Exploring Mechanisms to Restore Fertility of Degraded Lixisols for Enhanced Crop Productivity under Smallholder Farmer Management Systems

by

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Abstract

Croplands in smallholder farming areas of Southern Africa are in a degraded state, with most cereal and legume crops yielding less than 1 t ha\(^{-1}\) of grain. Restoring productivity of these degraded croplands is therefore key to intensifying crop production to meet household food and nutritional security needs. The objective of this study was to evaluate sequences of integrated soil fertility management (ISFM) technology components for rehabilitation of degraded sandy soils and intensification of maize (\textit{Zea mays} L.)-based cropping systems in Hwedza and Makoni smallholder farming areas in Eastern Zimbabwe. Farmer participatory research approaches, laboratory characterization, remote sensing and Geographic Information Systems were first employed to formulate criteria for assessing degradation of croplands. Second, field experiments were conducted to evaluate alternate sequences of ISFM options based on nitrogen (N)-fixing green manure and grain legumes, low quality organic resources and mineral N and phosphorus (P) fertilizers for rehabilitating the degraded croplands. Third, biophysical data generated from field experimentation were combined with simulation modelling to best-fit the ISFM sequences to different resource categories of farmers. Farmers delineated croplands as productive, moderately productive, degraded and severely degraded based on common indicator weeds, crop performance and soil physical attributes. Overall, laboratory-based soil chemical and biological properties, and most of the weed species closely matched farmer categorization. Spatially, forty percent of the arable land was classified as degraded to severely degraded. Over a 3-year period, rehabilitation of the degraded sandy soils was positively influenced by high quality organic resource application and P fertilization. Indigenous legumes and sunnhemp (\textit{Crotalaria juncea} L.) planted on otherwise degraded soils, with addition of mineral P fertilizer, led to higher biomass C and N production than under natural fallow. A combination of biomass generated under indigenous legume fallow (indifallow) and sunnhemp fallow, and cattle manure increased soil basal respiration and microbial biomass. Maize grain yields averaged 2.5 t ha\(^{-1}\) under the legume-based sequences compared with 1 t ha\(^{-1}\) under continuous fertilized maize and natural fallow-based options. Over a 4-year period, ISFM sequences based on cattle manure/woodland litter-, NP fertilizer- and legume-based rotations accumulated the highest maize and soyabean grain yields. This was largely explained by a significant accumulation of soil P. These sequences were more productive than farmers’ designated most-and least-productive fields. Cattle manure-based sequences gave the highest cumulative crop yields, while sunnhemp-based sequences attained the highest increase in soil P. Based on costs of seed, fertilizers and labour, the ISFM sequences gave better financial returns than the farmers’ most-and least-productive fields. When assessed over a 49-year period (1962-2011) using Agricultural Production Systems Simulator (APSIM) under agronomic management of different resource categories of farmers, simulated maize yields of the ISFM sequencing options averaged 3.8, 2.4 and 1.8 t ha\(^{-1}\) for resource-endowed, resource-intermediate and resource-constrained households, respectively. The major conclusions from this study were as follows: (i) ethnopedological approaches could aid assessment of soil degradation on smallholder farms to inform decision-making, (ii) degraded croplands are not beyond remedy, and ISFM sequences based on herbaceous legumes are potential entry points to rehabilitate them and (iii) ISFM sequences are a suitable option for intensifying smallholder cropping systems in Southern Africa through increasing crop yields to meet energy and protein requirements of households, and allowing for systematic allocation of the often limited and variable nutrient, seed and labour resources in space and time.
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Dedication

To my wife Lindah, and our children Takudzwa and Tinodiwanashe
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<th>Description</th>
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<tr>
<td>AGDP</td>
<td>Agricultural Gross Domestic Product</td>
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<tr>
<td>APSIM</td>
<td>Agricultural Production Systems Simulator</td>
</tr>
<tr>
<td>CA</td>
<td>Conservation Agriculture</td>
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<tr>
<td>FPRA</td>
<td>Farmer Participatory Research Approaches</td>
</tr>
<tr>
<td>FTLRP</td>
<td>Fast Track Land Reform Programme</td>
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<tr>
<td>GIS</td>
<td>Geographic Information Systems</td>
</tr>
<tr>
<td>GLASOD</td>
<td>Global Assessment of Soil Degradation</td>
</tr>
<tr>
<td>ISFM</td>
<td>Integrated Soil Fertility Management</td>
</tr>
<tr>
<td>m.a.s.l.</td>
<td>meters above sea level</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
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<tr>
<td>NR</td>
<td>Natural Region</td>
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<tr>
<td>PCA</td>
<td>Principal Components Analysis</td>
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<tr>
<td>RG</td>
<td>Resource Group</td>
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<tr>
<td>SOFECSA</td>
<td>Soil Fertility Consortium for Southern Africa</td>
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<td>SOM</td>
<td>Soil Organic Matter</td>
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<tr>
<td>SSA</td>
<td>Sub-Saharan Africa</td>
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<td>ZimAsset</td>
<td>Zimbabwe Agenda for Sustainable Socio-Economic Transformation</td>
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CHAPTER 1

Introduction and Problem Definition

1.1 Background

Demographic projections indicate that the number of people living in Sub-Saharan Africa (SSA) will reach 2.1 billion by 2050, surpassing growth in other developing regions such as Asia and Latin America (United Nations, 2013; Gerland et al., 2014). The projected population rise presents food and nutritional security concerns for SSA as most countries are still grappling with low agricultural productivity to feed the current, and let alone growing, population against a largely finite and degrading land resource base (Millennium Ecosystem Assessment, 2005; Lal, 2006a; FAO, 2011). It is estimated that of the 800 million people suffering from chronic hunger worldwide, the majority are in rural areas of SSA (FAO, IFAD and WFP, 2014). The situation is worsened by the limited livelihood opportunities to source food elsewhere and a poor capital base. As a result, in most African countries, including Zimbabwe, rural dwellers are perennial recipients of food handouts (Frost et al., 2007; FAO, 2011).

With over 70% of the African population residing in rural areas and directly deriving its livelihood from agriculture, managing the soil resource base to increase food production is at the core of eradicating hunger and poverty. Both the United Nations Millennium Development Goals targeted for the year 2015 (United Nations, 2010) and the Sustainable
Development Goals, aimed at guiding the development agenda in the post 2015 era (SDSN TG7, 2013), recognize the need to increase agricultural production on existing croplands to keep pace with rising demands for food, fibre and fuel. The Rio+20 United Nations Conference on Sustainable Development identified human-induced soil degradation as a major threat to sustainable crop production and consequently attainment of food security in SSA (United Nations, 2012). Emerging evidence of the potential negative impacts of climate change and variability (Vermeulen et al., 2012; IPCC, 2013), present yet another over-arching challenge to already burdened African smallholder farming communities. Given that regions such as Southern Africa are anticipated to experience increased frequency and severity of droughts (Unganai, 1996; Shongwe et al., 2009; Knox et al., 2012), managing soil fertility will be key to maximizing crop production during favourable rainfall seasons (Rurinda et al., 2013).

In most parts of West and Southern Africa, smallholder farms lie on old sandy soils formed billions of years ago from Precambrian rocks (FAO/ISRI/ISSS, 2006). These soils are highly susceptible to degradation as they have low amounts of major nutrients, low soil organic matter (SOM), low water holding capacity due to low clay content of predominantly 1:1 mineralogy, and few weatherable minerals (Hatermink and Huting, 2008). Prior to the mid-20th century, shifting cultivation was the dominant option for managing soil fertility on African smallholder farms (Nye and Greenland, 1960; Padwick, 1983). Nutrient losses through harvested crop products, leaching and erosion were restored through natural fallowing. With the increase in population, shifting cultivation was replaced by permanent cultivation (Muchena et al., 2005). Challenges associated with farmer access to mineral fertilizers and locally-available nutrient resources (e.g. Nyikahadzoi et al., 2012; Mapfumo et
al., 2013) have, however, led to suboptimal addition of nutrients to crops leading to declining yields. Coupled with lack of proper soil and water conservation structures, which have also significantly contributed to carbon (C) and nutrient losses through soil erosion (Vogel, 1993; Thierfelder and Wall, 2009), most croplands on African smallholder farms now have severe nutrient deficiencies (Smaling et al., 1997; Bekunda and Manzi, 2003; Haileslassie et al., 2005). This has culminated in the creation of degraded croplands characterized by poor crop productivity and low response to mineral fertilizer inputs (Mtambanengwe and Mapfumo, 2005; Tittonell et al., 2012).

According to global assessments 65% of the African agricultural land is degraded (Oldeman et al., 1991; Millennium Ecosystem Assessment, 2005; Vlek et al., 2008). It is estimated that in SSA annual crop yield loss due to soil degradation alone ranges between 6 and 8%, and could increase to 17% by 2020 if the degradation continues unabated (Lal, 1995; Eswaran et al., 2001). In Zimbabwe, the annual cost of soil degradation was found to account for up to 9% of the Agricultural Gross Domestic Product (AGDP), (Bojö, 1996; Scherr, 1999). Restoring productivity of these degraded croplands will not only be key to increasing crop yields to meet income and food and nutritional security requirements of African smallholder farmers, but also for providing other ecosystem services such as C sequestration, nutrient cycling and increasing soil biodiversity.

1.2 Rationale

While global assessments are important in highlighting the extent of soil degradation in SSA (e.g. Bai et al., 2008; Vlek et al., 2008), the nature and context of the degradation at farm and community levels are likely to vary as dictated by soil type and farming system, among other
factors. Smallholder farming systems of SSA have diverse biophysical and socio-economic settings (Giller et al., 2011). To enable better targeting of rehabilitation options, there is therefore need for context-specific understanding of soil degradation to corroborate the global assessments.

In Zimbabwe, soil degradation on smallholder farms is compounded by shortage of additional arable land for expansion and extensification. Consequently, most smallholder farmers in Communal Areas† have traditionally resorted to growing crops on soils surrounding granitic rock outcrops — commonly known as magwidi in the local Shona language (Whitlow, 1980; Nyamapfene, 1989). These soils are often more productive than the main arable croplands because they are less leached and have better water holding capacity (Nyamapfene, 1989). Although the Zimbabwean Government embarked on agrarian reform programs between 1980 and 2000s to decongest overpopulated Communal Areas by resettling some of the farmers on former large-scale commercial farms, the majority of the population still resides in the Communal Areas typified by easily degradable and fragile sandy soils (Andersson, 2007; Chimhowu and Woodhouse, 2008). Most of the newly-resettled farmers also grow crops on sandy soils given that over 70% of the country is covered by such soils (Nyamapfene, 1991). In the Communal Areas, average household land holding is less than 3 ha, with maize grain yields rarely surpassing 1 t ha\(^{-1}\) year\(^{-1}\) (Zimbabwe National Statistics Agency, 2012a; Mapfumo et al., 2013). This scenario indicates that at farm level, all fields should maintain a certain level of productivity to meet household food requirements and

†Smallholder farms formed for indigenous black people by the British colonial settlers following the enactment of the Land Apportionment Act in 1930 in Rhodesia (now Zimbabwe) (Hanlon et al., 2012).
possibly generate income. Where some of the fields have been degraded, deliberate measures to restore their fertility are therefore necessary.

