Pauw E. (1995) Strategies for the management of soil acidity. In: Date R.A., Grundon N.J., Rayment G.E., Probert M.E. (eds) Plant-Soil Interactions at Low pH: Principles and Management. Developments in Plant and Soil Sciences, vol 64. Springer, Dordrecht


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Table 4.1: Comparative summary results of soil nutrient indicators in 2010 and 2017 from the same sample locations

Region	ADD	District	pH	OC	N	P	K	Ca	Mg
				%		ppm	cmol/kg		
North	Karonga	Chitipa	5.80	0.668	0.058	8.95			
		Karonga	6.52	0.787	0.068	73.69			
	Mzuzu	Nkhata-Bay	5.50	0.894	0.077	23.81	0.214	7.969	1.751
		Rumphi	5.84	0.764	0.066	62.19			
		Mzimba							
Average			5.91	0.78	0.07	42.16	0.21	7.97	1.75
Central	Lilongwe	Dedza	5.18	1.157	0.100	59.30	2.177	3.367	1.527
		Lilongwe	5.76	0.995	0.086	30.92	0.486	4.525	1.170
		Ntcheu	6.14	0.835	0.072	16.36	0.000	7.791	2.892
	Salima	Nkhotakota	5.66	0.576	0.050	8.18	0.001	5.905	2.349
		Salima	6.23	0.802	0.069	13.60	0.000	5.019	0.112
	Kasungu	Kasungu	5.04	0.602	0.052	7.86	0.189	3.820	1.763
		Dowa	4.82	1.162	0.100	3.79	0.190	1.454	1.106
		Ntchisi	5.30	1.046	0.090	8.20	0.779	4.808	1.464
		Mchinji							
Average			5.52	0.90	0.08	18.53	0.48	2.21	1.11
South	Shire Valley	Chikwawa	6.81	1.038	0.076	32.68	0.292	6.340	0.901
		Nsanje	6.70	0.758	0.065	27.23	0.231	4.206	0.939
	Blantyre	Chiradzulu	6.49	0.634	0.055	128.74	0.407		
		Mulanje	5.76	0.919	0.079	57.01	0.576	5.562	0.403
		Mwanza	6.10	0.984	0.085	100.82	0.458		
		Neno	7.46	0.791	0.068	119.67	0.720		
		Blantyre							
		Phalombe	5.72	1.233	0.107	16.49	0.374	2.579	2.654
		Thyolo	5.44	0.749	0.065	93.56	0.374		
	Machinga	Mangochi	6.09	1.406	0.078	24.40	0.138	4.918	0.880
		Balaka	6.38	1.066	0.053	23.050	0.139	8.817	1.595
		Machinga							
		Zomba							
Average			6.29	0.96	0.07	62.36	0.37	2.90	1.23
	Grand Total		5.986	0.957	0.076	43.934	0.417	3.505	1.733

Using the soil attributes in 2010 and 2017, probability distributions of the nutrient indicators were determined (Figure 4.2). This was done to establish the threshold soil nutrient availability and to compute nutrient requirements.

	pH	OC	N	P	K	Ca	Mg
		%		ppm	cmol/kg		
	5.22	0.654	0.066	13.64	0.551	5.229	3.535
	6.08	1.207	0.123	28.68	0.311	6.324	1.666
	5.06	1.412	0.169	32.02	0.274	5.206	1.985
	5.46	0.467	0.048	36.86	0.500	4.122	0.905
	5.44	0.574	0.058	38.51	0.508	4.155	1.332
	5.45	0.86	0.09	29.94	0.43	5.01	1.88
	4.95	1.110	0.113	30.82	0.583	3.172	2.272
	5.17	0.962	0.112	25.10	0.489	4.232	1.260
	5.13	0.759	0.078	55.22	0.350	6.116	2.796
	5.05	0.764	0.078	37.00	0.575	4.946	1.508
	5.82	0.982	0.100	50.69	0.450	4.733	1.643
	5.01	0.700	0.071	37.75	0.315	3.158	1.540
	5.17	1.123	0.114	48.12	0.479	4.258	1.426
	4.87	1.014	0.103	22.03	0.337	3.621	1.468
	5.21	0.657	0.067	41.21	0.456	5.289	1.429
	5.15	0.90	0.09	38.66	0.45	4.95	1.70
	7.17	1.189	0.121	26.63	0.806	3.702	1.539
	6.64	0.796	0.082	48.90	0.510	2.344	1.897
	4.67	1.037	0.105	39.81	0.386	4.462	1.864
	5.13	1.057	0.107	17.50	0.640	4.185	1.301
	5.55	0.498	0.051	32.64	0.391	5.515	1.986
	5.50	0.946	0.096	22.40	0.406	1.615	2.597
	5.91	0.947	0.096	23.28	0.378	4.879	1.171
	5.61	0.722	0.074	23.10	0.540	2.231	1.214
	4.68	1.157	0.118	41.97	0.537	3.809	2.019
	5.55	0.953	0.097	48.49	0.551	3.797	1.229
	5.94	0.520	0.053	53.82	0.486	5.974	2.055
	5.78	0.313	0.032	45.40	0.405	2.934	1.905
	5.59	0.619	0.063	46.07	0.287	6.810	1.419
	5.61	0.83	0.08	36.15	0.49	5.71	1.94
	5.478	**0.93**	**0.095**	**38.312**	**0.534**	**4.73**	**2.223**

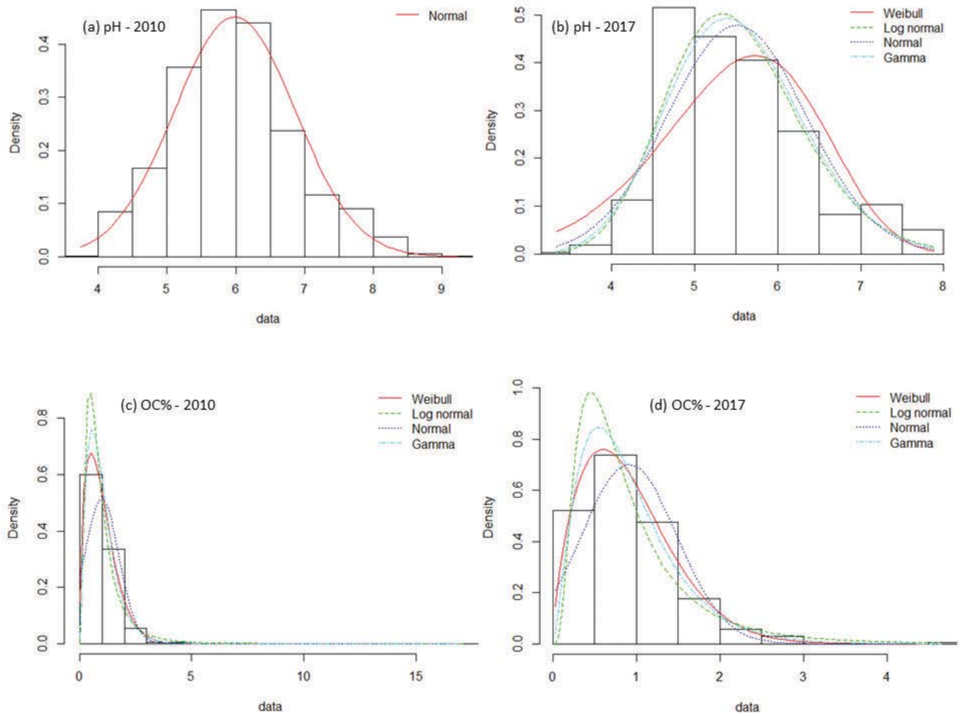


Figure 4.2: Fitting probability distribution to measure soil nutrient indicators

The majority of the indicators had a log normal distribution. Using this probability distribution and reported critical soil pH ≥ 5.2 for (say) maize production in Malawi (Snapp, 1998), then in 2010, more than 77% of all the ADDs were above the critical topsoil pH except in Kasungu in which only 39% of the ADD were above the critical soil pH for maize production (Table 4.2). In 2017, all the ADDs declined in the proportionate areas with topsoil pH ≥ 5.2, except Kasungu, that nearly remained constant with 40% of the ADDs still above the critical soil pH of 5.2 (Table 4.2). In 1998, Snapp (1998) found that: 78% of Blantyre ADD had pH > 5.2; 87.9% of Karonga ADD had a pH>5.2; 99.2% of Kasungu ADD; 66.1% of Lilongwe ADD; and 87.1% of Mzuzu ADD. From these findings it seems that there could have been a steady increase in areas affected with soil acidity in the country over the years.

Table 4.2: Proportion of the ADD's with topsoil pH ≥ 5.2 (critical pH for maize production)

Agriculture Development Division (ADD)	2010			2017		
	Mean pH	St.Dev (pH)	Proportion of area (%) with pH ≥ 5.2	Mean pH	St.Dev (pH)	Proportion of area (%) with pH ≥ 5.2
Blantyre	6.17	0.139	89.80	5.29	0.149	54.56
Karonga	6.16	0.136	90.10	5.65	0.153	70.82
Kasungu	5.05	0.107	39.11	5.07	0.108	39.61
Lilongwe	5.69	0.120	77.67	5.08	0.081	38.51
Machinga	6.24	0.088	99.15	5.50	0.092	73.09
Mzuzu	5.67	0.116	77.65	5.32	0.120	57.54
Shire Valley	6.76	0.097	100.00	6.91	0.108	83.63
Salima	5.95	0.116	88.39	5.44	0.106	66.59

A similar approach was used to deduce spatial proportions of the country above critical levels of OC, N, P, K, Ca, Mg, and Zn nutrient indicators. It is important to note that the drop in soil pH could decrease nutrient availability in the soil. Furthermore, the decline in nutrient availability may also be due to soil loss problems. Combined assessment of acidification and soil loss problems can potentially identify areas with nutrient depletion and magnitude of required nutrients (e.g. through fertilizer application or manuring) to sustain agricultural productivity.

4.1.2 Spatial distribution of topsoil nutrient levels

Analysis of spatial distribution of topsoil pH showed the most affected areas with low pH (Figure 4.3). In Karonga ADD, the most affected areas were Chisenga, Musuku, and Kavukuku EPAs in Chitipa district. Chisenga and Musuku EPAs have Haplic Lixisol as the major soil type while the in Kavukuku EPA, the most affected areas have Haplic Lixisol and Ferralic Cambisol. Although Lixisols naturally have a nearly neutral pH and low cation exchange capacity, they are susceptible to acidification from excessive fertilizer application (owing to their low natural soil fertility).

In Mzuzu ADD, the affected areas increased by about 20% between 2010 and 2017 (Table 4.2). The most affected areas are in Mzimba district and they include Mbawa, Manyamula, Champira, Vibangalala, Kazomba, Luwelezi, KhosoloBulala, Njuyu, and Emsizini EPAs. All these areas are dominated by Haplic Lixisol except Khosolo, which is dominated by the Haplic Ferralsol soil type. In Nkhata Bay District, the western parts of the district in Chitheka and Chikwina EPAs are the areas affected with acidification. In Chitheka, the soil is mainly Rhodic Ferralsol whereas in Chikwina the soil is Haplic Lixisol. Generally, Ferralsols are slightly acidic soils (ISSS Working Group RB, 1998[55]). However, their pH can also drop as a result of continuous application of nitrogenous fertilizers. In Rumphi district, the Nyika National Park EPA is the only area with low soil pH. This is mainly due to the acidic nature of the inherent Haplic Acrisols that dominate the soil types in the area. The soil pH has fairly remained at the same level between 2010 and 2017. This could be due to the area being a protected national park.