The need to arrest hunger and poverty in Zimbabwe by first increasing crop production at household level is recognized nationally. The Zimbabwe Agenda for Sustainable Socio-Economic Transformation (ZimAsset) policy framework, put forward by the Government of Zimbabwe to guide the development agenda between 2013 and 2018, clearly stipulates the need to increase cereal productivity as well as manage the natural resource base under its food security and nutrition cluster (Government of Zimbabwe, 2013). Internationally, crop production at household level is also considered key to ensuring food security with the United Nations declaring the year 2014 as the International Year of Family Farming (www.fao.org/family-farming-2014/en/).

While the Green revolution in the 1960s led to significant increases in agricultural production in Asia and Latin America through widespread promotion of improved germplasm and mineral fertilizers, the same approach yielded little benefits in SSA (Dudal, 2002). In most African countries mineral fertilizer costs are prohibitive while nutrient resources from within and around the farm are often inadequate to sustain crop production (Mapfumo and Giller, 2001; Camara and Heinemann, 2006, Vanlauwe and Giller, 2006). For example, in Zimbabwe, a 50 kg bag of ammonium nitrate [34.5% nitrogen (N)] cost an average of US$ 38 between 2009 and 2014. Given the limited income sources in smallholder communities, such a price is beyond the reach of most farmers, the majority of whom live on less than US$ 1 day$^{-1}$ (World Bank, 2013). The realization that nutrient resources for soil fertility replenishment are scarce on African smallholder farms prompted soil fertility studies, over
the last three decades, to focus on integrated soil fertility management (ISFM) (Buresh et al., 1997a; Vanlauwe et al., 2001a; Mafongoya et al., 2006). ISFM is anchored on combined use of available organic resources and mineral fertilizers, use of improved germplasm and systematic rotations of cereals with N\textsubscript{2}-fixing legumes according to farmer biophysical and socio-economic settings (TSBF-CIAT, 2005; Vanlauwe et al., 2010; Mapfumo et al., 2013). ISFM is considered a viable option for sustainable intensification of African smallholder cropping systems (Vanlauwe et al., 2010; Rusinamhodzi, 2013; Tittonell and Giller, 2013). Crop production intensification in the context of African smallholder farming is considered to hinge on efficient use of external resources such as mineral fertilizers, herbicides, and hybrid seeds to raise crop production per unit area while reducing negative environmental externalities (Pretty et al., 2011; Tittonell, 2014). While some of the 'best-bet' ISFM technology options such as rotations of cereals with N\textsubscript{2}-fixing grain legumes and green manures (Snapp et al., 1998; Muza, 2003), agroforestry (Mafongoya et al., 2006) and combinations of cattle manure and mineral fertilizers (Waddington et al., 2007; Zingore et al., 2008) have been shown to increase crop yields on soils of different background fertility, they have largely been promoted as ‘stand alone’ options. Little work has been done to sequence the different ISFM technology options in order to enhance build up of soil C and nutrients whilst maintaining short-term crop yield benefits on both degraded and already productive soils.

Apart from identifying ISFM sequences that can increase productivity, it is also important to align the sequences to complements of farm-level resources that enable a household to reach critical land areas necessary to attain production levels that meet household food needs. While emerging evidence indicates that crop production on African smallholder farming systems
will increase largely through intensification rather than extensification (Erenstein, 2006; Rusinamhodzi, 2013; Tittonell and Giller, 2013), farmer resource endowment should be considered. Farm-level resources such as labour, land size and knowledge have been shown to strongly determine adoption of technologies, including ISFM (Mekuria and Waddington, 2002; Mugwe et al., 2009; Gwandu et al., 2014).

1.3 Hypotheses

The study was guided by the following hypotheses:

1. Degradation of soils under smallholder cropping is directly linked to depletion of carbon and phosphorus beyond laboratory detectable thresholds and can be appraised through farmers’ local indicators

2. Nitrogen-fixing herbaceous indigenous legumes of the genera *Chamaecrista, Crotalaria, Eriosema, Indigofera, Neonotonia* and *Tephrosia* are a pre-requisite for initial carbon fixation on degraded soils to enhance the effectiveness of manure- and mineral fertilizer-based integrated soil fertility management (ISFM) sequences

3. Alternate sequences of manure-, fertilizer- and legume-based ISFM options cumulatively result in differences in use efficiencies of fertilizer nitrogen and phosphorus, and maize and soyabean productivity on degraded sandy soils
4. Farmers of different resource categories require different minimum land areas under ISFM to produce sufficient maize grain yields to meet household food self-sufficiency under intensification

1.4 Objectives

The main objective of the study was to evaluate alternate sequences of integrated soil fertility management (ISFM) options for rehabilitation of degraded sandy soils and intensification of maize-based cropping systems in smallholder farming systems in Zimbabwe.

Specific study objectives were:

1. To develop, with communities, criteria for assessing soil degradation on arable fields under smallholder cropping

2. To explore mechanisms for enhancing carbon sequestration on degraded sandy soils as an entry point to restore their productivity

3. To evaluate the influence of alternate sequences of manure-, fertilizer- and legume-based ISFM options on crop productivity and resource use efficiencies under maize-based cropping.

4. To determine best-fit ISFM sequences for different resource categories of farmers under intensification.
1.5 Thesis structure

Chapter 1 gives the problem statement and rationale, while a detailed literature review of the drivers of soil degradation and potential options for rehabilitating degraded croplands in smallholder farming areas in Southern Africa is given in Chapter 2. An overview of study sites, research methodology and conceptual framework are given in Chapter 3. Chapter 4 looks at assessment of soil degradation in a smallholder farming area of Zimbabwe through a combination of farmer participatory research approaches (FPRA), laboratory characterization, and remote sensing and Geographic Information Systems (GIS). In Chapter 5, entry points for rehabilitating degraded croplands are explored using principles of ISFM. The influence of sequencing different ISFM options on degraded croplands with respect to crop productivity and resource use efficiencies are looked at in Chapter 6. In Chapter 7, biophysical data generated from field experimentation (Chapter 6), detailed characterization of farming systems and simulation modelling are combined to explore best-fit ISFM sequences for different resource categories of farmers. The overall study findings, conclusions, recommendations and areas for further studies are given in Chapter 8.
CHAPTER 2

Literature Review

2.1 Dominant soils in Communal Areas of Zimbabwe

Communal Areas of Zimbabwe are broadly covered by granite-derived sandy soils, largely classified as Lixisols and Arenosols (Nyamapfene, 1991; FAO/ISRI/ISSS, 2006). Lixisols are defined as soils in which considerable clay, sesquioxides (iron/aluminium oxides and hydroxides) and colloidal humus have been removed from the A horizon and deposited in subsurficial horizons such as B and C through pedogenetic processes, particularly eluviation (FAO/ISRI/ISSS, 2006). The removal of the clay, sesquioxides and colloidal humus often result in the formation of an albic or eluviated horizon (E horizon). Lixisols are therefore characterized by higher amounts of low-active clays and more exchangeable bases in the subsurfical horizons than the upper horizons. The clay removed from the A horizon is usually deposited in the B horizon to form a clay-rich zone called an argillic/argic (Bt) horizon. In SSA, Lixisols occupy approximately 220 million ha of land, with more than half of the area under agriculture (FAO-ISRIC, 2003; FAO/ISRI/ISSS, 2006).

Arenosols are deep sands formed from either in situ weathering of quartz-rich sediments or eolian deposition of sand particles (FAO/ISRI/ISSS, 2006). In Southern Africa, approximately 6.5 million ha of Arenosols are under agriculture (Hatermink and Huting, 2008). Both Lixisols and Arenosols are overly characterized by poor aggregation, high proneness to
erosion and low nutrient reserves. Based on the Zimbabwe soil classification system, Arenosols can be classified as Regosols while Lixisols transcend the Fersiallitic, Paraferrallitic and Orthoferrallitc groups (Nyamapfene, 1991).

2.2. What is soil degradation?

Although there are numerous definitions of soil degradation (e.g. Lal et al., 1989; Hulugalle, 1992; Karlen et al., 1997; Vlek et al., 2008), the process is underpinned by negative changes in soil properties due to natural and/or human factors. Consequently, the soil loses its actual and potential productivity (Riquier, 1978; Lal, 1993). Resilient soils are able to recover to antecedent levels following natural or human-induced perturbation (Lal, 1993). Despite being intricately linked, soil degradation can be divided into physical, chemical and biological.

Soil physical degradation involves a deterioration of physical and hydrological properties, with subsequent negative impacts on ecosystem services (Lal et al., 1989; Omuto, 2008). Soil physical degradation is sequential. First, the structure of the soil collapses mainly due to compaction and crusting. Second, the compacted soil impedes drainage and circulation of air leading to anaerobiosis, increased soil erosion and high runoff. Loss of clay and humus to subsoil horizons through eluviation is also considered another form of physical degradation (Dexter, 2004). Soil physical degradation is often caused by laterization, hardsetting, cultivation and deforestation, particularly on light-textured soils (Lal et al., 1989).

Soil chemical degradation involves depletion of essential nutrients for plant growth, salts and heavy metal accumulation in toxic amounts, leaching of basic nutrients and loss of SOM (Lal
et al., 1989). Continuous cropping with no or sub-optimal nutrients addition, disposal of toxic wastes and use of poor quality irrigation water are some of the major contributors to soil chemical degradation in cropping systems. Soil biological degradation is mainly caused by organic matter loss, which in turn leads to decline in populations, diversity and activity of flora and fauna (Lal, 2006b). Biologically-degraded soils are usually characterized by failure to detoxify toxic waste, limited decomposition of organic matter and a change from favourable to unfavourable biological processes. Low addition of organic matter, tillage, pesticide use and soil erosion contribute to soil biological degradation.

Despite N and P-based straight and compound fertilizers being widely used on most smallholder farms in Southern Africa (Mapfumo and Giller, 2001; Kazombo-Phiri, 2005; Mapila et al., 2012), emerging evidence indicate that some of the degraded soils show weak or no crop yield responses to addition of these fertilizers (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2008). Most of these "non-responsive soils" are characterized by severe SOM depletion, high acidity and deficiencies in most plant nutrients (Tittonell et al., 2012). The poor fertilizer responses on the degraded soils indicate that mineral fertilizers alone may not rehabilitate such soils, especially where the fertilizers do not supply multiple nutrients. It is noteworthy that, in some cases, the non-responsiveness of soils to addition of mineral fertilizers could be due to other factors such as water logging and salinity (Patrick and Mahapatra, 1968; Darwish et al., 2005).
2.3 Drivers of soil degradation in smallholder farming systems in Southern Africa

2.3.1 Land marginality as the underlying cause of soil degradation

The enactment of the Land Apportionment Act in Zimbabwe in 1930 by the then colonial government paved way for the eviction of the indigenous black people from inherently fertile soils to marginal and small land holdings now known as Communal Areas (hitherto referred to as Tribal Trust Lands or Native Reserves) (Phimister, 1986; Rukuni et al., 2004; Hanlon et al., 2012). Albeit with different institutional arrangements and historical legacies, a similar land tenure system also exist in other Southern African countries such as South Africa and Malawi (Meadows and Hoffman, 2002; Carr, 2003; Wessels et al., 2007). More than 70% of the smallholder areas are located on sandy soils, which are highly leached and therefore deficient in base nutrients. Most these soils can release appreciable quantities of potassium (K) to support crop production because of the presence of feldspars in granite (Hatermink and Huting, 2008). However, they are largely low in mafic minerals to release sufficient quantities of other plant nutrients such as P, sulphur (S), calcium (Ca) and magnesium (Mg). Under continuous cropping, the sandy soils easily degrade as most farmers add inadequate nutrients to replenish those removed through crop harvests.

Most cropped soils on smallholder farms of Southern Africa have low clay content for maintenance of good physical structure, moisture retention and protection of added organic matter (FAO/ISRI/ISS, 2006; Hatermink and Huting, 2008). As a result of its charge contribution, clay is important in the formation and stabilization of soil aggregates through clay-organic matter interactions and clay-cationic complexation (Feller and Beare, 1997; Six et al., 2002). Physically, clay also enhances soil aggregation through encapsulation of organic
matter within aggregates thus restricting access by decomposer organisms (Hassink, 1997; Mtambanengwe et al., 2004). Susceptibility of sandy soils to degradation therefore stems from their low clay and silt contents, which limit aggregation. On such soils, anthropogenic activities such as tillage immediately set in motion degradative processes upon conversion from virgin lands. More than 50% of the soil organic carbon (SOC) is usually lost in the first 5-10 years of cultivation (Zingore et al., 2005; Solomon et al., 2007; Moebius-Clune et al., 2011). Management practices to maintain the SOC and other soil properties above productivity threshold levels will therefore be key to sustaining crop production on these fragile soils. In cases where the soils have been degraded to curtail crop production, rehabilitation is required.

2.3.2 Soil erosion

Loss of topsoil from croplands, mainly through water movement, is one of the major causes of soil degradation in cropping systems not only in SSA, but globally (Hudson, 1973; Stocking and Peak, 1987; Kaihura et al., 1998). Erosion presents a total form of degradation as it results in the loss of soil physico-chemical and biological properties. Due to their poor aggregation and therefore low resistance to raindrop impact, the predominantly Lixisols and Arenosols in smallholder farming areas in Southern Africa are highly susceptible to erosion. In Zimbabwe, soil losses of between 10 to 40 t ha\(^{-1}\) year\(^{-1}\) have been recorded on granitic sandy soils (Elwell and Stocking, 1988; Moyo, 1993; Vogel, 1993). Concomitantly, substantial SOC losses of up to 200 kg C ha\(^{-1}\) year\(^{-1}\) have also been reported on similar soils in Southern and West Africa (Moyo, 1998; Roose and Barthes, 2001). Emerging evidence of increased frequency of rain storms in Southern Africa (Shongwe et al., 2009; Rurinda et al.,
2013) will likely exacerbate soil erosion suggesting the need to widen options for controlling erosion and rehabilitation of eroded croplands.

2.3.3 Overpopulation

Increase in human population in smallholder farming areas in Southern Africa, including Zimbabwe, has not only led to reduced land holdings and permanent cultivation of fields, but also encroachment into marginal and fragile areas earlier considered as non-arable (Whitlow, 1980; Carr, 2003). In Zimbabwe, some of the Communal Areas have a population density of up to 40 people km\(^{-2}\) on a household land holding of less than 3 ha (Zimbabwe National Statistics Agency, 2012a). Often, farmers are faced with a dilemma that the majority of the arable land is severely degraded to support crop production and there is limited land for expansion (Davies et al., 2010). However, it is noteworthy that population increase as a proximate cause of soil degradation is debatable. While a number of studies shown a positive relationship between population rise and increased soil degradation (e.g. Carr, 2003; Muchena et al., 2005), there are cases where population increase led to better management of agricultural land (e.g. Tiffin et al., 1994; Mazzucato and Niemeijer, 2001).

2.3.4 Tillage

Tillage breaks soil aggregates and improves aeration leading to depletion of aggregate-protected organic matter through exposure to microbial decomposition (Six et al., 1999; Chivenge et al., 2011). Conversely, no-till cropping systems increase soil aggregation and SOM protection through chemical and physical stabilization (Lal, 2011; Paul et al., 2013). Other degradative processes associated with tillage include increased soil pulverization
leading to high erodibility, disruption of soil macroporosity, and reduced soil biodiversity and faunal activity (Lal, 1993). Over the past two decades, numerous studies conducted in Zimbabwe have shown increased soil erosivity and reduced soil C sequestration with conventional tillage, particularly on sandy soils (e.g. Nyagumbo, 2002; Chivenge et al., 2007; Thierfelder and Wall, 2009). As in other parts of Southern Africa, most smallholder farmers in Zimbabwe plough the whole field to loosen the soil and incorporate residues before planting. Such tillage practices have been viewed as the major cause of high rates of soil erosion (Stocking, 1978; Campbell et al., 1997). As such, soil degradation in smallholder farming areas in Zimbabwe has often been linked with the introduction of the mouldboard plough during the 1920s and the subsequent widespread promotion of conventional ploughing (Marongwe et al., 2011; Baudron et al., 2012a). To combat soil degradation due to tillage, minimum soil disturbance options are now being promoted across SSA, and other parts of the world, as one of the core principles of Conservation Agriculture (CA) (IIRR and ACT, 2005; Hobbs, 2007; FAO, 2009a).

2.3.5 Low addition of organic matter and mineral fertilizers

Organic materials remain important sources of plant nutrients on African smallholder farms where mineral fertilizers are often added at sub-optimal rates (Swift et al., 1994; Mtambanengwe, 2006; Bationo et al., 2007a). However, high organic matter turnover rates of up to 2% per year (Janssen et al., 1990) imply that farmers need to frequently add large amounts of organic materials to significantly improve soil quality. On the contrary, smallholder farmers usually apply no more than 5 t ha\(^{-1}\) year\(^{-1}\) of organic materials to their fields (Campbell et al., 1998; Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007). Livestock manure and crop residues are usually in short supply due to low livestock numbers
and competing uses (Vanlauwe and Giller, 2006; Rufino et al., 2011). On the other hand, collection of woodland litter is labour intensive (Nyathi et al., 1993; Campbell et al., 1998). Identifying other sources of organic materials could be key to sustaining productivity on these soils.

Fertilizer use on most African smallholder farms is low, with most farmers applying less than 10 kg ha$^{-1}$ year$^{-1}$ (Bationo et al., 2006; Camara and Heinemann, 2006). The low fertilizer use prompted a Fertilizer Summit by African Heads of Government in June 2006 whose declaration was for farmers to apply at least 50 kg fertilizer ha$^{-1}$ year$^{-1}$ (Africa Fertilizer Summit, 2007). The target is unlikely to be met in most African countries in the short-term because of challenges of high costs and inaccessibility, among other factors (Yanngen et al., 1998; Vanlauwe and Giller, 2006).

Another predicament on the predominantly sandy soils on smallholder farms is low fertilizer use efficiency due to a number of factors including leaching, erosion and poor agronomic management practices. Under maize cropping on sandy soils, fertilizer N use efficiency can be as low as 5 kg grain kg$^{-1}$ N (Mushayi et al., 1999; Waddington et al., 2007). Extensification where farmers increase production by expanding the area under cultivation while reducing fertilizer input per unit area also accelerates soil nutrient mining (Erenstein, 2006; Rusinamhodzi, 2013).
2.4 Options for rehabilitating degraded soils

2.4.1 Fallowing

Long natural fallows have traditionally been used to rehabilitate degraded soils as they allow for re-colonization by natural vegetation in the absence of anthropogenic disturbance (Nye and Greenland, 1960). Above and below ground biomass generated by the natural vegetation leads to build up of SOM, which, in turn, improves soil physical properties such as aggregation, porosity, drainage and aeration while reducing bulk density (Oades and Waters, 1991). Colloidal organic matter, gums and mucous from live roots of the natural vegetation also improve soil aggregation (Elliot, 1986). The natural vegetation provides organic substrates for stimulating soil biological activity. When the organic matter decomposes and mineralizes, it leads to release of nutrients such as N and P for plant uptake.

Increase in human and livestock populations in Southern Africa have, however, led to reductions in fallow periods, thereby compromising the soil rehabilitation process (Carr, 2003; Muchena et al., 2005). Improved fallows where fast growing N2-fixing legume trees are planted on fallowed lands to shorten the fallow period, have been widely promoted across SSA, including Southern Africa (Kwesiga and Coe, 1994; Mafongoya et al., 2006). Adoption of this technology by smallholder farmers has, nevertheless, been largely constrained by high labour demands and challenges in fitting the trees into existing cropping systems (Kiptot et al., 2007). Abandonment of degraded fields to natural fallowing due to low crop yields and lack of responses to mineral fertilizers has been documented (Chuma, 2000; Mtambanengwe and Mapfumo, 2005; Kamusoko and Aniya, 2007). Besides soil degradation challenges,
smallholder farmers also fallow some of their fields due to other constraints such as lack of draught power and fertilizers (Nyakanda et al., 2000; Manzungu and Mtali, 2012).

2.4.2 Soil conservation structures

Due to the high erodibility of the predominantly sandy soils in smallholder farming systems of Southern Africa, conservation structures to rehabilitate degraded croplands have been extensively studied (Elwell, 1981; Botha et al., 2003; Motsi et al., 2004). Some of the major soil conservation structures include storm drains, contour ridges and tied ridges. Storm drains and contour ridges are usually constructed at the upper slope of a field to prevent excess water entering the field (Machingaidze, 1991; Mutekwa and Kusangaya, 2006; Mupangwa et al., 2012). Tied ridges are mounds of soils heaped along crop rows to reduce water velocity (Elwell and Norton, 1988; Nyamangara and Nyagumbo, 2010). A study conducted on sandy soils in Zimbabwe reported a soil loss of less than 1 t ha\(^{-1}\) under tied ridging compared with 3.3 t ha\(^{-1}\) under conventional tillage (Vogel, 1993). These results concurred with later findings by Moyo and Hagmann (1994) and Nyagumbo (2002) on similar soils. Conservation structures rehabilitate degraded soils in a number of ways. By reducing water velocity, there is increased infiltration into the soil, reduced detachment of soil particles from aggregates and reduced erosion of SOM and other plant nutrients. Consequently, soil physical properties such as aggregation and porosity are increased while bulk density is lowered. SOM accumulation due to reduced water erosivity leads to increased populations, diversity and activity of soil fauna, and increased plant nutrients through decomposition and mineralization.

Despite proven evidence to rehabilitate degraded croplands, most soil conservation structures have not been widely adopted by smallholder farmers mainly due to high labour demands and
costs (Giller et al., 2009; Mupangwa et al., 2012). On smallholder farms in Zimbabwe, most storm drains and contour ridges were last constructed during the colonial era (before 1980) when every farmer was compelled by law to put soil conservation structures following the gazetting of the Natural Resources Act of 1941 (Machingaidze, 1991; McGregor, 1995).