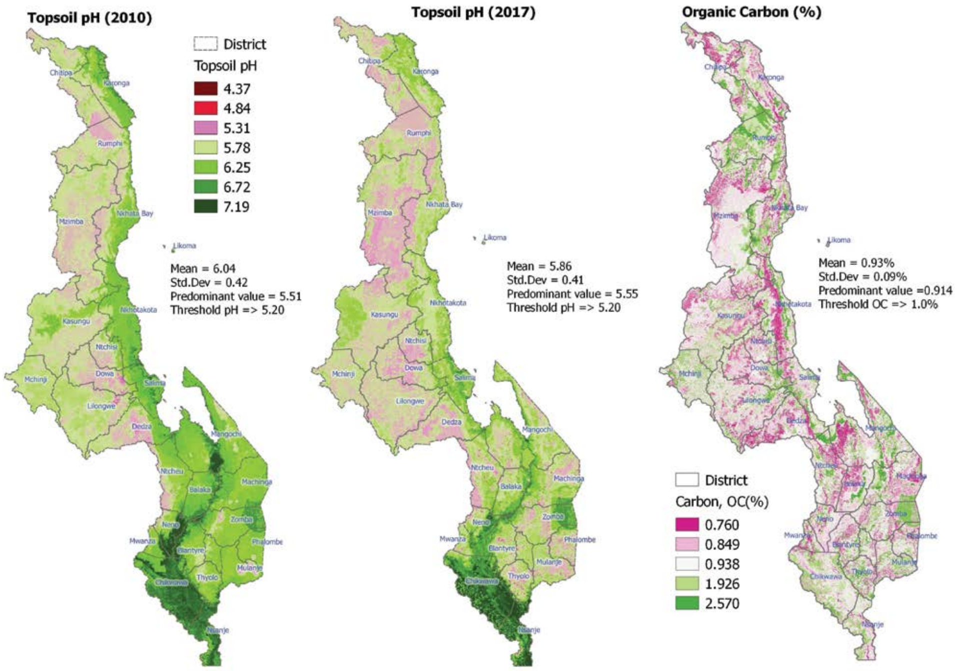


Figure 4.3: Spatial distribution of topsoil pH in 2010 and 2017 and organic carbon in 2017

In Kasungu ADD, Dowa and Ntchisi districts are the most affected by the issue of acidification. Some parts of the northern and eastern Kasungu districts were also partly affected by acidification (see Figure 4.3). In the Dowa district, Mponela, Mndolera, Chibwala, and western Nachisaka are the affected EPAs. In Ntchisi, Bowe, Chipukwa, and Kalira are the affected EPAs while in Kasungu Kaluluma and Chamama are the affected EPAs. The major soil type in these affected areas is Chromic Luvisol. Luvisols generally have a high base saturation, high cation exchange capacity, and fertile conditions with a pH ranging from 6.9 to 7.9. However, the cation exchange capacity can drop with decreasing pH.

Lilongwe ADD seems to be the most affected ADD in Malawi by the problem of soil acidification (Table 4.2). Nearly half of the ADD showed a decrease in topsoil pH between 2010 and 2017; implying that most of the areas were affected. Indeed, when conducting a

55 ISS Working Group RB. 1998. World Reference Base for Soils Resources: Atlas (Bridges *et al.* Eds). ISRIC-FAO-ISSS-Acco. Leuven.

spatial analysis, almost all EPAs showed dropping soil pH levels except for the Dzalanyama Ranch EPA (see Figure 4.3). Interestingly, the ADD, which is dominated by Chromic Luvisols (over 80%) and Eutric Cambisols (20%), the Cambisol areas (including Dzalanyama Ranch EPA) were least affected by a decline in soil pH.

In the Machinga ADD, Zomba and Machinga districts had the lowest soil pH. The affected EPAs were: Msondole, Mpokwa, Thondwe and Malosa in Zomba and Chikweo, Nampewa, Nanyumbu, and Mtubwi in Machinga. Katuli and Chilipa in the Mangochi district were also slightly affected. In Zomba, the affected areas are dominated by Chromic Luvisol and Eutric Cambisol soil types, while in the Machinga district, the affected soil types are Haplic Luvisol and Haplic Lixisol in Katuli, Mangochi district.

In the Blantyre ADD, Mulanje, Thyolo, Blantyre, Phalombe, and Mwanza seem to have been the most affected districts by soil acidification. Similarly to the other districts, the affected soils were Cambisols and Luvisols. However, in Phalombe (Milonde and Waluma EPAs) and Thyolo (Thyolo EPA) districts, the most affected soil is the Humic Alisol. Alisols are naturally acidic soils with a slight aluminium saturation. Consequently, they are expected to have a low soil pH. In fact, in most places they are used for growing aluminium tolerant crops such as tea, rubber and oil palm.

Overall, it can be said that the soils affected by acidification problems are the Lixisols in the northern region, Luvisols in central region, and Luvisols, Cambisols and pockets of Lixisols in the southern region. Acidic soils such as Acrisols and Ferralsols in the north and Alisols in the south may also be slightly affected by a decline in soil pH. One of the potential risks of acidification in these soils could be inappropriate fertilizer application in the agricultural areas. As pointed out by various researchers in Malawi, the long-term use of blanket fertilizer recommendations for these soils could be a potential contributor to the soil acidification problems (Kumwenda *et al.*, 1996[56]; Ngwira *et al.*, 2013[57]; Mutegi *et al.*, 2015[58]).

<u>NPK soil nutrients</u>

Spatial distribution of the NPK soil nutrients in 2017 showed that exchangeable K may not be a significant problem in Malawian topsoil except in Kasungu, Thyolo, Zomba, and Machinga districts (Figure 4.4). In these areas, exchangeable K was below the critical level both in 2010

56 Kumwenda, J.D.T., S.S. Snapp, V.H. Kabambe, A.R. Saka, and R.P. Ganunga. 1996. Effects of organic legume residues and inorganic fertilizers on maize yield in Malawi. Target Newsletter No. 7, Soil Fertility Network for Maize-Based Farming Systems, CIMMYT, Harare, Zimbabwe

57 Ngwira RA, Nyirenda M, Taylor D. 2013. Toward Sustainable Agriculture: An Evaluation of Compost and Inorganic Fertilizer on Soil Nutrient Status and Productivity of Three Maize Varieties Across Multiple Sites in Malawi, Agroecology and Sustainable Food Systems, 37:8, 859-881, DOI: 10.1080/21683565.2013.763889

58 Mutegi J, Kabambe V, Zingore S, Harawa R and Wairegi L (2015) The Fertilizer Recommendation Issues in Malawi: Gaps, Challenges, Opportunities and Guidelines: Soil Health Consortium of Malawi. CABI, Nairobi.

and 2017. Reports by Snapp (1998[59]), Lakudzala (2013[60]), and Njoloma *et al*. (2016[61]) also indicate that the majority of soils in the country seem to have sufficient levels of exchangeable K. This implies that, over the years, exchangeable K may be sufficiently available in Malawian soils. However, for available organic P and total N, there seem to be some deficiencies in certain parts of the country (Figure 4.4).

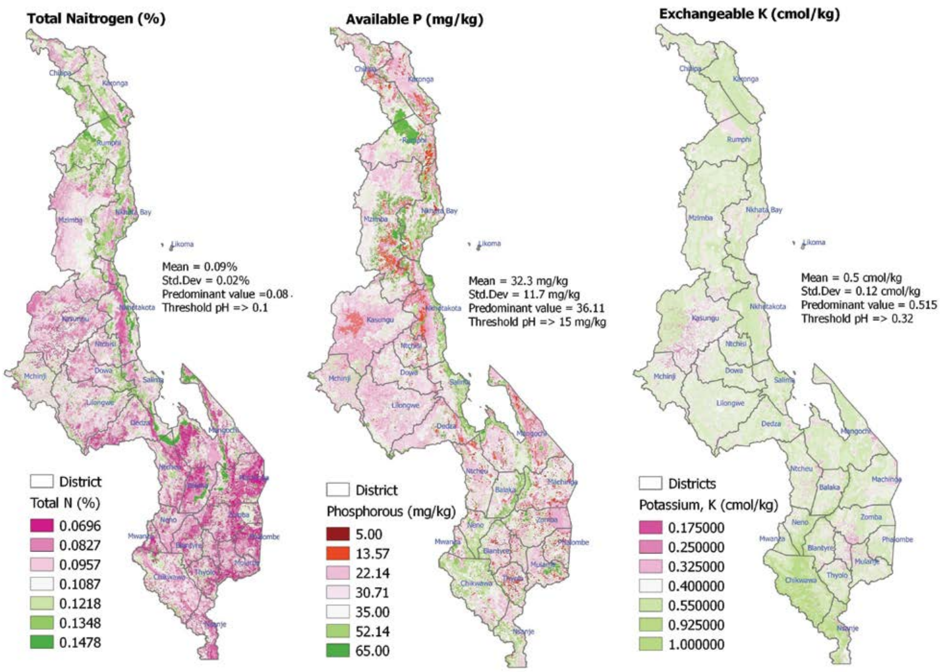


Figure 4.4: Spatial distribution of NPK topsoil nutrient indicators in 2017

In northern Malawi, the areas with low available organic P were: central to southern Chitipa district (Chisenga and Kavukuku EPAs); Karonga district; Nkhata Bay district (Chikwina, Mphompha, Mpamba, and Chiweta EPAs), and in Mzimba district (Champira, Kazomba, Njuyu, and EMsizini EPAs). These areas were also identified by Mhango *et al*. (2008[62]) as areas with soils having low available P. The main soil types with low available soil P in these areas are: Haplic Lixisol, Rhodic Ferralsols, Ferralic Cambisols, Eutric Cambisols and Eutric Fluvisols. Most of these soils have a slightly acidic to neutral soil pH levels and acidification problems were reported (Figure 4.2). Hence, they can potentially experience

59 Snapp SS. 1998. Soil nutrient status of smallholder farms in Malawi. Communications in Soil Science and Plant Analysis, 29(17):2571-2588

60 Lakudzala DD. 2013. Potassium response in some Malawi soils. International Letters of Chemistry, Physics and Astronomy 8(2): 175-181.

61 Njoloma JP, Sileshi WG, Sosola BG, Nalivata PC, Nyoka BI. 2016. Soil fertility status under smallholder farmers' fields in Malawi. African Journal of Agricultural Research, 11(19): 1679-1687

62 Mhango WG, Mughogho SK, Sakala WD, Saka AR. 2008. The effect of phosphorous and Sulfur fertilizers on grain legume and maize productivity in northern Malawi. Bunda Journal of Agriculture, Environmental Science and Technology, 3: 20-27.

oxidation of soil P. Oxidation of soil P can produce unavailable forms of P and result in the decline in bioavailable P (Arai and Sparks, 2007[63]). Most of the areas with adequate/high available P values were mainly those that still had natural vegetation cover and farmer fields which received adequate P fertilization. The areas with natural vegetation are the protected areas such as Nyika National Park in northern Rumphi district and pockets of forest reserves in Musuku EPA in the north Karonga district and in Vinthuku EPA in the south Karonga district. The forest reserve in eastern Mzimba and western Nkhata Bay districts also showed relatively high values of available P (Figure 4.4).