2.4.3 Conservation Agriculture (CA)

Built on three principles of minimum soil disturbance, diversified crop rotations and mulching, CA has been extensively promoted in SSA as a technology to combat soil degradation and sustainably intensify production on smallholder farms (IIRR and ACT, 2005; Hobbs, 2007; Gowing and Palmer, 2008). Conceptually, CA is considered to contribute to rehabilitation of degraded soils in the following ways: (i) minimum soil disturbance leads to improved soil structure thus increasing water infiltration and reducing soil erosion (physical rehabilitation); (ii) minimum tillage promotes SOM sequestration resulting in improved soil aggregation, soil biological activity and availability of plant nutrients (physical, biological and chemical rehabilitation); (iii) mulching reduces soil erosivity and water evaporation, enhances water infiltration and builds SOM (physical, biological and chemical rehabilitation). While numerous studies have provided empirical evidence to substantiate the contribution of CA to rehabilitation of degraded soils (Lal et al., 1989; Scopel et al., 2004), some of the findings have remained contentious and inconclusive. Working on sandy soils in Zimbabwe, Baudron et al. (2012b) reported higher runoff under minimum tillage than on conventionally-ploughed soils contrary to the commonly reported results that minimum tillage reduces soil loss and increases water infiltration (e.g. Nyagumbo, 2002; Thierfelder and Wall, 2009). The contribution of minimum tillage to build up of SOM has also been contested. The reported increases in C sequestration under CA have been found to be inconsistent as they do not take
cognisance of C stratification with the soil profile (Mrabet, 2002; Luo et al., 2010; Signh et al., 2015). Despite its demonstrable benefits in soil rehabilitation (e.g. Erenstein, 2002; Scopel et al., 2004), mulching remains one of the least adopted principles of CA by African smallholder farmers largely due to competing uses for crop residues (Vanlauwe et al., 2014).

Overall, the adoption of CA and therefore its contribution to rehabilitation of degraded soils on smallholder farms is likely to be compromised by a number of challenges that include high labour demands, shortage of mulch, lack of immediate crop yield benefits and high fertilizer investments (Giller et al., 2009; Andersson and Giller, 2012; Rusinamhodzi, 2015).

2.4.4 Integrated soil fertility management (ISFM)

The ISFM paradigm drew from decades of research on soil biological processes, which provided evidence that combinations of organic nutrient resources and mineral fertilizers could be manipulated for increased crop productivity and improved soil quality (Bationo et al., 1993; Swift, et al., 1994; Vanlauwe et al., 2001a). Combining organic nutrient resources and mineral fertilizers improves soil quality as the former provide the much needed organic C to increase soil microbial respiration, while mineral fertilizers provide nutrients for both microbial and plant growth. Besides improving soil biological properties, the addition of organic nutrient resources can also positively impact on soil physical properties as structure, aeration and water holding capacity. As reported by Vanlauwe et al. (2001b), combined application of organic nutrient resources and mineral fertilizers led to increased maize yields and N uptake through microbial regulation of mineralization-immobilization processes in synchrony with crop demand. The inclusion of N$_2$-fixing legumes in cropping sequences, as one of the core components of ISFM, provides high-N containing organic substrates to
increase soil faunal activity. Increased soil biological activity in legume-cereal rotations compared with cereal monocrops has been reported (Balota et al., 2003; Yusuf et al., 2010).

Several studies have reported rehabilitation of degraded soils under ISFM. Zingore et al. (2008) reported increased maize productivity on once degraded soils following repeated application of cattle manure and mineral fertilizers over three years. Working in Nigeria, Vanlauwe et al. (2005) recorded a reduction in soil acidification due to repeated application of _Senna siamea_ prunings. Overall, soil water, nutrients and crop productivity have been shown to significantly increase under combined application of organic and inorganic nutrient resources, with the benefits attributed to direct and indirect interactions (Vanlauwe et al., 2001b; Gentile et al., 2009). Unlike CA, which is often promoted as an indivisible package, ISFM presents a viable option for rehabilitating degraded soils and intensification of cropping systems in SSA because of its flexibility to accommodate a wide range of soil fertility management practices as determined by farmer biophysical and socio-economic circumstances. This is particularly important in African smallholder farming systems where farmers fall in different wealth classes, and therefore have diverse resources for managing soil fertility (Mtambanengwe and Mapfumo, 2005; Tittonell et al., 2005; Zingore et al., 2007).

### 2.5. Crop simulation models

A model is a simplified representation of a system or process. Modelling hinges on the principle that a process can be expressed as a mathematical function(s). Crop simulation models simulate biomass accumulation in plants as determined by interactions between weather, soil properties and management factors (Azam-Alli et al., 1994; Kho, 2000; Keating
et al., 2003). Over the years, crop simulation modelling has developed due to scientific advances in soil science, crop physiology, crop ecology and computing technology. Most crop simulation models are based on the hierarchical modelling approach (de Wit, 1992; 1994). According to the hierarchical modelling approach, crop growth is determined by defining (e.g. radiation, temperature, crop characteristics), limiting (e.g. water, nutrients) and reducing (e.g. weeds, diseases, pests) factors. Some of the crop simulation models which have been used in smallholder cropping systems of SSA include Agricultural Production Systems Simulator (APSIM) (Shamudzarira and Robertson, 2002; Dixit et al., 2011; Rurinda et al., 2015), Crop Environment Resource Synthesis (CERES) (Schulze et al., 1993; Phillips et al., 1998), Decision Support System for Agrotechnology Transfer (DSSAT) (Jones and Thornton, 2003; Thornton et al., 2009) and Erosion-Productivity Impact Calculator (EPIC) (Folberth et al., 2012).

Overall, crop simulation models enable creation of virtual experiments to explore different scenarios, allow for unraveling of complexity of cropping systems, disentangle and explain effects of yield determining, limiting and reducing factors, and integrate agronomic with biophysical data and extrapolate in time and space. However, simulation models have limitations. Most crop simulation models require large amounts of data, which may not be readily available, particularly on smallholder farming systems of SSA (van Keulen, 1995; van Wijk et al., 2009). Models do not take into consideration all biological processes, which allows for errors in simulations. Most crop simulation models were developed for particular agro-ecological regions and farming systems making it difficult to directly apply them in other regions without rigorous parameterization and calibration (van Keulen, 1995). In as
much as crop simulation models can allow exploration of different scenarios, they do not eliminate the need for continued experimentation to better understand crop growth.

2.6 Overview of smallholder farming systems in Zimbabwe

Agrarian reform programs conducted in Zimbabwe before and after attainment of independence culminated in different models of smallholder farms (Rukuni et al., 2004). Firstly, the establishment of native reserves or tribal trust lands by the then colonial government created Communal Areas where the majority of farmers have < 3 ha of arable land (Hanlon et al., 2012). Secondly, in the early 1980s, the Government of Zimbabwe acquired some of the under-utilized large-scale commercial farms to resettle farmers in a bid to relieve pressure on overpopulated Communal Areas (Government of Zimbabwe, 1981). Under this scheme, known as old resettlement areas or 'minda mirefu' in the local Shona language, a household was allocated an average of 6 ha of arable land. Thirdly, in the early 2000s, the Government embarked on a Fast Track Land Reform Program (FTLRP) to compulsorily acquire approximately 11 million ha of prime agricultural land under white settler large-scale commercial farming for resettling black farmers, the majority whom were still residing in the overpopulated Communal Areas (Government of Zimbabwe, 2001). The FTLRP led to the establishment of smallholder farms, known as the A1 model, where a household was allocated between 12 and 70 ha of arable land depending on agro-ecological region.

In all the three models, the farming system is predominantly low-input maize-based, and characterized by strong crop-livestock interactions. In the rainy season (November to April),
livestock that include cattle, goats and donkeys are herded in designated grazing areas during the day and kept in kraals close to homesteads at night. In the dry season the livestock graze freely on rangelands and farmers' fields. Cattle provide draught power and are also a major source of manure for crop production. Other sources of crop nutrients commonly used in the smallholder areas are composted woodland litter and NPK mineral fertilizers. Agricultural activities such as land preparation, planting, weeding and harvesting are mostly conducted using household labour, particularly by women and children. During the dry season, assorted vegetables are grown in fenced gardens located near water sources such as wells, rivers and wetlands. Other dry season livelihood activities conducted in these smallholder farming areas include brick moulding, construction and repairing of houses, pottery, petty trading and beer brewing.
CHAPTER 3

Study sites and Research Methodology

3.1 Study sites

The study was conducted on-farm in Hwedza and Makoni Districts, both in Eastern Zimbabwe (Figure 3.1). Zimbabwe is classified into five natural regions (NR), with total annual rainfall decreasing in the order: > 1500 mm (NR I), > 750 mm (NR II), 650-750 mm (NR III), 450-650 mm (NR IV) and < 450 mm (NR V) (Vincent and Thomas, 1961; Surveyor-General, 1984). Overall, Hwedza District lies in NRs II and III. In Makoni District, the study was specifically conducted in Chinyika Resettlement Area, which falls under NRIII. As in most smallholder farming areas in Zimbabwe and other parts of Southern Africa, cropping in Hwedza and Makoni is largely conducted under rain-fed conditions on dominantly sandy soils. The study sites also typify the majority of smallholder farming systems of Southern Africa with regards to low external input soil fertility management practices, land degradation, low crop yields, erratic seasonal rainfall and high dependence on agriculture for food and income needs.

3.1.1 Hwedza

Hwedza District (18° 41´S; 31°42´ E; 1300 m.a.s.l) is in Mashonaland East Province lying approximately 140 km east of the capital Harare. The district comprises of 15 wards, with 12 being under smallholder farming.
In Zimbabwe, a ward is the smallest administrative and planning unit headed by a councilor. A ward is made up of between 25 and 30 villages resulting in approximately 1000 households. Specifically, the study was conducted in two wards: Goto (ward 8) and Ushe (ward 10). Goto and Ushe were one of the areas designated as native reserves (Communal Areas) following the enactment of the Land Apportionment Act in 1930. Therefore, both areas have been under smallholder farming for more than 80 years. Goto is in NR II while Ushe lies in NRIII. In Goto, soils are predominantly granitic sands (Lixisols), with scattered intrusions of dolerite derived clayey-clay loams (Luvisols) (Nyamapfene, 1991; van Engelen et al., 2004; FAO/ISRI/ISS, 2006). Similarly, Ushe is largely dominated by Lixisols, with
some patches of Arenosols (Rurinda et al., 2013). Maize is the dominant crop grown in both wards while cowpea (Vigna unguiculata (L.) Walp), groundnut (Arachis hypogaea L.), sweet potato (Ipomoea batatas (L.) Lam.), finger millet (Eleucine coracana L.) and pearl millet (Pennisetum glaucum L.) are grown on small field sections. Over the past 3 years, the area under tobacco (Nicotiana tabacum L.) has also increased, particularly in Goto.

3.1.2 Makoni

Chinyika Resettlement Area (between 18° 13´S, 32° 20´E and 18° 14´S, 32° 24´E; 1300-1500 m.a.s.l) is part of Makoni District and falls under Manicaland Province. The 32 wards in Makoni District are spread across communal, resettlement and large-scale commercial farming areas. Located approximately 250 km east of the capital Harare, Chinyika is a Resettlement Area established by the Government of Zimbabwe in the early 1980s to decongest overpopulated Communal Areas (Mtambanengwe and Mapfumo, 2005). The study was carried out in Bingaguru (ward 9) and Nyahava (ward 10), which are part of Chinyika Resettlement Area. Both Bingaguru and Nyahava are in NR III, and dominated by Lixisols and scattered patches of Arenosols (Vincent and Thomas, 1961; Nyamapfene, 1991; FAO/ISRI/ISS, 2006). In both wards, each household has an average of 6 ha arable land, with the majority owning at least 5 cattle. Maize and tobacco are the main crops grown in the two wards. As in Hwedza, grain legumes and small grains are grown on smaller areas.
3.2 Research methodology and conceptual framework

The study employed farmer participatory research approaches (FPRA), remote sensing and Geographic Information Systems (GIS), field experimentation, laboratory analyses and simulation modelling to assess soil degradation on arable fields under low external nutrient input and evaluate alternate sequences of ISFM options for rehabilitating the degraded soils. Conceptually, rehabilitation of degraded soils was envisaged as a step-wise process which starts with a simultaneous fixation of C and N to stimulate soil microbial activity, followed by progressive build up of soil C and other nutrients through systematic sequencing of ISFM options based on organic-inorganic fertilizer combinations and N$_2$-fixing legumes (Figure 3.2). First, participatory identification and mapping of degraded croplands was conducted with the target communities and extension. The indicators of soil degradation were subsequently confirmed through laboratory analyses. Field experiments were then conducted to evaluate alternate ISFM sequences for rehabilitating the degraded soils with respect to crop productivity, profitability and changes in soil quality. Lastly, biophysical data generated from field experimentation were combined with detailed characterization of farming systems and simulation modelling to determine best-fit ISFM sequences for different resource categories of farmers. Laboratory methods used for soils, plants, cattle manure and woodland litter analyses in the study are presented in Table 3.1. Rainfall received during each cropping season was measured using rain gauges placed at experimental sites.
Degraded cropland (characterized through farmers' local indicators & laboratory analysis)

Phosphorus-fertilized N$_2$-fixing legumes & cattle manure (soil C & N fixation)

Carbon building phase

Base maize yields and build up of soil C pools - Enhanced nutrient cycling

Stimulation of soil microbial activity

Systematic sequencing of ISFM options based on organic-inorganic fertilizer combinations & N$_2$-fixing grain and green manure legumes

Consolidation of C & build-up of soil N & P phase (increasing efficiency of recycling)

Early production

Nutrient-rich field and high productivity - Further build up of soil N, P & C pools dependent on texture

Maintenance (saturation) and expansion phase - determining land thresholds for different farmer groups and most feasible sequences

Expansion to other degraded croplands - determined by resources and production objectives

Time (years)

Intensity of management

Figure 3. 2 A conceptual framework for rehabilitation of a degraded cropland and cropping intensification. The light grey boxes indicate perceived major stages in the restoration pathway. The unshaded boxes show the interventions (entry points) in the rehabilitation process.
Table 3. Laboratory methods used for soils, plant biomass, grain, cattle manure and woodland litter analyses in the study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analytical method</th>
<th>Brief description of analytical method</th>
<th>Reference</th>
<th>Chapter where method was used</th>
</tr>
</thead>
</table>
| pH (soils)                       | 0.01 M CaCl₂  
Distilled water | 0.01 M CaCl₂: Soil and 0.01 M CaCl₂ were mixed in a ratio of 1 part to 2.5 parts, respectively. The CaCl₂ stabilizes the cation composition of the soil exchange sites because it closely resembles the ion concentration of the soil solution. Soil pH was then measured using a pH electrode.  
Distilled water: Soil and water were mixed in a ratio of 1 part soil to 2.5 parts water, respectively. Soil pH was then measured using a pH electrode. | Anderson and Ingram, 1993 | Chapters 4, 5, 6 and 7          |
| Total organic carbon (soils)     | Wet oxidation (Colorimetric)           | Soil was oxidized using a combination of K₂Cr₂O₇ and concentrated H₂SO₄ with external heating. The amount of chromic (Cr³⁺) produced was then measured colorimetrically, and organic C determined from the following equation:  
2 Cr₂O₇²⁻ + 3C + 16H⁺ = 4Cr³⁺ + 3CO₂ + 8H₂O | Anderson and Ingram, 1993 | Chapters 4, 5, 6 and 7          |
<p>| Total N (soils, plant biomass, maize and soyabean grain, cattle manure and woodland litter) | micro-Kjeldahl | Soil/plant material was digested using a mixture of concentrated H₂SO₄ and H₂O₃ at 360°C. Selenium powder was used as a catalyst and Li₂SO₄ added to raise the boiling temperature of the mixture. Total N was then determined colorimetrically against a set of standards. | Anderson and Ingram, 1993 | Chapters 5 and 6               |
| Total K, Ca and Mg (cattle manure and woodland litter) | Flame emission (K) and atomic absorption (Ca, Mg) spectroscopy following micro-Kjeldahl digestion | Following micro-Kjeldahl digestion, the concentration of K⁺ was determined by flame emission spectroscopy, and Ca²⁺ and Mg²⁺ by atomic absorption spectroscopy. | Anderson and Ingram, 1993 | Chapters 5 and 6               |
| Total P (soils, plant biomass, maize and soyabean grain, cattle manure and woodland litter) | micro-Kjeldahl | Following micro-Kjeldahl digestion, ascorbic acid was added for colour development, and total P measured colorimetrically against a set of standards. | Anderson and Ingram, 1993 | Chapters 5 and 6               |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Reference</th>
<th>Chapter where method was used</th>
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</thead>
<tbody>
<tr>
<td>Ammonium (NH$_4^+$)-N (soils)</td>
<td>Phenate</td>
<td>NH$_4^+$-N was extracted using 2M KCl. Sodium Nitroprusside and Sodium hypochlorite were used for colour development, and the concentration determined colorimetrically.</td>
<td>Keeney and Nelson, 1982</td>
<td>Chapters 4, 5 and 7</td>
</tr>
<tr>
<td>Nitrate (NO$_3^-$)-N (soils)</td>
<td>NO$_2^-$-N cadmium reduction</td>
<td>NO$_3^-$-N was extracted using 2M KCl. A combination of NH$_4$Cl, Borax, cadmium, Sulphanilamide and Naphthyleylene-Diamine-Dyhydrochloride were used for colour development, and the concentration determined colorimetrically.</td>
<td>Keeney and Nelson, 1982</td>
<td>Chapters 4, 5 and 7</td>
</tr>
<tr>
<td>Available P (soils)</td>
<td>Olsen</td>
<td>Available P was extracted using 0.5 M NaHCO$_3$. Acidified ammonium molybdate was added to form a phosphorus-molybdate complex, and the concentration determined colorimetrically.</td>
<td>Anderson and Ingram, 1993</td>
<td>Chapters 4, 5 and 6</td>
</tr>
<tr>
<td>Exchangeable bases (soils)</td>
<td>Acidified ammonium acetate</td>
<td>Exchangeable Ca, Mg and K were extracted using 1M acidified ammonium acetate. The concentration of K$^+$ was then determined by flame emission spectroscopy, and Ca$^{2+}$ and Mg$^{2+}$ by atomic absorption spectroscopy.</td>
<td>Anderson and Ingram, 1993</td>
<td>Chapters 4, 5 and 6</td>
</tr>
<tr>
<td>Effective Cation Exchange Capacity (soils)</td>
<td>Saturation</td>
<td>Exchangeable cations were displaced into solution using 1M NH$_4$Cl. The NH$_4^+$ ions on the soil exchange sites were in turn displaced by 1 M KCl. The concentration of displaced NH$_4^+$ ions was then determined by distillation.</td>
<td>Anderson and Ingram, 1993</td>
<td>Chapters 4, 5 and 6</td>
</tr>
<tr>
<td>Exchangeable Acidity (Al and H) (soils)</td>
<td>Titration</td>
<td>Exchangeable cations were displaced into solution using 1M NH$_4$Cl. The solution was then titrated to pH 7 using 0.02 M NaOH. Exchangeable acidity was determined as the difference between the sample and blank.</td>
<td>Anderson and Ingram, 1993</td>
<td>Chapters 4 and 5</td>
</tr>
<tr>
<td>Parameter</td>
<td>Analytical method</td>
<td>Brief description of analytical method</td>
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<tr>
<td>Microbial biomass (soils)</td>
<td>Chloroform-fumigation extraction</td>
<td>Soil samples were fumigated with alcohol free chloroform and kept in the dark for 24 hrs. Another set of unfumigated samples was also kept in the dark over the same period. The chloroform was then removed by repeated evacuation. Microbial biomass C was then determined as the difference in CO$_2$-C evolved between the fumigated and unfumigated samples. Microbial biomass N was determined as the difference in soil mineral N between the fumigated and unfumigated samples.</td>
<td>Amato and Ladd, 1988</td>
<td>Chapters 4 and 5</td>
</tr>
<tr>
<td>Readily oxidizable C (soils)</td>
<td>Potassium permanganate</td>
<td>Readily oxidizable C was extracted using 33 mM KMnO$_4$, with the concentration determined colorimetrically against a set of standards.</td>
<td>Blair et al., 1995.</td>
<td>Chapter 4</td>
</tr>
<tr>
<td>Soil basal respiration</td>
<td>Sealed incubation-alkali absorption method</td>
<td>Soils were incubated in the dark for 21 days and the CO$_2$ released during decomposition trapped in vials containing 0.1 M NaOH. The trapped CO$_2$ was then precipitated with excess 1.0 M BaCl$_2$ and back titrated with 0.1 M HCl using phenolphthalein indicator (0.5 %) to obtain the amount of CO$_2$-C evolved.</td>
<td>Yuste et al., 2007</td>
<td>Chapter 5</td>
</tr>
<tr>
<td>Bulk density (soils)</td>
<td>Core</td>
<td>Sharpened, open-ended cylindrical metal cores were used to collect soil samples. Bulk density was then calculated by dividing the oven dry mass of soil by the total volume of the core.</td>
<td>Anderson and Ingram, 1993</td>
<td>Chapters 4, 5 and 7</td>
</tr>
<tr>
<td>Gravimetric moisture (soils)</td>
<td>Thermogravimetric</td>
<td>Soils were sampled and oven-dried, and gravimetric water calculated by dividing mass of water by mass of oven dry soil.</td>
<td>Anderson and Ingram, 1993</td>
<td>Chapter 7</td>
</tr>
<tr>
<td>Texture (soils)</td>
<td>Sedimentation (Hydrometer)</td>
<td>Sodium hexametaphosphate (calgon) was used for soil dispersion. Density of sand, silt and clay were then measured using a hydrometer at different times as determined by Stoke's Law. Soil textural class was determined using a texture triangle.</td>
<td>Anderson and Ingram, 1993</td>
<td>Chapters 4, 5 and 6</td>
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</tbody>
</table>
CHAPTER 4