In the central region, the areas with low available P include the central Lilongwe district, eastern to northern Ntchisi district, northern Nkotakota district, south-eastern Dedza district, central Kasungu district, and northern Ntcheu district (see Figure 4.4). Here, the most affected soil types are Cambic Arenosols in central Kasungu district, Cambisols in northern Nkotakota district, and Eutric Cambisols in Dedza, Ntchisi, and Ntcheu districts. The Luvisols (in the Lilongwe district) and along the lake shore in the Salima district do not seem to have been affected by soil P depletion. This may be due to P fertilization by farmers.

In the southern region, all the areas with low soil available P had Eutric Cambisols, Haplic Lixisol, and Humic Alisol (in Thyolo and Mulanje Districts). Since these areas and soils also showed acidification problems, it can be said that the low available P were largely due to the acidic reaction in such soils.

The assessment of total N was done as an index of soil nitrogen content (Robinson, 1968[64]; Bordoloi *et al.*, 2013[65]; Mariano *et al.*, 2017[66]). The spatial distribution of total N showed an indication of deficiency in soil nitrogen in the country (see Figure 4.4). This pattern was also observed in the soil analysis of 2010; implying a strong indication of N deficiency in most soils in Malawi.

Spatial analysis of other elements in the soil also revealed significant deficiencies throughout the country in addition to a trend decline in mean values between 2010 and 2017. Most affected areas are croplands and some of the rangelands (Figure 4.5). Fe content in the soil was not found to be largely deficient, as the levels were higher than 10 mg/kg except in Shire Valley (Table 4.3). The mean levels of Manganese > 20 mg/Kg could be cause for concern, especially in Blantyre, Karonga, Lilongwe, Mzuzu, and Salima ADDs where there could be the threat of toxicity (Millaleo *et al.*, 2010[67]).

63 Arai Y, Sparks DL. 2007. Phosphate reaction dynamics in soils and soil minerals: a multiscale approach. Advances in Agronomy, 94:135–179

64 Robinson JBD. 1968. Chemical Index for Available Soil Nitrogen. East Agricultural & Forestry Journal 33:299-301.

65 Bordoloi LJ, Singh AK, Kumar-Manoj P, Hazarika S. 2013. Evaluation of nitrogen availability indices and their relationship with plant response on acidic soils of India. Plant Soil Environment 59(6): 235-240.

66 Mariano E, Otto R, Monezano FZ, Cantarella H, Trivelin PCO. 2017. Soil nitrogen availability indices as predictors of sugarcane nitrogen requirements. European Journal of Agronomy, 89: 25-37.

67 Millalleo R, Rayes-Diaz M, Ivanov AG, Mora ML, Alberdi M. 2010. Manganese as essential and toxic element for plants: transport, accumulation and resistance mechanisms. J. Soil Sci. Plant Nutr. 10 (4): 476 - 494

Table 4.3: Summary of iron and manganese contents in soil in 2017

	Iron, Fe^{2+} (mg/kg)				Manganese, mn^{2+} (mg/kg)			
ADD	Mean	Std. Dev	Max	Min	Mean	Std. Dev	Max	Min
Blantyre	21.04	13.95	76.06	1.42	24.42	12.12	78.65	4.07
Karonga	15.03	7.70	40.91	1.60	25.37	13.53	63.01	1.74
Kasungu	13.63	7.40	42.74	0.99	21.54	11.19	41.50	0.90
Lilongwe	22.68	16.58	137.58	0.95	27.41	12.68	73.32	3.52
Machinga	13.95	7.29	32.16	0.05	19.31	9.58	39.79	0.06
Mzuzu	16.68	11.84	58.44	0.71	24.01	17.02	72.26	0.48
Salima	28.68	29.49	128.28	1.57	26.05	9.54	41.54	6.23
Shire Valley	7.56	8.34	31.52	0.79	9.96	7.40	38.74	1.34
Average	17.49	14.7	137.58	0.05	22.49	13.14	78.65	0.06

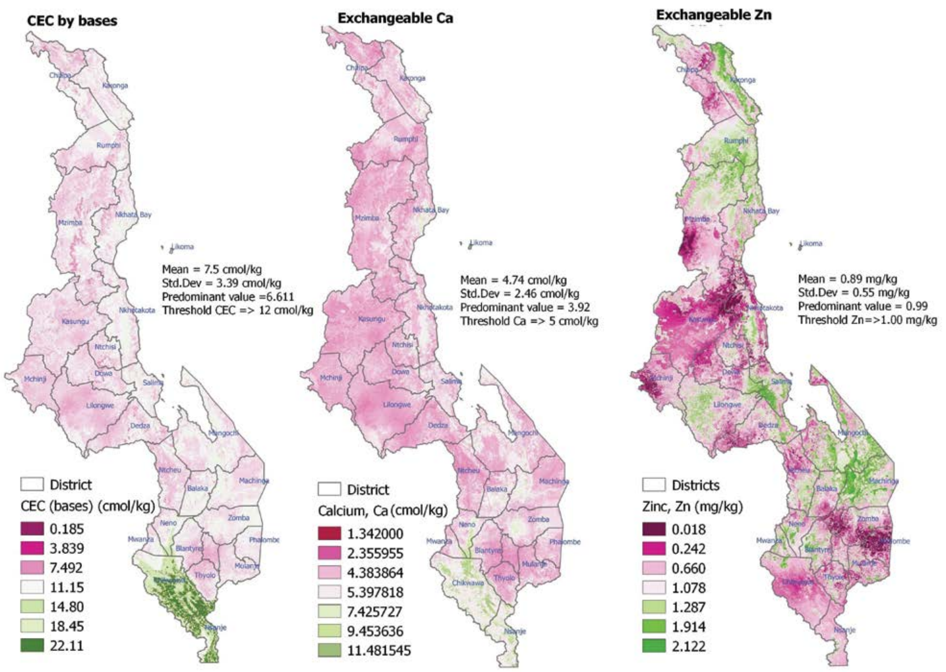


Figure 4.5: Spatial distribution of soil nutrients from field measurements in 2017

The spatial analysis of soil nutrients in Malawi showed significant deficiencies in certain key soil nutrients that are crucial for plant growth and development. These nutrients include N, P, Ca, and Zn. This implies that the harvested crops may also be lacking these essential elements unless appropriate fertilizers had been used to supplement these nutrients during plant development (Joy *et al.*, 2015[68]). Early studies indicate that K was available in adequate levels in most places in the country (Nkhoma, 1986[69]; Snapp, 1998). However, recent studies have shown a declining trend; implying that K could be soon in the category of deficient soil nutrient in Malawi (Lakudzala, 2013[70]).

4.1.3 Changes in soil carbon stock

Soil Organic Carbon (SOC) is an important indicator of soil quality. It is a well-known source of N, P and S in the soil. Besides holding positively charged potassium (K+), calcium (Ca++), and magnesium (Mg++) ions in the soil, SOC provides natural chelates that maintain micronutrients such as zinc, copper, and manganese in forms that plants can use (Bot and Benites, 2005[71]). Furthermore, the growth-promoting substances produced during organic matter decomposition and the structure it gives to soil tilth help the plant develop a more extensive root system, allowing it to obtain nutrients from a larger volume of soil. SOC is globally recognized as the largest store of terrestrial carbon and a major player in climate change factors.

SOC, like other soil properties, is influenced by factors such as climate, topography, parent material, soil fauna, and land use practices (Gray *et al.*, 2016[72]). Soil fauna and land use practices are within the realm of a farmer to impact on the soil carbon pools at the farm level. In this study, changes in SOC in farmers' fields were analysed (see Table 4.4). The results demonstrate a net decline in SOC throughout the whole country, detracting further from the country's already low overall soil carbon stocks. All the ADDs had a significant drop in topsoil OC except Blantyre, Karonga, and Kasungu (see Table 4.4). Croplands had the most significant decline in OC content (see Figure 4.6). This may be partly because of continuous cropping and harvesting without carbon replacement. Farming tends to mine the soil for nutrients and to reduce soil organic matter levels through repetitive cultivation of soils, harvesting of crops and inadequate efforts to replenish nutrients and restore soil quality (Ross, 1993[73]; Lal, 2018[74]). In Malawi, long-term research has shown that 5 to 10 years of continuous cultivation can

68 Joy E.J.M., Broadley R.M., Young S.D., Black R.C., Chilimba A.D.C., Ander E.L., Barlow T.S., Watts M.J. 2015. Soil type influences crop mineral composition in Malawi. Science of the Total Environment 505: 587–595.

69 Nkhoma D. D., Potassium in Malawi soils, M Sc. Thesis. North Carolina State University, United States of America 1986.

70 Lakudzala DD. 2013. Potassium response in some Malawi soils. International Letters of Chemistry, Physics and Astronomy 8(2): 175-181

71 Bot A, Benites J. 2005. The importance of soil organic matter Key to drought-resistant soil and sustained food production. FAO Soils Bulletin # 80. FAO, Rome. http://www.fao.org/docrep/009/a0100e/a0100e00.htm#Contents

72 Gray JM, Bishop FAT, Wilson BR. 2016. Factors Controlling Soil Organic Carbon Stocks with Depth in Eastern Australia. Soil Science Society of America Journal, 79:1741–1751

73 Ross SM. 1993. Organic matter in tropical soils: current conditions, concerns and prospects for conservation. Progress in Physical Geography: Earth and Environment, 17(3):265-305.

74 Lal R. 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biology (Early View), https://doi.org/10.1111/gcb.14054

reduce the SOC content by as much as 40% (Maida and Chilima, 1976[75]).

Table 4.4: Topsoil organic carbon content between 2010 and 2017

	2010 topsoil organic carbon (%)				2017 topsoil organic carbon (%)				% Change (2010-2017)
	Mean	Std. Dev	Min	Max	Mean	Std. Dev	Min	Max	
Blantyre	0.876	1.523	0.060	17.100	0.99	0.45	0.31	2.44	13.50
Karonga	0.729	0.352	0.000	2.086	0.77	0.33	0.14	1.55	5.10
Kasungu	0.953	0.758	0.059	12.703	0.97	0.44	0.14	2.14	1.80
Lilongwe	1.006	0.612	0.055	5.139	0.93	0.41	0.14	2.41	-7.10
Machinga	1.278	0.751	0.000	4.046	0.69	0.41	0.08	2.49	-46.30
Mzuzu	0.834	0.424	0.176	2.456	1.04	0.73	0.20	5.07	25.40
Salima	0.685	0.443	0.029	2.426	0.93	0.43	0.34	2.45	35.60
Shire Valley	0.965	0.756	0.024	4.970	0.89	0.44	0.25	2.49	-7.30
Average	**0.916**	**0.880**	**0.000**	**17.100**	**0.902**	**0.49**	**0.08**	**5.07**	**-1.40**

It is therefore expected that the decline in OC in the cropland areas may be due to the unsustainable farming activities. This reinforces the suggestions of certain researchers that fertility problems in Malawi may be solved through the use of integrated soil fertility management (ISFM) (Kanyama-Phiri, 2005[76]; Sauer *et al.*, 2007[77]).

In addition to the decline of carbon content in the cropland areas, some natural forests (thickets) along the Rift Valley and rangelands in Rumphi and Nkhata Bay districts also reported declines in topsoil OC between 2010 and 2017. Some cropland areas in Karonga district in the north region showed a slight increase in topsoil OC in 2017 (Figure 4.6). Increasing carbon was also observed in the central region along the lake shore in Nkhotakota District, Kasungu and Mchinji Districts and in the southern region in Chiradzulu, Thyolo, and Chikwawa districts (Figure 4.6). There are some sites in these districts where conservation agriculture efforts have been attempted in the last decade (Ngwira *et al.*, 2014[78]). It was not investigated whether the CA efforts significantly contributed to the change in carbon content.