Assessing soil degradation in smallholder farmers' fields in Eastern Zimbabwe

4.1 Abstract

Crop production on smallholder farms in Southern Africa is increasingly being constrained by deteriorating land quality. Assessing soil degradation at farm-level is therefore important to enable formulation and better targeting of rehabilitation options. In this study, farmers’ local indicators and laboratory characterization were combined to develop criteria for assessing soil degradation on croplands in Hwedza smallholder farming area in Eastern Zimbabwe. Remote sensing and GIS were then employed to quantify the spatial distribution of the degraded soils. Farmers used common weeds, crop performance and soil physical attributes to categorize arable soils into four productivity classes: productive, moderately productive, degraded and severely degraded. Broad-leafed weeds, Commelina benghalensis L., Bidens pilosa L. and Leucas martinicensis (Jacq.) Ait. f., were considered as the major indicators of productive soils, while the high frequency of grassy weeds, Melinis repens (Willd.) Zizka and Eragrostis minor Host, was perceived to typify severely degraded soils. Maize grain yields of 6-8 scotch carts ha\(^{-1}\) (3-4 t ha\(^{-1}\)) and < 2 scotch carts ha\(^{-1}\) (< 1 t ha\(^{-1}\)) were indicative of productive and degraded soils, respectively. Consistent with farmer criteria, broad-leafed weeds contributed most of the weed biomass on productive soils, with diversity higher on productive and moderately productive than on degraded soils. Properties of soils sampled from the different field types significantly \((P < 0.05)\) differed by field productivity class and farmer resource endowment. Organic C, mineralizable N, available P, exchangeable Ca and effective CEC decreased from productive to severely degraded soils, and from resource-endowed (RG1) to resource-constrained (RG3) farms. On both productive and degraded croplands, available P and exchangeable Ca were below critical limits for optimum crop production on sandy soils in Zimbabwe. Using principal components analysis, mineralizable N, microbial biomass N, exchangeable bases and available P were found to be the most important parameters influencing soil productivity. The relationship between weed species populations and soil properties observed in this study provides a basis for developing a scheme to assess soil degradation and aid farmer decision-making on rehabilitation options at field and farm scales.
4.2 Introduction

Assessments conducted over the past decade indicate extensive degradation of croplands in SSA (Eswaran et al., 2005; Vlek et al., 2008) largely due to soil erosion, low retention of organic matter, nutrient mining and soil tillage (Diagana, 2003; Carr, 2003; Thierfelder et al., 2013). Supranational assessments such as the Global Assessment of Soil Degradation (GLASOD) (Oldeman et al., 1991), and evaluations based on satellite imagery and remote sensing of vegetation vigour (e.g. Bai et al., 2008; Vlek et al., 2008; Obade and Lal, 2013) have given insights on the extent of soil degradation in SSA. However, such appraisals are at scales too coarse to provide an understanding of the characteristics of soils at different stages of degradation at farm-level so as to identify those requiring specific corrective action.

On most smallholder farms in SSA, particularly in East and Southern Africa, soils often exhibit different levels of fertility within and across field, farm and watershed scales (Mtambanengwe and Mapfumo, 2005; Tittonell et al., 2005). This is often in differential patterns of crop performance, SOC and nutrient stocks, as farmers selectively allocate organic and mineral fertilizer inputs to specific fields or field sections within the farm. The nutrient resource allocation strategies are influenced by farmer resource endowment, with wealthier farmers applying higher amounts and over larger areas than their poorer counterparts (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007). Such management practices suggest that certain fields or field sections could be at different stages of either degradation or productivity for farmers of varying resource categories. This has critical implications on available productive land areas for farmers to attain sufficient crop yields to meet household food requirements. Therefore, there is need to develop a scientific understanding of what
constitute a degraded soil in the context of smallholder farming in order to enable formulation and targeting of appropriate agronomic management and soil restoration options.

Participatory research approaches that tap on farmers' local knowledge of soils can be used to assess soil degradation (Barrios and Trejo, 2003; Lima et al., 2011). This approach forms the basis of ethnopedology, which is premised on the theory that people who have been using soils over a long time are knowledgeable about indicators of productivity (Pawluk et al., 1992; Winklerprins, 1999; Barrios et al., 2006). Some of the advantages of the ethnopedology approach include local relevance, the 'integrative' nature of the indicators, and the involvement of local communities in monitoring soil degradation (Hecht, 1990; Pawluk et al., 1992). However, the ethnopedology approach has its own limitations such as site specificity and being largely qualitative (Barrios and Trejo, 2003). A more quantitative methodology often used in soil degradation assessment is that based on soil quality parameters (Moebius-Clune et al., 2011). The soil quality concept involves measuring a suite of soil properties, as influenced by management practices, against a set of reference values obtained from literature or benchmark sites (Abubakar, 1997; Karlen et al., 1997). While some studies have used both quantitative soil quality indices and the ethnopedology approach to assess soil degradation on African smallholder farms (e.g. Mtambanengwe and Mapfumo, 2005; Mairura et al., 2008; Tesfahunegn et al., 2011), there has been little emphasis on developing soil degradation assessment criteria in a way that informs decision-making by both farmers and other land managers. Developing such criteria will not only assist farmers and researchers to identify and monitor early signs of soil degradation, but also (re) evaluate land use options.
Local-level quantification of the spatial distribution of degraded soils is critical in raising awareness on the extent of the problem and informing potential options for rehabilitation. The increased availability and technical capabilities of remote sensing and GIS tools present opportunities for increasing precision with which field and farm level land degradation can be assessed (Prince et al., 2009). Remote sensing and GIS have been widely used in Southern Africa to assess land use and land cover changes using such indices as vegetation cover and net primary production (Murwira and Skidmore, 2006; Prince et al., 2009; Manzungu and Mtali, 2012). In this Chapter, farmers’ local indicators, laboratory characterization, and remote sensing and GIS were combined to assess soil degradation on arable croplands in Hwedza smallholder farming area in Eastern Zimbabwe. Specific objectives were to (i) develop criteria for assessing soil degradation using farmers' local indicators and laboratory characterization of soils and plant species and (ii) quantify the geographical distribution of degraded soils at farm-level on the basis of the resulting criteria.

4.3 Materials and methods

4.3.1 Selection of villages for assessing soil degradation

Mapping of soil degradation was conducted in Goto ward (18° 73´S; 31° 78´E; 1300 m altitude) in Hwedza District in Eastern Zimbabwe (Figure 4.1) between 2009 and 2013. Goto ward has a total area of 157 km², with a population density of approximately 12 people km⁻² (Zimbabwe National Statistics Agency, 2012b). A description of Goto is given in Section 3.1.1.
To enable detailed mapping of soil degradation at farm-level, a cluster of villages were selected based on common natural resource pools (woodlands, wetlands, rivers) dominant across them, and that they were dominantly covered by sandy soils (Figure 4.2). Consequently, 13 villages were selected out of the 64 villages in the ward. Village heads and extension staff working in the ward participated in the identification of the villages through key informant interviews and consultations. In addition, farmers who have been resident in the ward for a long time (> 30 years) and those with local knowledge of the area were also consulted through individual interviews. The extension assisted in identifying prospective interviewees. The selected villages were Chikanya, Chiswa, Tapfuya, Makaza, Muvirimi, Chiweshe, Masungo, Mapfumo, Chiutsu, Zimbudzana, Jerahuni, Mashonganyika and Marecha. The common natural resource pools were geo-referenced by taking coordinates at
the boundaries using a Global Positioning System (GPS) device (Garmin eTrex 10 model). To locate the villages, coordinates were collected at each village head's homestead.

Figure 4.2 Location of the villages used in the study and the surrounding common natural resource pools, Goto ward, Zimbabwe

4.3.2 Participatory identification of indicators of soil productivity

Key informant interviews, focus group discussions (FGDs) and a community meeting were conducted to elicit farmers' knowledge of indicators of soil productivity. Drawn from village heads, extension and community leaders, a total of 22 key informants were interviewed. The
focus group comprised of 15 men and 15 women randomly selected from village lists provided by the extension staff. Each man or woman represented a household. The average number of households was 25 across the villages. The selected farmers were of different resource endowment based on a typology developed in similar smallholder communities in Zimbabwe by Mtambanengwe and Mapfumo (2005). The typology recognizes the existence of 3 farmer resource categories: resource-endowed (RG1), resource-intermediate (RG2) and resource-constrained (RG3) households. These farmer resource categories are mainly based on farm-level resources such as farm size, capacity to secure crop production inputs and livestock ownership, among other factors. An earlier evaluation confirmed that the criteria represented the breadth of households in each resource group and was therefore ‘true to type’ (Mtambanengwe and Mapfumo, 2005). Both the key informant interviews and FGDs were guided by the following questions: (i) what are the indicators of a productive cropland?, (ii) what are the indicators of a degraded (least productive) cropland?, (iii) based on the indicators, in how many productivity classes would you place your fields?, (iv) in the past 3 seasons, have you fallowed any of your fields and why? and (v) in your view, what soil fertility management practices can farmers employ to rehabilitate degraded croplands? A combination of key informant interviews and FGDs were employed as complementary methodologies. Key informant interviews allow for an in-depth assessment of issues, usually by experienced individuals in the subject matter, in a more controlled discussion than in FGDs (Legard et al., 2003). On the other hand, FGDs are an important qualitative data collection tool in that they enable respondents to share experiences. Also, the respondents can build on each other's ideas, and the tool can be deployed in illiterate communities (Basch, 1987).
During the FGDs, the farmers were first divided into women and men groups, and a moderator assigned to each group to facilitate the deliberations while rapporteurs recorded the discussions. The farmers then re-grouped for consensus building in a plenary session. After the key informant interviews and FGDs, the findings were synthesized. A community meeting, attended by 32 men and 45 women, was then conducted to build consensus on the identified soil productivity indicators and classes as well as ranking the indicators in order of importance. The indicators were ranked by assigning scores that were based on head counts of farmers who had selected those indicators. A group of participants, who included village heads, community leaders and volunteer farmers then undertook community transect walks to locate the productive and degraded croplands, and verify the indicators. One transect walk was conducted during the dry season (September 2010) and another one in the wet season (January 2011) to capture differences in diagnostic indicators. The dry and wet season transect walks were 5.6 and 4.9 km long, respectively (Figure 4.3).

Figure 4. 3 A map of transect walks conducted during the dry (T1) and wet (T2) seasons in Goto smallholder farming area, Zimbabwe
4.3.3 Determining spatial distribution of productive and degraded fields

Based on the indicators of soil productivity, the farmers grouped fields into 4 classes: productive, moderately productive, degraded and severely degraded. A survey was then conducted to quantify the spatial distribution of the fields based on these productivity classes. A total of 120 households were purposively selected from the village household lists. Purposive sampling was done to ensure inclusion of an equal number of farmers in different resource endowments (40 farmers per RG) (Mtambanengwe and Mapfumo, 2005). Given that RG3 farmers apply sub-optimal rates of organics and mineral fertilizers to their fields resulting in nutrient mining, it was therefore hypothesized that degraded soils would be more spatially distributed on RG3 farms than their better resourced counterparts. For each household, the farmer was asked to classify their fields based on the 4 productivity categories. The fields were then geo-referenced by taking coordinates at the boundaries and centre of each field using a Global Positioning System (GPS) device (Garmin eTrex 10 model). Additional information gathered during the mapping exercise included (i) field catenary position in the landscape, and (ii) cropping history and soil fertility management practices commonly applied to the different fields and (iii) crop yields obtained in the previous seasons.

4.3.4 Sampling and laboratory characterization of plants and soils

During the 2011-2012 cropping season (December 2011), weed species richness and diversity were measured from unweeded productive, moderately productive, degraded and severely degraded fields. All the sampled fields where under a maize crop at the vegetative stage, and farmers had not yet carried out any weeding since planting. Under RG1 farms, measurements were done on 17 productive, 12 moderately productive, 15 degraded and 11 severely degraded
fields. For RG2 farms, samples were collected from 16 productive, 11 moderately productive, 14 degraded and 12 severely degraded fields. Under RG3 farms, the sampled fields were 17, 9, 16 and 12 for productive, moderately productive, degraded and severely degraded classes, respectively. The inconsistency in numbers of fields sampled was because available unweeded maize fields at the time of sampling varied across RGs and productivity classes. A 0.25 m² quadrat was randomly located at 5 positions in each field and the species richness determined by recording the number of species in each plot.

Species diversity was determined using the Shannon Wiener diversity index as follows:

\[ H' = - \sum_{i=1}^{s} (P_i \times \ln(P_i)) \]  

Equation 4.1

where \( P_i \) = Number of individuals of species \( i \)/total number of samples; \( s \) = number of species or species richness (Wang et al., 2009).

Biomass productivity of the individual weed species was quantified by harvesting the above-ground biomass in the quadrat, and oven-drying it at 60°C to obtain the dry mass. Scientific identification of some of the weed species was done with the assistance of botanists from the National Herbarium Botanic Gardens under the Department of Research and Specialist Services of the Ministry of Agriculture, Mechanization and Irrigation Development, Zimbabwe. Alongside weed species richness, diversity and biomass measurements, soil samples (0-20 cm) were collected from the same fields using an auger. The soils were collected from 10 random positions in each field and homogenized before a composite sample was withdrawn for laboratory analyses. The samples were air-dried and passed through a 2 mm sieve and analyzed for total C, N, available P, pH, exchangeable bases, exchangeable acidity, effective CEC and texture (Table 3.1) Part of the samples were analyzed for microbial
biomass C and N, and labile C, while potential mineralizable N was quantified from part of the soils incubated for 2 weeks under anaerobic conditions. Soil sampling was also done for bulk density determination. Soil porosity was estimated using the following relationship:

\[
\text{Porosity (\%)} = 1 - \frac{D_b}{D_p}
\]  

Equation 4.2

where \(D_p\) = bulk density; \(D_p\) = particle density

It was assumed that the particle density of the soil was 2650 kg m\(^{-3}\) (Hillel, 1998).

4.3.5 Quantifying area and vegetation reflectance of productive and degraded fields

Using coordinates collected during mapping of fields, a point map was created in Integrated Land and Water Information System (ILWIS) GIS. The point map was imported into Google Earth (version 7.1.3.22.3) and boundaries of the surveyed fields digitised. Area under each field was then quantified in Arcview GIS (version 10.3). In order to detect differences in the farmer identified productivity classes, a normalised difference vegetation index (NDVI) for each productivity class was calculated based on Landsat 7 Enhanced Thematic Mapper (ETM) + image for January 2013 and Landsat 8 Operational Land Imager (OLI) for February 2013. NDVI is a numerical indicator that uses the visible and near-infrared bands of the electromagnetic spectrum, and is adopted to analyze remote sensing measurements and assesses whether the target being observed contains live green vegetation (Birky, 2001; Hill and Donald, 2003). Chlorophyll, the green pigment in plant leaves, strongly absorbs visible light (from 0.4 to 0.7 \(\mu\)m) for use in photosynthesis, while it strongly reflects near-infrared light (from 0.7 to 1.1 \(\mu\)m).
Based on this principle, NDVI is calculated as follows:

\[
NDVI = \frac{NIR - VIS}{NIR + VIS}
\]

Equation 4.3

where NIR = Near infra-red; VIS = visible red

The January and February images were used because they coincide with peak vegetative crop and weed growth on farmers' fields in Zimbabwe. The Landsat images were obtained from the United States Geological Survey (USGS) EarthExplorer (http://earthexplorer.usgs.gov/). The visible red (R) and near infra-red (NIR) bands on the Landsat ETM + and OLI were normalized by converting digital numbers to at-satellite reflectance to correct for atmospheric distortions (Shepherd and Drymond, 2003). The normalization makes it possible to derive land surface information more consistently (Huang et al., 2001). The NDVI method has previously been used to assess vegetation cover changes and land degradation in smallholder farming areas in Zimbabwe (e.g. Manzungu and Mtali, 2012). It was envisaged that NDVI values will decrease from productive to severely degraded croplands due to a reduction in vegetation vigour. The NDVI values for each productivity class were obtained by extracting the centre coordinates of each map polygon using map value algorithms in ILWIS GIS. Comparison of the NDVI reflectance values was only done for the soil productivity classes after an analysis of variance (ANOVA) of the NDVI data showed no significant differences among farmer resource groups.

4.3.6 Data analyses

Data on soil properties were tested for normality and analyzed through an unbalanced ANOVA model, with means compared using the Tukey’s Test at \( P < 0.05 \). Principal
components analysis (PCA) was used to reduce the dimension of the dataset, analyze the structure of the variance and correlation among variables, and to select soil properties that best reflected differences between (most strongly associated with) soil productivity classes. Based on the Latent Root Criterion, only principal components with eigen values of > 1 were retained, and only principal component loadings of > +0.3 or < -0.3 were considered (Cliff, 1988, McGarigal et al., 2000). In order to assess the effect of management, soil nutrients (available P, mineral N, exchangeable K, Ca and Mg), soil pH and SOC from the different productivity classes were compared against critical values for crop production on sandy soils in Zimbabwe. The relationships between weed species populations and soil parameters were explored using Spearman's Rank Correlation analysis.

4.4 Results

4.4.1 Farmers' local indicators of soil productivity

Farmers categorized arable soils into 4 productivity classes namely productive, moderately productive, degraded and severely degraded based on dominant weed species, soil attributes and crop performance (Table 4.1). Broad-leafed weeds such as Commelina benghalensis L. (Wandering dew), Bidens pilosa L. (Black jack) and Leucas martincensis (Jacq.) Ait. f. (Bobbin weed) were highlighted as the most common indicators of productive soils, while the high frequency of grassy weeds, notably Melinis repens (Willd.) Zizka (Natal red top) and Eragrostis minor Host (Little love grass), were perceived to typify severely degraded soils. Hibiscus meeusei Exell (Stoke rose) and Richardia scabra L. (Mexican clover) were noted as the dominant weed species on moderately productive and degraded soils, respectively.
Table 4. Soil productivity classes and indicators of degradation (ranked) identified through farmer participatory research approaches in Goto smallholder farming areas in Zimbabwe.

<table>
<thead>
<tr>
<th>Productivity class</th>
<th>Description</th>
<th>Dominant weed species</th>
<th>Soil attributes</th>
<th>Crop/Weed performance</th>
</tr>
</thead>
</table>
| 1                  | Productive | 1. Commelina benghalensis L. (Wandering dew)  
2. Bidens pilosa L. (Black jack)  
3. Amaranthus hybridus L. (Pig weed)  
4. Leucas martinicensis (Jacq.) Ait. f. (Bobbin weed)  
5. Galinsoga parviflora L. (Gallant soldier)  
6. Conyza albida (Retz.) E.Walker (Fleabane) | 1. Top soil is thick (may require 2 pairs of oxen to plough, particularly when too wet)  
2. Form clods on tillage  
3. High presence of earthworm holes and castings when wet  
4. Presence of millipedes and ants when wet  
5. High soil moisture retention  
6. Soil drains well (water moves freely)  
7. Dark-grey/brown/red in colour | 1. Soils give 6-8 scotch carts\(^1\) of maize grain per hectare  
2. Crops have dark-green leaves, tall and establish uniformly  
3. Crops show high response to addition of small doses of organic and inorganic fertilizers  
4. Crops mature early  
5. Overall, high weed biomass with good plant vigour |
| 2                  | Moderately productive | 1. Hibiscus meeusei Exell (Stoke rose)  
2. Ageratum conyzoides L. (Billy goat weed)  
3. Cynodon dactylon (L.) Pers. (Couch grass)  
4. Acanthospermum hispidum D.C. (Upright starbur) | 1. Fewer clods formed during tillage  
2. Soil macro-fauna dominated by millipedes and ants  
3. Top soil becomes loose (can be easily eroded by water)  
4. Light-grey/brown in colour | 1. Soils give 4-6 scotch carts\(^1\) of maize grain per hectare  
2. Crops only respond to high rates of mineral fertilizers  
3. Crops have light-green leaves, and are of medium height  
4. Crops quickly show signs of moisture stress after a rainfall event  
5. Overall, moderate weed biomass and plant vigour |

\(^1\)A scotch cart carries approximately 400-500 kg of maize grain (Mapfumo and Giller, 2001). Common names of weed species are indicated in brackets.
Table 4.1 (continued)

<table>
<thead>
<tr>
<th>Degradation class</th>
<th>Description</th>
<th>Dominant weed species</th>
<th>Soil attributes</th>
<th>Crop/Weed performance</th>
</tr>
</thead>
</table>
| 3                 | Degraded             | 1. *Richardia scabra* L. (Mexican clover)  
2. *Eragrostis minor* Host (Little love grass)  
3. *Bulbostylis hispidula* (Vahl) R.W. Haines  
4. *Melinis repens* (Willd.) Zizka (Natal red top) | 1. Top soil becomes loose when dry (can be easily eroded by wind and water)  
2. Shallow plough depth (hard pan close to the soil surface)  
3. Low macro-fauna activity when wet  
4. Low moisture retention  
5. Light-coloured, with high sandy content | 1. Soils give < 2 *scotch carts* of maize grain per hectare  
2. Crops have yellowish leaves, stunted and poorly established (uneven stand)  
3. Low crop response to addition of mineral fertilizers  
4. Crops quickly show signs of moisture stress after a rainfall event  
5. Low weed diversity and vigour |
| 4                 | Severely degraded    | 1. *Melinis repens* (Willd.) Zizka (Natal red top)  
2. *Eragrostis minor* Host (Little love grass)  
3. *Richardia scabra* L. (Mexican clover) | 1. High erodibility after ploughing  
2. Soil is "powdery" upon ploughing (no clods)  
3. Sub-soil close to the surface and highly compacted  
4. Light-coloured, with very high sandy content (*Jecha remakurwe*) | 1. Crops fail to yield any grain  
2. Poor crop establishment  
3. Low crop response to addition of mineral fertilizers  
4. Crops quickly show signs of moisture stress after a rainfall event  
5. Low weed diversity and vigour |
The farmers also used soil physical attributes such as colour, texture, macro-faunal activity and workability to group croplands into productivity classes. For example, while clod formation during tillage and high presence of earthworms and millipedes were associated with productive and moderately productive soils, degraded and severely degraded croplands were linked with easily erodible soils and low macro-faunal activity. Maize grain yields of 6-8 scotch carts ha\(^{-1}\) (3-4 t ha\(^{-1}\)) and < 2 scotch carts ha\(^{-1}\) (1 t ha\(^{-1}\)) were noted as indicators of productive and degraded soils, respectively.