75 Maida J.H.A., Chilima Z.W. 1976. Changes in Soil Fertility under continuous cropping of Tea: Technical Bulletin No. l/Bv/76. Bvumbwe Research Station, Limbe, Malawi.

76 Kanyama-Phiri, GY. 2005. Best-bet soil fertility management options: The case of Malawi. African Crop Science Conference Proceedings, Vol. 7. pp. 1039-1048.

77 Sauer J, Tchale H, Wobst P. 2007. Alternative Soil Fertility Management Options in Malawi: An Economic Analysis. Journal of Sustainable Agriculture, 29: 29-53.

78 Ngwira A, Johnsen FH, Aune BJ, Mekuria M. 2014. Adoption and extent of conservation agriculture practices among smallholder farmers in Malawi. Journal of Soil and Water Conservation, 69(2): 107-119.

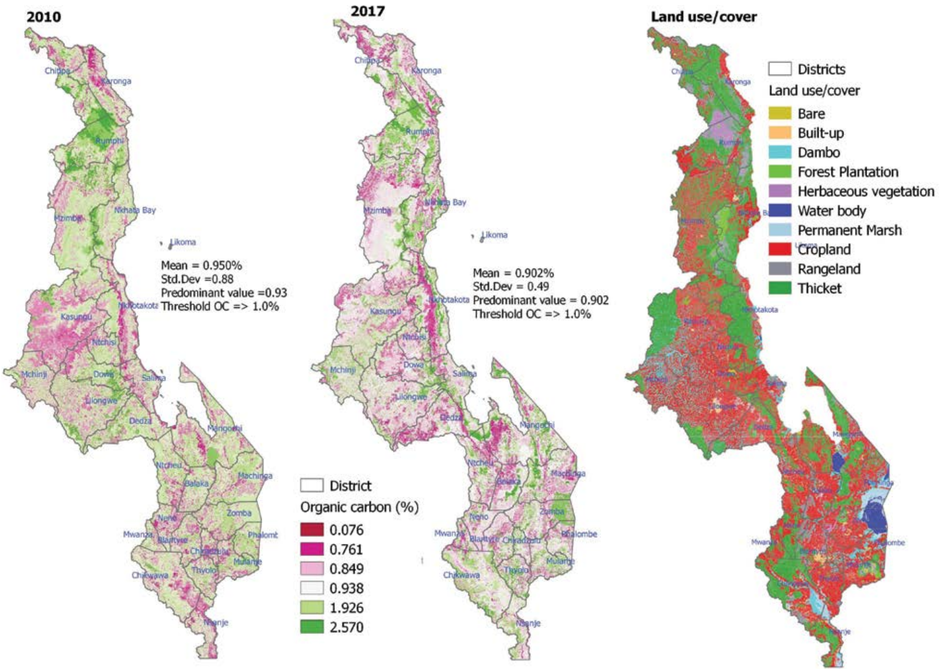


Figure 4.6: Topsoil carbon changes between 2010 and 2017

The decline in soil organic matter content is an indication of soil degradation and nutrient depletion (Sanchez and Miller, 1986[79]). In Malawi, many research activities have indicated potential decline in SOC throughout the country over the years (Wend, 1993[80]; Snapp, 1998; Nakhumwa, 2004[81]). Together with the results from the presented study, the evidence from the literature point to low levels of SOC and declining trends over the years.

4.2 Topsoil loss and nutrient loss

4.2.1 Field assessment of topsoil loss

Signs of soil degradation were recorded during the field survey and interviews taken with farmers about the status of soil fertility in their farmlands. The results showed that nearly half of the districts in Malawi had more than 40% observable signs of soil degradation in the farmlands (Figure 4.7). This portrays a significant level of prevalence of soil degradation in the country. The most prevalent degradation types are: soil fertility decline and erosion (sheet, rill, and gully).

79 Sanchez, P.A. and R.H. Miller, 1986. Organic Matter and Soil Fertility Management in Acid Soils of the Tropics. International Society of Soil Science Transactions 13th Congress 6:609-625

80 Wendt, J.W. 1993. Diagnosis of regional topsoil nutrient deficiencies in Malawi. Proceedings of the Southern Africa Farming Systems-Extension Conference, 1-3 June 1993, Ezulwini, Swaziland. CIMMYT, Harare, Zimbabwe

81 Nakhumwa TO. 2004. Dynamic costs of soil degradation and determinants of adoption of soil conservation technologies by smallholder farmers in Malawi. PhD Dissertation, University of Pretoria. South Africa.

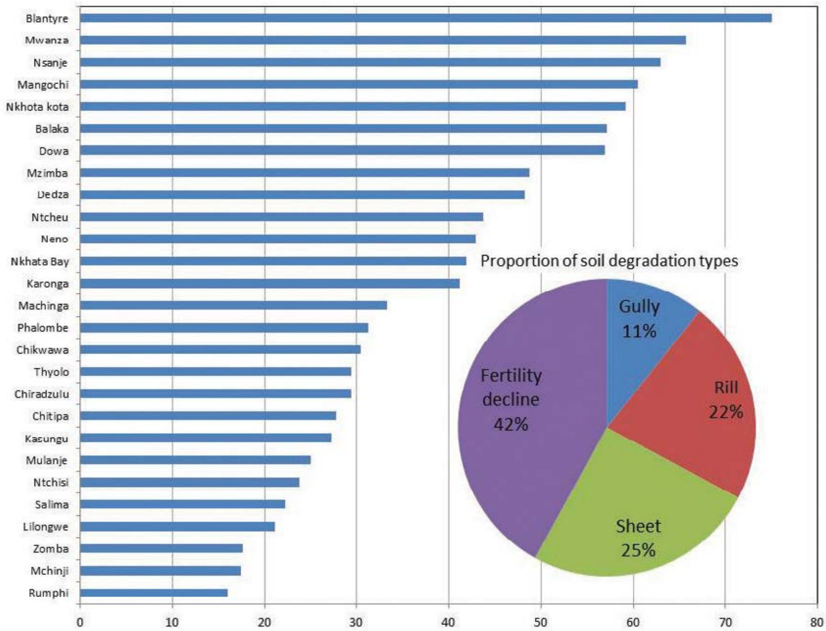


Figure 4.7: Proportion of sampled sites with signs of soil degradation

Some of the features of these degradation types are shown in Figure 4.8. In the northern region, Mzimba, Nkhata-Bay, and Karonga districts had the highest prevalence of these features while in the central region Nkhotakota, Dedza, and Dowa had the highest prevalence of the degradation features. In the south, Blantyre, Mangochi, and Mwanza districts were indicated to have had the highest prevalence of degradation features.

Signs of sheet and rill erosion at Dedza (Mtakataka EPA)

Signs of sheet and surface hardsetting at Thyolo (Thekerani EPA)

Signs of sheet and gully erosion at Thyolo (Thekerani EPA)

Signs of sheet and rill erosion at Ntcheu (Manjawira EPA)

Figure 4.8: Examples of observed signs of degradation during a field survey in 2017

In Mwanza, Mangochi, Nkhotakota, Nsanje, Blantyre, Balaka, and Dowa districts, 50% of the surveyed locations had signs of soil degradation (see Figure 4.7). Relative to other parts of the country, these districts seemed to have more observable signs of soil degradation. Average field measurements of topsoil loss from these districts were between 12 to 24 ton/ha/yr. Compared to average field measurements of topsoil loss rates in Rumphi, Mchinji, Lilongwe and Zomba districts, which ranged between 2 and 9 ton/ha/yr, it can be said that the soil loss rates were high in the areas that had a high prevalence of signs of degradation.

In addition to observing signs of degradation in the study areas, interviews with farmers/land owners attempted to establish their opinion about the land quality and potential drivers of soil degradation in their plots. Results showed that the majority of the farmers/land owners believed that the lands' fertility decreased. Consequently, according to the land owners/farmers, the current land quality can be best described as fair (Figure 4.9). Their opinion reinforces the results shown in Figure 4.8 that portrays farmlands in Malawi as having a prevalence of soil degradation. In 2006, Chinangwa (2006[82]) found that 73% of farmers in the Machinga and Zomba districts perceived that the farmlands had low fertility while 63% felt that the soil fertility was consistently declining annually.

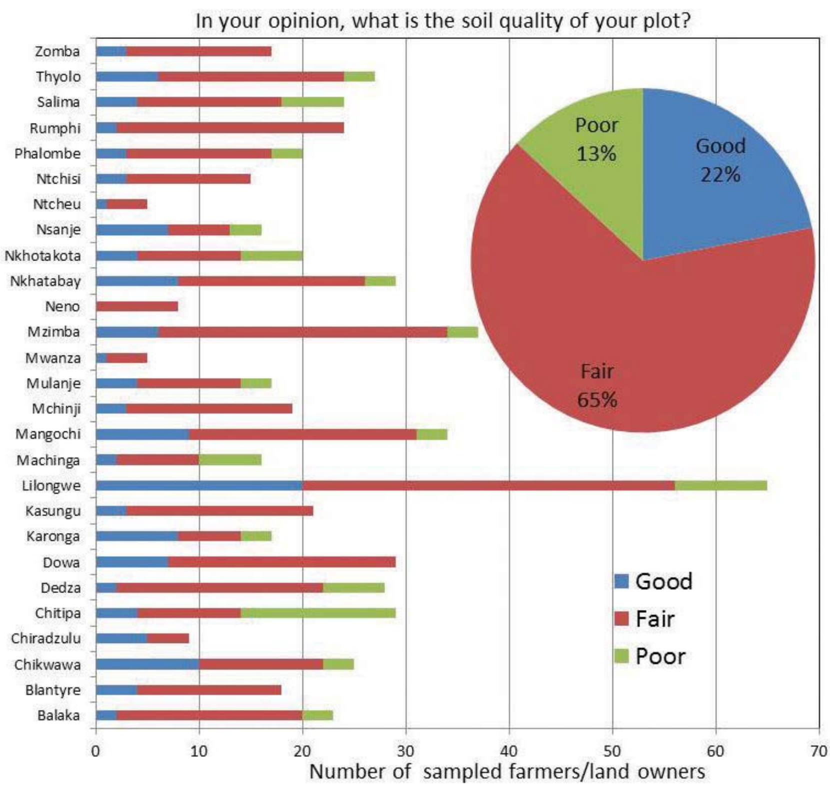


Figure 4.9: Farmers' opinion on the land quality of their croplands

82 Chinangwa LLR. 2006. Adoption of soil fertility improvement technologies among smallholder farmers in southern Malawi. M.Sc Thesis. Norwegian University of Life Sciences. Norway.

Figure 4.10 illustrates the perceptions of the farmers with regard to potential drivers of soil degradation in their farmlands. These perceptions have been summarized by the prevalent degradation types. In general, farmers think that the following factors contribute to the prevalence of soil degradation: poor maintenance of existing erosion control structure, inadequate soil fertility management, prevalent fragile soils, steep slopes, limited extension services, poor uptake of soil conservation technologies, low levels of awareness of soil degradation and conservation technologies, low level of farmer-investment in soil conservation, erratic and high rainfall intensities, and reduction of protective soil cover (Figure 4.10). Poor uptake of soil conservation technologies, limited extension services, low awareness levels on on-going soil degradation and available soil conservation technologies, and low levels of farmer investment in soil conservation came out as strong drivers of soil degradation in the country. After careful assessment of these drivers, they were categorized as limitations in socio-economic, knowledge and attitude, and policy environments. Previous research activities on adoption of soil conservation technologies in Malawi have also identified similar categories of limitations in the country (see for example, Mustafa-Msukwa *et al.*, 2011[83]; Chisenga, 2015[84]; Nakhumwa and Hassan (2003[85]).

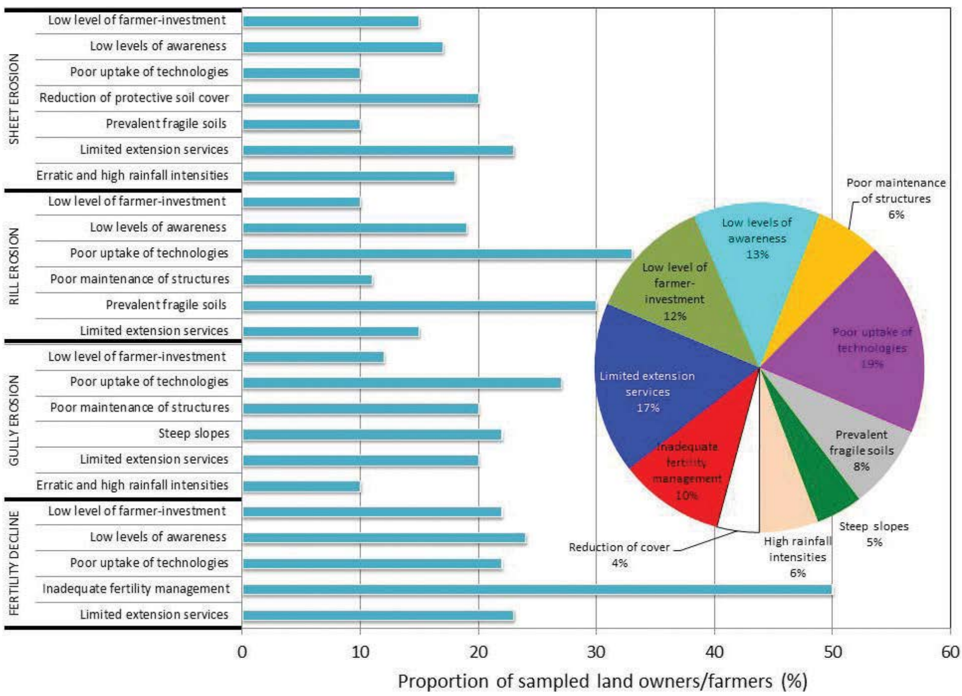


Figure 4.10: Farmers' opinions on drivers of soil degradation in their farmlands

83 Mustafa-Msukwa AK, Mutimba JK, Masangano C, Edriss AK. 2011. An assessment of the adoption of compost manure by smallholder farmers in Balaka District, Malawi. South African Journal of Agricultural Extension, 39(1):

84 Chisenga CM. 2015. Socio-economic factors associated with the adoption of conservation agriculture among women farmers in Balaka District, Malawi. PhD Dissertation. Purdue University. Indiana

85 Nakhumwa TO, Hassan RM. 2003. The adoption of soil conservation technologies by smallholder farmers in Malawi: a selective Tobit analysis. Agrekon, 42(3): 271-284.

A low to non-existent level of farmer/land owner-investment in soil conservation is another interesting driver of soil degradation identified by farmers in Malawi. During this study, it was found that nearly half of smallholder farmers do not invest their income on soil conservation (Figure 4.11). This is partly due to low levels of income and stiff competition from other household budgetary allocations and partly due to land tenure insecurity in some regions (Lovo, 2016[86]). The majority of the districts with low farmer-investment in soil erosion control were from the southern region (Figure 4.11). Some of them were also identified as having a high prevalence of observable signs of soil erosion (Figure 4.7).

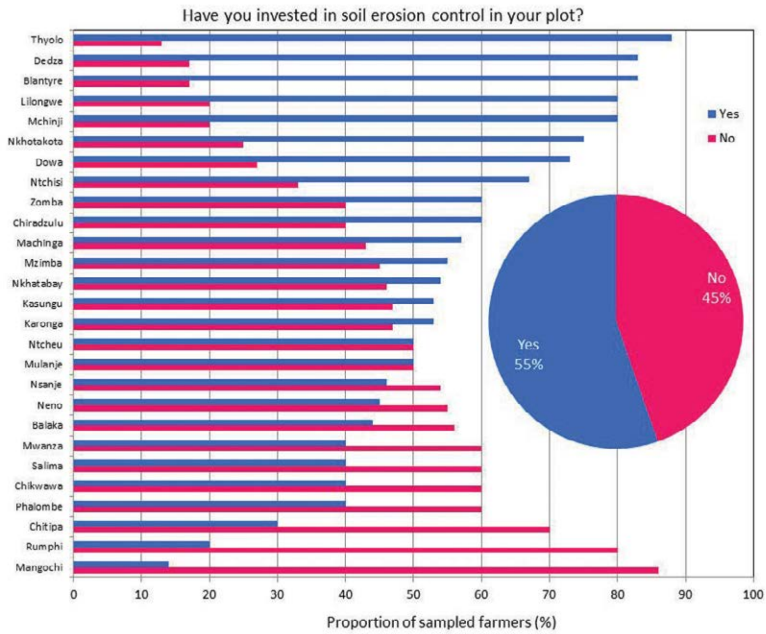


Figure 4.11: Level of investment in soil erosion control at the farmer-level

4.2.2 Topsoil loss rate and trend

A spatial analysis of soil loss rate was done for 2017 and the results were compared with previous national assessments of topsoil loss rate in Malawi (Vargas and Omuto, 2015[87]). The results showed that the Rift Valley section was still experiencing high soil loss rates compared to the other parts of the country between 2010 and 2017 (see Figure 4.12). In the northern region, Karonga and Mzimba had the highest topsoil loss rates in 2010. In 2017, their district level topsoil loss rates slightly increased by over 10% (Table 4.5). The most affected areas are those in the northern parts of Mzimba and central to the northern Karonga district.

86 Lovo, S. 2016. Tenure insecurity and investment in soil conservation. Evidence from Malawi. World Development, 78: 219-229.

87 Vargas RR, Omuto CT. 2015. Soil loss assessment in Malawi. FAO. http://www.fao.org/3/a-i6387e.pdf

Table 4.5: Summary of topsoil loss at the district level in 2010 and 2017

		2010 Topsoil loss(ton/ha/yr)				2017 Topsoil loss(ton/ha/yr)			
REGION	DISTRICT	Mean	St.Dev	Min	Max	Mean	St.Dev	Min	Max
North	Chitipa	9.87	4.31	0.83	18.02	10.53	4.42	0.98	12.11
North	Karonga	11.11	5.28	0.80	17.17	16.44	5.80	0.72	18.88
North	Nkhata Bay	6.96	3.92	0.38	16.04	17.81	3.95	0.23	28.33
North	Rumphi	9.15	3.99	0.74	18.00	9.08	4.11	0.61	11.25
North	Mzimba	11.31	4.65	0.63	24.08	11.88	4.66	1.02	20.12
Central	Kasungu	5.76	2.78	0.79	12.71	8.60	3.85	0.62	16.01
Central	Nkhotakota	14.45	3.07	0.78	30.22	15.47	6.74	0.55	32.81
Central	Ntchisi	19.47	5.65	4.47	36.76	12.43	2.49	2.17	22.07
Central	Dowa	13.79	4.38	1.21	29.02	13.23	4.61	0.69	29.04
Central	Salima	7.37	5.79	0.33	20.17	8.68	6.09	0.22	19.86
Central	Lilongwe	1.98	0.15	0.78	9.02	4.99	1.30	0.65	10.77
Central	Mchinji	1.29	0.05	0.31	5.04	2.27	0.37	0.16	5.82
Central	Dedza	13.07	5.63	0.79	20.92	23.31	6.52	0.74	26.91
Central	Ntcheu	5.27	4.17	0.88	17.86	14.82	5.34	1.01	20.02
South	Mangochi	14.60	7.73	0.61	23.73	24.43	19.82	0.37	33.85
South	Machinga	13.97	11.30	0.29	33.17	15.43	6.03	0.20	27.23
South	Zomba	3.84	8.19	0.69	19.09	6.06	6.95	0.52	17.08
South	Chiradzulu	10.95	4.89	0.69	23.30	12.85	7.03	0.61	33.08
South	Blantyre	12.69	5.72	0.61	30.02	24.74	8.11	0.78	34.17
South	Thyolo	12.75	6.89	0.78	20.10	11.85	7.26	0.54	31.12
South	Mulanje	6.05	3.56	0.18	10.11	7.25	4.36	0.45	12.08
South	Phalombe	7.96	4.09	0.46	17.54	10.00	4.96	0.74	19.16
South	Chikwawa	10.74	6.92	0.31	20.88	21.18	7.28	0.32	33.08
South	Nsanje	14.21	10.83	0.35	30.02	16.29	9.52	0.23	23.08
South	Balaka	22.38	10.90	1.29	30.92	23.87	5.91	0.36	33.05
South	Mwanza	13.95	6.13	0.37	20.55	17.88	7.52	0.96	21.92
South	Neno	13.86	6.67	0.42	23.14	16.09	6.69	1.40	24.88

In the Mzimba and Karonga districts, the areas which showed high topsoil loss rates were the same areas that had a high proportion of observable signs of soil degradation. The most affected soils in these districts are Cambisols, especially Ferralic and Humic Cambisols on steep slopes.

In the central region, Nkhotakota, Ntcheu, Dedza and Dowa districts had high topsoil loss rates in 2010 and 2017. Similarly to the northern regions, the most affected soil type with topsoil loss is the Cambisol. However, in this case, the areas dominated by Chromic and Eutric Cambisols with steep slopes showed high topsoil loss rates. The Ntchisi district, which had a higher soil loss rate in 2010, overwent a remarkable improvement in 2017. The cause of this decline in soil loss rate was not investigated during this study.

In the south, the Blantyre, Mangochi, Neno, Mwanza, and Nsanje districts showed signs of high topsoil loss rates in 2010 and 2017. The areas that showed high topsoil loss rates had Cambisol as the dominant soil type.

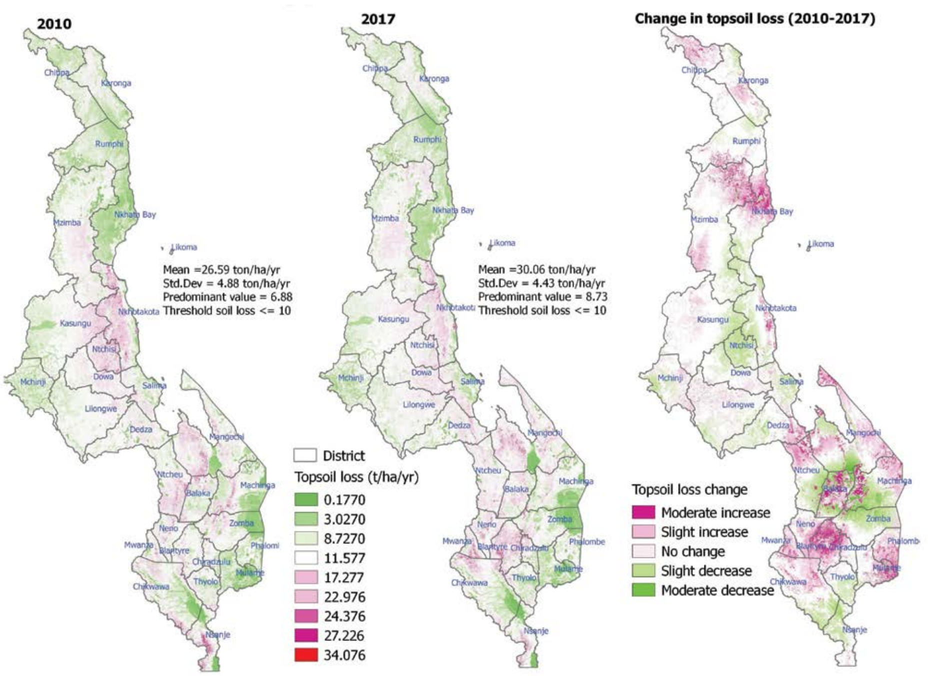


Figure 4.12: Topsoil loss rates in 2010 and 2017

In general, the areas dominated by Cambisols on steep slopes tended to have a high risk for topsoil loss. According to the IUSS Working Group WRB (2015[88]), Cambisols have high nutrient contents and are highly favoured for agricultural exploitation. However, owing to their young profile development and location in the hilly areas, they are susceptible to soil erosion. In Malawi, Cambisols comprise 21% of the country and are found predominantly in the steep slopes of the Rift Valley region. Although they are mainly under forest, they have been actively turned into croplands in the past few decades (Chibwana *et al.*, 2013[89]; Bone *et al.*, 2017[90]).

88 IUSS Working Group WRB. 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

89 Chibwana C, Jumbe CBL, Shively V. 2013. Agricultural subsidies and forest clearing in Malawi. Environmental Conservation, 40(1): 60-70.

90 Bone RA, Parks KE, Hudson DM, Tsirinzeni M, SWillcock S. 2017. Deforestation since independence: a quantitative assessment of four decades of land-cover change in Malawi, Southern Forests: a Journal of Forest Science, 79:4, 269-275, DOI: 10.2989/20702620.2016.1233777

4.2.3 Nutrient loss due to soil erosion

The average annual loss rate of main plant nutrients due to topsoil loss was between 66 and 117 g/ha of total N, 205 – 364 g/ha of available P and 9.3 - 17.4 g/ha of exchangeable K in the north in 2017 (Figure 4.13). The Mzimba and Karonga districts lost most of these nutrients. The EPAs that have lost more than 0.5 kg/ha of the combined NPK plants nutrients were all in Mzuzu ADD. They were: Kazomba (631 g/ha), Manyamula (588 g/ha), Vibangalala (573 g/ha), Mbawa(567 g/ha), Luwelezi (564 g/ha), Bwengu (557 g/ha), Eswazini (548 g/ha), Zombwe (499 g/ha), Khosolo (495 g/ha), and Bulala (490 g/ha). Nchenachena EPA in Rumphi District and Chitheka EPA in Nkhata Bay had the lowest NPK loss (< 250 g/ha) in the northern region in 2017.

In the central region, the average annual nutrient loss rate was between 76 and 154 g/ha of total N, 226 – 407 g/ha of available P, and 4.8 - 154 g/ha of exchangeable K in 2017 (Figure 4.13). The Nkhotakota, Ntcheu, Ntchisi, Dowa, and Salima Districts had more than 0.5 kg/ha loss of the combined NPK nutrients. Mtakataka, Manjawila, Chiwamba, and Chikwatula EPAs had the highest NPK loss rates in the central region (> 550 g/ha), while the Chiwaoshya, Kasungu National Park, and Mlonyeni EPAs had the lowest NPK loss rates (<280 g/ha).

In the southern region, the average annual soil nutrient loss was between 73 and 160 g/ha of total N, 179 – 570 g/ha of available P, and 5.7 – 179 g/ha of exchangeable K in 2017 (Figure 4.13). The Blantyre and Mwanza districts lost more than 700 g/ha of combined NPK nutrients while Mulanje was the only district that lost less than 230 g/ha of the combined NPK nutrients in the southern region in 2017. The Kunthumbwe, Chipande, Mwanza, and Kalambo EPAs had lost more than 750 g/ha of NPK nutrients in 2017, while the Thekerani, Msondole, Mulanje Mountain and Nsanama EPAs lost less than 200 g/ha of NPK nutrients in 2017.

In the north, the areas with high nutrient loss rate (> 500 g/ha of NPK) were in the Mzuzu ADD and in the Haplic Lixisol soil type. The soils are relatively deep (more than 1 m deep) and are currently under crop cultivation. In the central region, the areas with high soil nutrient loss rate due to erosion were dominated by Eutric Cambisols (in steep slopes), Eutric Fluvisols and Haplic Luvisols (on the lake plains), Haplic Lixisols (Kasungu-Mchinji plains), and Chromic Luvisols (in the Lilongwe-Dowa plains). In the southern region, the most affected areas have Chromic Cambisols (in the steep slopes and footslopes) and Chromic Luvisols (in the footslopes). Cambisols, Fluvisols, and Luvisols are largely dominated by agriculture in Malawi, which increases their risk for soil erosion.

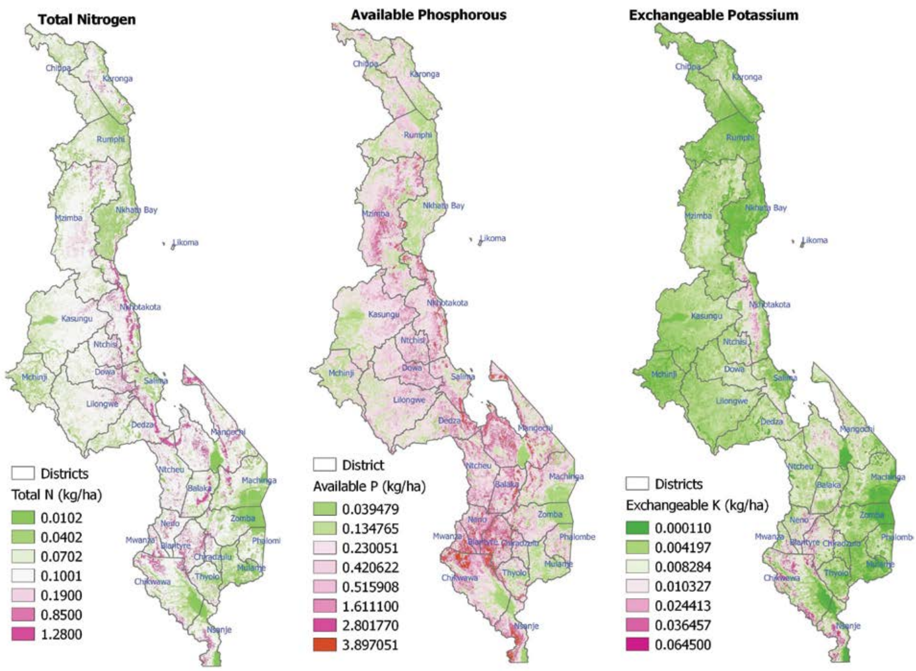


Figure 4.13: Estimates of annual topsoil nutrient loss for main plant nutrients in 2017

In general, according to this study, Malawi was averagely losing 108 g/ha of total N, 350 g/ha of available P, and 16.6 g/ha of exchangeable K on average in 2017.

According to the farmer survey results, over 90% of the farmers use Chitowe (NPK 23:21:0 +4S) and Urea fertilizers on their farms. A 50 kg-bag of Chitowe fertilizer contains 23% N (equals 11.5 kg of N), 21% P_2O_5 (equals 4.62 kg of P) and 0% K_2O (equals 0 kg of K). This translates to 16.12 kg of NPK nutrients/ 50 kg bag of Chitowe fertilizer. In terms of average NPK nutrient lost per ha in Malawi in 2017, it can be said that an equivalent of 3% of 50kg-bag of Chitowe fertilizer is lost per hectare annually due to soil loss. This amount is likely to be higher due to acidification and nutrient mining that are also prevalent in many areas in the country. During this study, the amount of nutrients lost due to acidification and nutrient mining were not addressed as they were out of the scope of the study.

4.3 Nutrient supplementation

In order to cover the nutrients lost due to soil erosion, nutrient supplementation is necessary. The agronomic options for supplementing the nutrients lost in the soil include: crop rotations, conservation agriculture, soil and water conservation practices, cover cropping, manure management and application, fertilizer application, etc. (Vanlauwe *et* *al.*, 2010[91]). Presently, inorganic fertilizer application is widespread in the country due to the support from government policies in the past few decades. The use of organic fertilizers is, however, still not as widespread as the use of inorganic fertilizers. This may be partly due to lack of knowledge, lack of sustained efforts and policy backing as is done for inorganic fertilizer use, and competitive use of input materials for organic fertilizers (Mlamba, 2010[92]; Ngwira *et al.*, 2014[93]). During this study, it was noted that 58% of all farmers use organic fertilizers and almost all farmers use inorganic fertilizers. Mustafa-Msukwa *et al.* (2011[94]), while studying farmers in the Balaka districts, found a manure adoption rate of 32%. In this study, 54% of interviewed farmers in the Balaka district stated that they use organic fertilizers.

Although the quality of organic fertilizers is still unknown and potentially problematic in many places in Malawi, a study by Chilimba *et al.* (2005[95]) found that 5000 kg/ha of organic manure was capable of supplying 10 to 74 kg/ha of N, 5 to 10 kg/ha of P, and 17 to 37 of K kg/ha across the country. This implies that, even 1% of this manure application rate is enough to restore the amount of NPK loss per hectare due to soil erosion. However, the economics of producing and applying this amount of fertilizer may need further consideration. Similar soil quality specifics arising from other strategies such as conservation agriculture, crop rotation, and fallowing. are recommended so that they can be incorporated in an integrated strategy for soil fertility management.

Due to the high current inorganic fertilizer application rate in the country and the threat of soil acidification and accompanied decline of soil nutrients, a critical assessment of the use of inorganic fertilizers is urgently needed. This may entail long-term research on the impacts of acidification on nutrient availability, soil testing and calculation of requisite acidity amelioration strategies, and matching fertilizer application with soil properties and crop needs. This procedure was not taken during this study owing to the scope and logistical limitations. There are some attempts in the literature that can be used as a starting point (see for example Benjala *et al.*, 2015[96] and references therein).

Soil fertility management is able to support soil conservation strategies. Presently, the majority of soil conservation and nutrient management efforts in Malawi are: contour ridges, fertilizer application, check dams, Vetiver hedge rows, and conservation agriculture

91 Vanlauwe B, Chianu J, Giller KE, Merckx R, Mokwunye U, Pypers P, Shepherd K, Snaling E, Woomer PL, Sanginga N. 2010. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook on Agriculture, 39(1): 17-24.

92 Mlamba JL. 2010. Factors affecting adoption of conservation agriculture in Malawi: A case study of Salima District. M.Sc Thesis. University College Dublin. Ireland.

93 Ngwira A, Johnsen FH, Aune BJ, Mekuria M. 2014. Adoption and extent of conservation agriculture practices among smallholder farmers in Malawi. Journal of Soil and Water Conservation, 69(2): 107-119.

94 Mustafa-Msukwa AK, Mutimba JK, Masangano C, Edriss AK. 2011. An assessment of the adoption of compost manure by smallholder farmers in Balaka District, Malawi. South African Journal of Agricultural Extension, 39(1):

95 Chilimba, A. D. K., Shano, B., Chigowo, M. T., Komwa, M. K. 2005. Quality assessment of compost manure produced by smallholder farmers in Malawi. http://www.ndr.mw:8080/xmlui/handle/123456789/350

96 Benjala MJ, Maida JHA, Lowole MW, Kabambe VH. Liming and fertiliser P interaction effects on some indices of fertility of selected Malawi acidic soils. Journal of Soil Science and Environmental Management, 6(9): 249-259

(see Figure 4.14). Except contour ridges and inorganic fertilizer application, the others can be found in small pockets throughout the country. Many farmers already apply some of the mentioned strategies in their farms, which represents a good way to promote integrated soil fertility management (ISFM). ISFM focuses on the combined use of inorganic fertilizers, soil amendments (e.g. lime, rock phosphate, etc.), and organic matter (e.g. crop residues, manure, legumes, etc.) to replenish lost soil nutrients. ISFM has been tested in some areas in Malawi with mixed results (see for example, Kanyama-Phiri *et al.*, 2000[97]; Munthali, 2007[98] and references therein). Further research is needed on the effects and benefits of ISFM, starting with the hotspot areas for nutrient decline and areas with potential risk for acidification identified in this study.

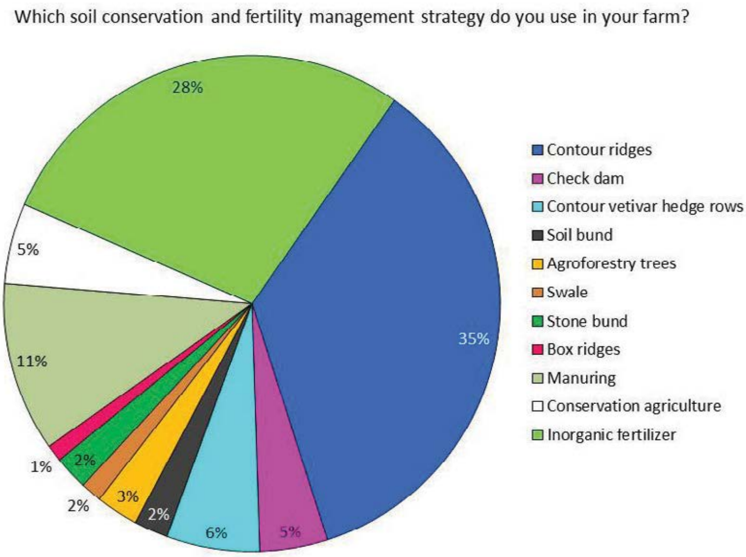


Figure 4.14: Options for on-farm soil conservation and fertility management

This study analysed the areas with potential risk of soil acidification and identified vulnerable soil types. The majority of the areas suspected with moderate risk of acidification are in the Lilongwe, Mzuzu, Karonga, and Shire Valley ADDs (Figure 4.15). These areas can be ear-marked for routine soil testing (such as exchangeable acidity, soil macro and micro nutrient indicators, CEC, pH buffering capacity, etc.). Subsequent requisite strategies and calculations may follow on how to amend soil acidity as well as determine the nutrient/fertilizer requirement for certain crops in those areas. The results should be added to the nutrient requirements to replace the lost NPK nutrients due to soil erosion as found in this study.

97 Kanyama-Phiri G, Snapp S, Kamanga B, Wellard K. 2000.Towards integrated soil fertility management in Malawi: incorporating participatory approaches in agricultural research. http://pubs.iied.org/pdfs/7422IIED.pdf

98 Munthali M.W. (2007) Integrated Soil Fertility Management Technologies: A Counteract to Existing Milestone in Obtaining Achievable Economical Crop Yields in Cultivated Lands of Poor Smallholder Farmers in Malawi. In: Bationo A., Waswa B., Kihara J., Kimetu J. (eds) Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities. Springer, Dordrecht

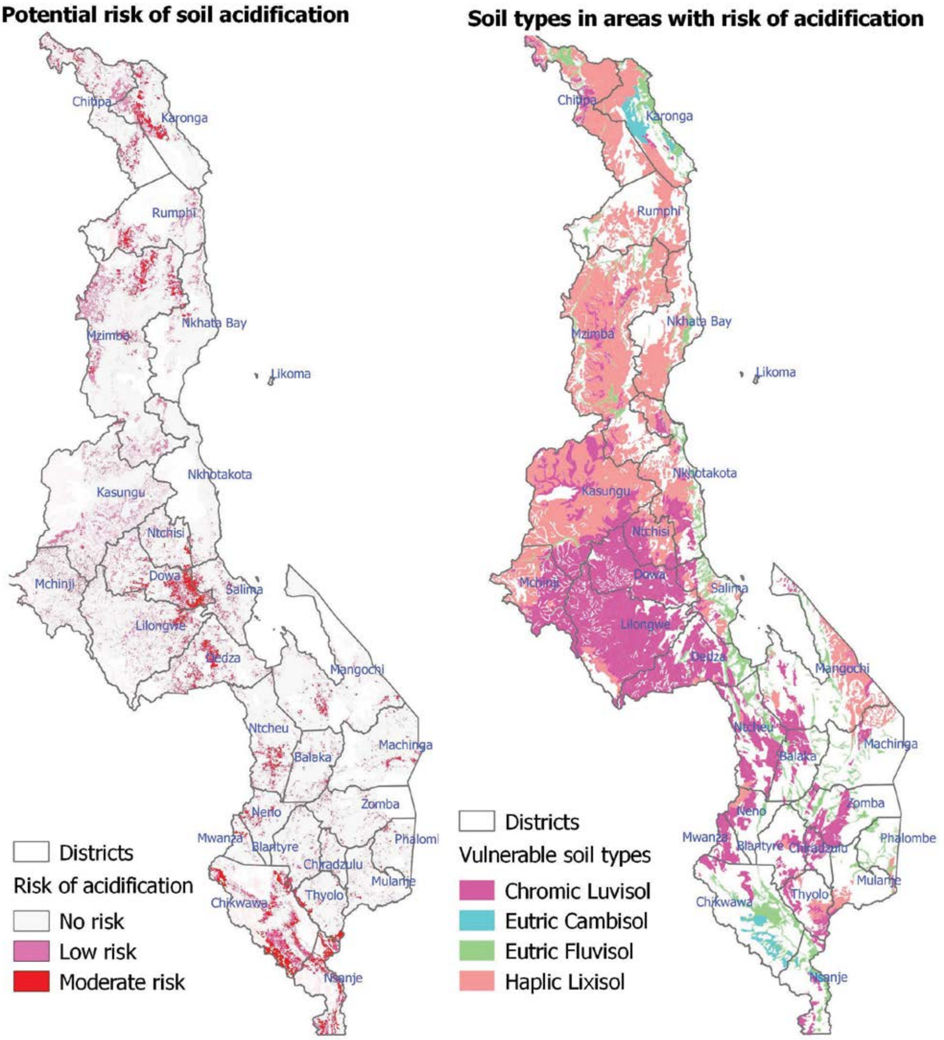


Figure 4.15: Areas showing potential risk for soil acidification in Malawi

5 Capacity development

This study also doubled as a cooperative arrangement between the GoM and its development partners. Consequently, the study incorporated selected aspects of capacity building to ensure the government gets the requisite support to continue with the activities of soil resource inventory, assessment, and monitoring in the country. Capacity development efforts were carried out for the Land Resources Conservation Department (LRCD) of the Ministry of Agriculture, Irrigation and Water Development. The capacity building included training and equipment support.

5.1 Training

A two-week training program was organized for about 15 LRCD staff members at the Mpatsa Lodge in Salima. The training covered diverse areas of soil resources inventorying, assessment, and monitoring, as well as Digital Soil Mapping (DSM). LRCD staff was trained on how to carry out field assessments, track field surveys using online and tractable mobile tablets, view data streaming from a centrally located server, and to troubleshoot field operations. The team later implemented the practical implementation of the training in a national survey of soil nutrient status and soil degradation (Figure 5.1).

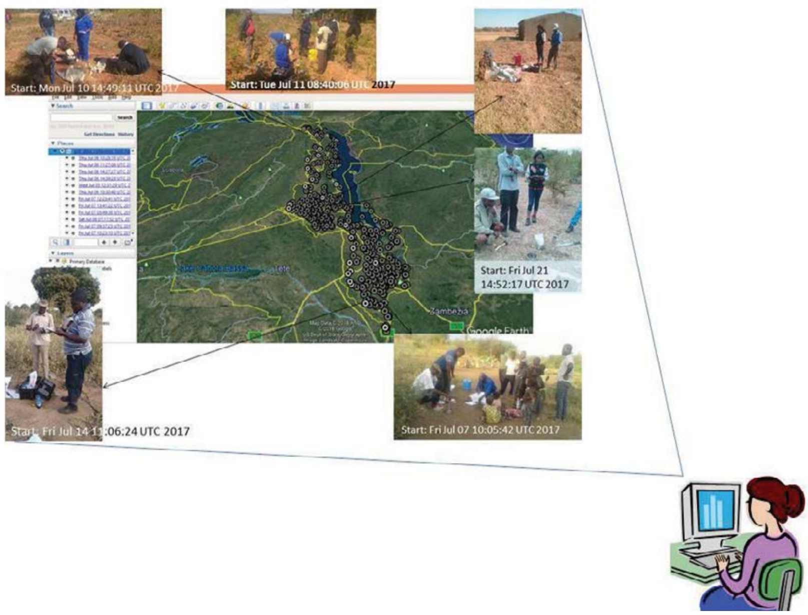


Figure 5.1: Data streaming and monitoring of fieldwork progress

The team was trained on soil sampling and surveying, in situ soil testing, data collection template design, data collection Mobile Apps development, and data collection and transmission in the field during field survey (Figure 5.2).

Figure 5.2: Practical lessons during capacity building

5.2 Institutional support

The technical cooperation between the GoM and its development partners had previously supported the procurement of three mobile tablets and soil testing kits to test their viability in rapid soil testing and data collection throughout the country (Vargas and Omuto, 2015). For this study, the equipment previously provided was further enhanced with the replenishment of used parts and procurement of additional supplies to strengthen their application for large-scale data collection in the country. Three more mobile tablets and their complete accessories were procured during this study and transferred to the government through LRCD.

In addition to equipment support, the GoM through the LRCD was also given requisite data collection and analysis software. The following were given to LRCD: software for developing Mobile Apps for data collection, software for GIS and remote sensing analysis, and software for soil mapping and inventorying according to the DSM paradigm. The responsible LRCD staff were adequately trained on how to use the software.

Some aspects of information management and development of soil information system are still lacking and may need future support. A concrete information management strategy and information system are central to storing and centrally organizing soil resource information, as well as sharing the information with intended users such as farmers, policy makers, developers, investors, etc. (Bhattacharyya *et al.*, 2016[99]; Hallett *et al.*, 2017[100]). During this study, a system was set up within the cloud server and operationalized. A physical system at LRCD would be more useful and within much control of the Department.

In addition to the above, this study has set some baseline spatial information that LRCD could build on for updating soil conservation efforts in the country. Figure 5.3 is an example of such information, which is also available in GIS format. LRCD can use the capacity developed during this study to build on the baseline

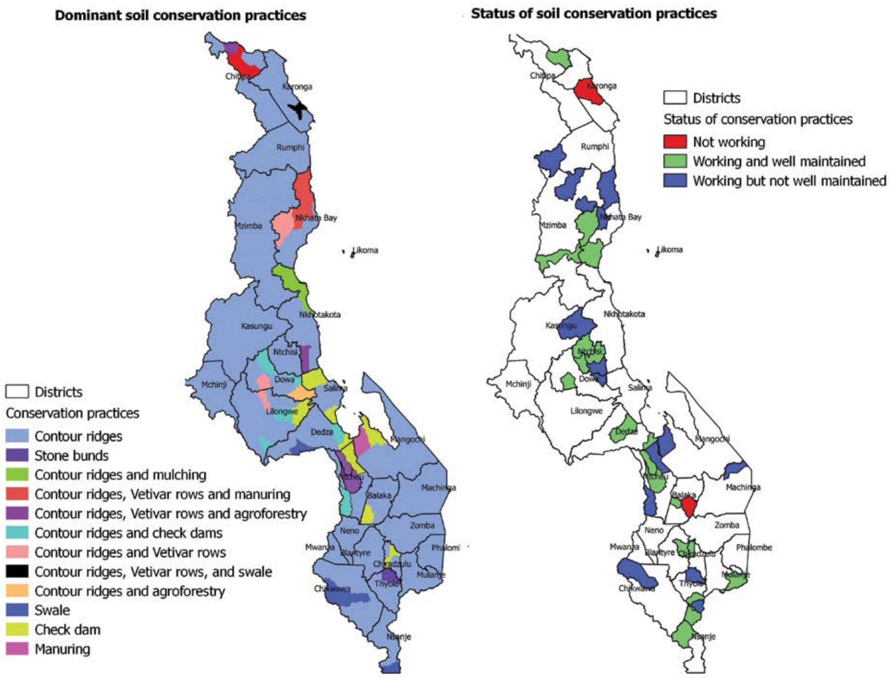


Figure 5.3: Example of baseline information on soil conservation in Malawi

99 Bhattacharyya, T and Wani, S P and Chandran, P and Tiwary, P and Pal, D K and Sahrawat, K L and Velayutham, M. 2016. Soil Information System: Web-Based Solution for Agricultural Land-use Planning. Current Science, 110 (2). pp. 241-245.

100 Hallett SH, Saktrabani R, Keay CA, Hannam JA. 2017. Developments in land information systems: examples demonstrating land resource management capabilities and options. Soil Use and Management, 33: 514-529.

6 Conclusions and recommendations

6.1 Conclusions

This study aimed to assess soil nutrient dynamics in Malawi for the sake of informing economic assessment of soil loss in the country. In order to assess changes in soil nutrient levels, the study reviewed past and present literature as well as soil data, and compared their results with those that were generated during the study. A remarkable observation from the comparison is the consistent decline in soil pH in the country. This decline, which is an indication of soil acidification, was found in at least 40% of each district in Malawi. Consequently, it was flagged as an important soil problem for the country to address. The most affected soils include Lixisols in the north region, Luvisols in the central region, and Luvisols, Cambisols and pockets of Lixisols in the southern region. Acidic soils such as Acrisols and Ferralsols in the north and Alisols in the south may also be slightly affected by a decline in soil pH. One potential cause of acidification in these soils is inappropriate fertilizer application/ misuse of fertilizer in the agricultural areas. As pointed out by various researchers in Malawi, the long-term use of blanket fertilizer recommendations in these soils potentially contributed to the observed soil acidification.

Along with the acidification and risk of bio-unavailability of certain soil nutrients, soil loss is currently a common problem in Malawi. During this study, observable signs of soil loss were found throughout the country. Analysis of soil loss rates revealed that the current soil loss rate is 30 ton/ha/yr and was 26 ton/ha/yr in 2010. Some of the potential drivers of this high rate of soil loss include: poor maintenance of existing erosion control structure, inadequate soil fertility management, prevalent fragile soils, steep slopes, limited extension services, poor uptake of soil conservation technologies, low levels of awareness of soil degradation and conservation technologies, low level of farmer-investment in soil conservation, erratic and high rainfall intensities, and reduction of protective soil cover. In terms of nutrient loss, the current soil loss rate was found to remove, on average, 108 g/ha of total N, 350 g/ha of available P, and 16.6 g/ha of exchangeable K in 2017. This is equivalent to 3% of a 50kg-bag of Chitowe fertilizer per hectare annually due to soil loss.

In order to overcome the soil loss and nutrient loss, this study found that sustainable soil management including integrated soil fertility management (ISFM) is the best option for the country. ISFM focuses on the combined use of inorganic fertilizers, soil amendments (e.g. lime, rock phosphate, etc.), and organic matter (e.g. crop residues, manure, legumes, etc.)

to replenish lost soil nutrients. Although there are practical examples of ISFM in Malawi, the widespread adoption of ISFM may need further research and trials on optimal alternatives and policy support backed with widespread campaign throughout the country. These efforts should be integrated with awareness creation, technology transfer, and farmer trainings supported by adequate extension services (The GSP's Global Soil Doctors programme could be of use in these situations).

Besides the soil nutrient and soil loss assessment, this study built sufficient baseline information from which LRCD can build on. LRCD staff were adequately trained on how to implement these aspects. For example, this study developed baseline information on soil conservation efforts and status throughout the country. This is a significant starting point since there is insufficient availability of data which is urgently needed for budgetary planning of activities within the Department.

6.2 Recommendations

- **The development of a national soil information system for Malawi:**

This study pointed to a clear lack of an organized and easily accessible national inventory of soil resources. A soil information system will provide necessary information on the status of soil resources, soil conservation efforts and possibilities for up-scaling soil conservation measures. Some aspects of information management and development of a soil information system are still lacking and may need future support. During this study, a system setup was done in the cloud server and operationalized. However, a physical system at LRCD is recommended.

- **The establishment of a detailed study of soil nutrients loss due to acidification:**

This study identified the issue of soil acidification, which can potentially lower the availability of soil nutrients. A quantification of nutrient dynamics in agricultural areas is needed to assess soil nutrient loss due to acidification. Due to the currently high inorganic fertilizer application rate in the country and the further threat of soil acidification and subsequent decline of soil nutrients, a critical assessment of the use of inorganic fertilizer is recommended. Research should be conducted on the impacts of acidification on nutrient availability, through soil testing and calculation of requisite acidity amelioration strategies. Results of this research should be entered into a soil information system to help farmers match fertilizer application with crop needs, based on the soil properties of their region.

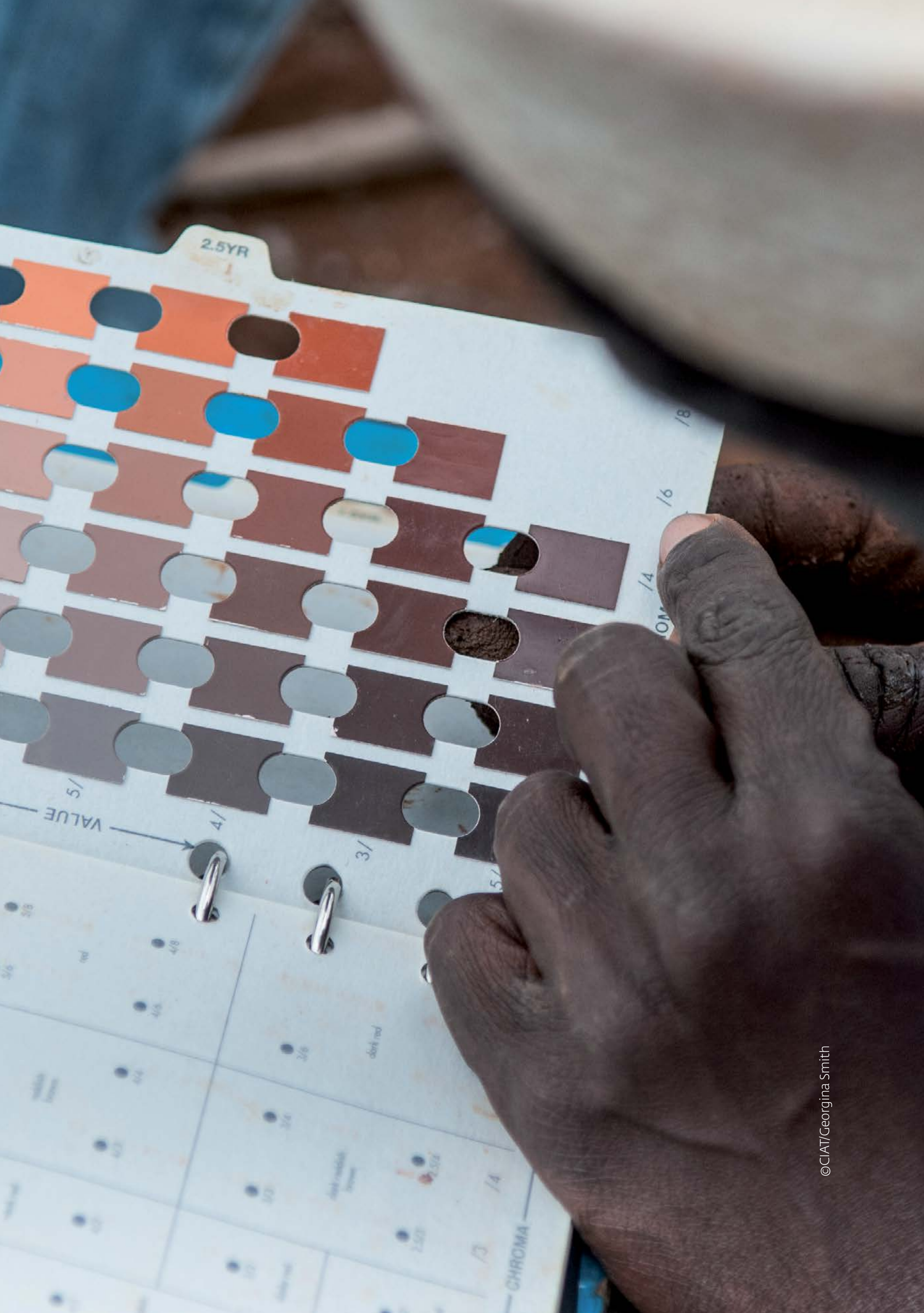
- **The establishment of a soil monitoring framework:**

This study established baseline information that can be used for future monitoring activities in Malawi to guide LRCD and the GoM in routine soil testing and assessment within each ADD. The framework should use the sampled sites in this study as benchmarks since they were sampled in 2010 and in 2017. It should also incorporate soil mapping and document soil conservation efforts, success and failures, as well as adoption efforts and planning.

It is suggested to consider opportunities to integrate sustainable soil management principles in agricultural and fertilizer policies and recommendations.

- <u>The establishment of a routine soil testing in potential soil acidification risk areas</u>

This study analysed the areas with potential risk of soil acidification and vulnerable soil types. It is recommended that the soils from these areas be routinely tested. The promotion of capacity development efforts for the development of a decentralized data collection strategy should also be implemented. The study developed data collection strategies that can be holistically used by the GoM to update its current database. It is recommended that the strategy is replicated in each ADD. The ADDs need to be supported with soil testing kits, mobile tablets, and mirror servers that are controlled at the headquarters.



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The **Poverty-Environment Initiative (PEI)** Malawi of the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP) supports country-led efforts to mainstream poverty-environment linkages into national development planning and budgeting. PEI provides financial and technical assistance to government partners to set up institutional and capacity-strengthening programs and carry out activities to address the particular poverty-environment context. PEI is funded by the governments of Norway, Spain, Sweden, the United Kingdom, and the European Union and with core funding of UNDP and UNEP.

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The **Global Soil Partnership (GSP)** was established in December 2012 as a strong interactive partnership to promote sustainable soil management. It is a mechanism that fosters enhanced collaboration and synergy of efforts between all stakeholders, from land users through to policy makers. Its mandate is to improve governance of the planet's limited soil resources in order to promote the sustainable management of soils and guarantee healthy and productive soils for a food secure world, as well as support other essential ecosystem services. Awareness raising, advocacy, policy development and capacity development on soils, as well as relevant implementation in the field are among the main GSP activities.

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