4.4.2 Weed species richness and diversity on fields in different productivity classes

Weed diversity was higher on productive and moderately productive fields of RG1 and RG2 farmers compared with the degraded and severely degraded fields, while fields belonging to RG3 farmers did not show marked differences (Figure 4.4).

![Weed species richness and diversity on fields in different productivity classes in Goto ward, Zimbabwe.](image)

Figure 4.4 Weed species richness and diversity on fields in different productivity classes in Goto ward, Zimbabwe. PF=Productive field; MPF=Moderately productive field; DF=Degraded field; SDF=Severely degraded field n = number of fields sampled. Error bars
represent least significant difference (LSD) for comparison of biomass contribution by weed species.

**Figure 4.4 continued**

Broad-leaf weeds such as *B. pilosa*, *A. conyzoides* and *L. martincensis* contributed most of the weed biomass on productive fields of RG1 farmers. However, *Eleusine indica* (L.) (Crowfoot grass), a grass weed, still contributed up to 25% of the weed biomass produced on these
fields. The degraded and severely degraded fields of the RG1 farmers were dominated by *R. scabra*, *M. repens* and *Acanthospermum hispidum* D.C. (Upright starbur). On RG2 farms, *A. hispidum*, *Ageratum conyzoides* L. (Billygoat weed) and *E. indica* constituted approximately 60% of the weed biomass on productive fields, while *A. hispidum* produced the highest biomass on moderately productive fields. The degraded and severely degraded fields were dominated by *R. scabra* and *M. repens*.

On productive fields of RG3 farmers, *A. hispidum* contributed the greatest biomass amounting to 32%. There were no significant differences in biomass yields among *B. pilosa*, *A. conyzoides* and *Galinsoga parviflora* L. (Gallant soldier). On moderately productive fields, *Cynodon dactylon* (L.) Pers. (Couch grass), *H. meeusei* and *A. hispidum* constituted 86% of the weed biomass. The severely degraded fields were dominated by grass weeds namely *Cyperus esculentus* L. (Yellow nutsedge), *Digitaria sanguinalis* (L.) Scop. (Hairy crabgrass) and *M. repens*.

### 4.4.3 Soil physico-chemical and biological characteristics across productivity classes

Soil chemical properties differed markedly by field productivity class and farmer resource endowment (Table 4.2a). On RG1 farms, available P was 11 ppm on productive fields compared with 4 ppm on severely degraded fields. While a similar trend was obtained on RG2 and RG3 farms, soils from these farms had available P of < 9 ppm. Across field types and farmer resource groups, available P was significantly lower than the recommended amounts required to support crop production on sandy soils in Zimbabwe. Mineralizable N averaged 32 mg kg\(^{-1}\) on productive fields of RG1 and RG2 farmers compared with < 20 mg
kg\(^{-1}\) on the degraded and severely degraded fields. With the exception of productive fields of RG1 and RG2 farmers, mineralizable N on the other fields was < 28 mg kg\(^{-1}\) against 30-40 mg kg\(^{-1}\) considered critical for crop production on sandy soils.

While exchangeable Ca was higher on productive fields than on degraded and severely degraded fields across farmer resource categories, it was markedly lower than the recommended critical amounts on sandy soils. Exchangeable Mg fell within the critical amounts on the productive and moderately productive fields, but was below recommended levels on the degraded and severely degraded fields. Exchangeable K values were within the critical amounts across farmer resource groups and field productivity classes.

Soil organic carbon and ECEC were greater on productive fields than the other fields. Productive fields of RG1 and RG2 farmers had 20 and 40% more SOC, respectively, above the critical level for crop production on sandy soils in Zimbabwe. Across the fields, the soils had no more than 15% clay (Table 4.2b). Soil bulk density was higher on degraded and severely degraded fields compared with the productive fields. Conversely, porosity and microbial biomass C and N were greater on the productive than the degraded fields.
Table 4. 2 Chemical (a) and, physical and biological (b) characteristics of soils (0-20 cm) sampled from fields in different productivity classes in Goto, Hwedza, Zimbabwe

(a)

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>Resource-endowed (RG1)</th>
<th>Resource-intermediate (RG2)</th>
<th>Resource-constrained (RG3)</th>
<th>*Critical values (sandy soils)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PF (n=17)</td>
<td>MPF (n=12)</td>
<td>DF (n=15)</td>
<td>SDF (n=11)</td>
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<td></td>
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</tr>
<tr>
<td>Available P (ppm)</td>
<td>11a</td>
<td>7b</td>
<td>5c</td>
<td>4c</td>
</tr>
<tr>
<td>pH (0.01M CaCl₂)</td>
<td>4.7a</td>
<td>4.7a</td>
<td>4.1a</td>
<td>4.4a</td>
</tr>
<tr>
<td>Mineralizable N (mg kg⁻¹)</td>
<td>34a</td>
<td>28a</td>
<td>19b</td>
<td>11c</td>
</tr>
<tr>
<td>Exc. Ca (cmol (c) kg⁻¹)</td>
<td>1.3a</td>
<td>0.6b</td>
<td>0.6b</td>
<td>0.4b</td>
</tr>
<tr>
<td>Exc. Mg (cmol (c) kg⁻¹)</td>
<td>0.6a</td>
<td>0.4b</td>
<td>0.2c</td>
<td>0.2c</td>
</tr>
<tr>
<td>Exc. K (cmol (c) kg⁻¹)</td>
<td>0.3a</td>
<td>0.3a</td>
<td>0.2a</td>
<td>0.2a</td>
</tr>
<tr>
<td>Exc. Al and H (cmol (c) kg⁻¹)</td>
<td>0.2a</td>
<td>0.3a</td>
<td>0.4a</td>
<td>0.4a</td>
</tr>
<tr>
<td>ECEC (cmol (c) kg⁻¹)</td>
<td>2.1a</td>
<td>1.7b</td>
<td>1.2c</td>
<td>1.0c</td>
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<tr>
<td>Organic C (%)</td>
<td>0.7a</td>
<td>0.5b</td>
<td>0.3c</td>
<td>0.3c</td>
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</table>

(b)

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>Resource-endowed (RG1)</th>
<th>Resource-intermediate (RG2)</th>
<th>Resource-constrained (RG3)</th>
<th>LSD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PF (n=17)</td>
<td>MPF (n=12)</td>
<td>DF (n=15)</td>
<td>SDF (n=11)</td>
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<tr>
<td>Clay (%)</td>
<td>15a</td>
<td>12a</td>
<td>10a</td>
<td>11a</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>77a</td>
<td>72a</td>
<td>78a</td>
<td>79a</td>
</tr>
<tr>
<td>Bulk density (kg m⁻³)</td>
<td>1400a</td>
<td>1500a</td>
<td>1700b</td>
<td>1720b</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>0.47a</td>
<td>0.43b</td>
<td>0.40b</td>
<td>0.34c</td>
</tr>
<tr>
<td>Readily oxidizable C (mg g⁻¹)</td>
<td>0.55a</td>
<td>0.43b</td>
<td>0.29c</td>
<td>0.27c</td>
</tr>
<tr>
<td>Microbial biomass C (mg kg⁻¹)</td>
<td>205a</td>
<td>196a</td>
<td>201a</td>
<td>186a</td>
</tr>
<tr>
<td>Microbial biomass N (mg kg⁻¹)</td>
<td>22a</td>
<td>19a</td>
<td>12b</td>
<td>11b</td>
</tr>
</tbody>
</table>

PF=Productive field; MPF=Moderately productive field; DF=Degraded field; SDF=Severely degraded field; Means followed by different letters in the same row are significantly different at p < 0.05; n = number of fields sampled; *Critical values for crop production on sandy soils in Zimbabwe (Sources: Mashirwingani, 1983; Nyamangara and Mpofu, 1996; CSRI, 2005; Mtambanengwe and Mapfumo, 2005; Mapanda and Mavenganahama, 2011; Tauro et al., 2011); nd = not determined.
From PCA of the soil properties, the first principal component explained 73% of the variance, with available P, mineralizable N, base nutrients (exchangeable Ca and Mg), microbial biomass N and organic C recording significant eigenvectors of > 0.3 (Table 4.3). Conceptually, the first principal component can be summarized as 'CARBON-PHOSPHORUS-BASES'. Although the second principal component had significant loadings on exchangeable K, exchangeable acidity and microbial biomass C, it only explained 8% of the variance. Aggregated, the first three principal components explained 86% of the total variance.

Table 4.3 Loadings of variables representing physico-chemical and biological characteristics of soils (0-20 cm) sampled from fields in different productivity classes with respect to the first three principal components

<table>
<thead>
<tr>
<th>Soil parameter</th>
<th>PC 1</th>
<th>PC 2</th>
<th>PC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>+0.237</td>
<td>-0.120</td>
<td>+0.236</td>
</tr>
<tr>
<td>Sand</td>
<td>-0.083</td>
<td>+0.048</td>
<td>-0.867</td>
</tr>
<tr>
<td>Available P</td>
<td>+0.351</td>
<td>+0.143</td>
<td>-0.009</td>
</tr>
<tr>
<td>pH</td>
<td>+0.222</td>
<td>+0.123</td>
<td>-0.003</td>
</tr>
<tr>
<td>Mineralizable N</td>
<td>+0.321</td>
<td>-0.018</td>
<td>-0.144</td>
</tr>
<tr>
<td>Exc. Ca</td>
<td>+0.364</td>
<td>+0.086</td>
<td>+0.050</td>
</tr>
<tr>
<td>Exc. Mg</td>
<td>+0.461</td>
<td>+0.091</td>
<td>+0.040</td>
</tr>
<tr>
<td>Exc. K</td>
<td>+0.230</td>
<td>-0.312</td>
<td>+0.163</td>
</tr>
<tr>
<td>Exc. Al and H</td>
<td>-0.174</td>
<td>+0.604</td>
<td>-0.052</td>
</tr>
<tr>
<td>ECEC</td>
<td>+0.261</td>
<td>+0.186</td>
<td>+0.044</td>
</tr>
<tr>
<td>Bulk density</td>
<td>-0.238</td>
<td>+0.084</td>
<td>+0.250</td>
</tr>
<tr>
<td>Porosity</td>
<td>+0.237</td>
<td>+0.095</td>
<td>-0.241</td>
</tr>
<tr>
<td>Organic C</td>
<td>+0.362</td>
<td>+0.078</td>
<td>-0.012</td>
</tr>
<tr>
<td>Readily oxidizable C</td>
<td>+0.252</td>
<td>+0.081</td>
<td>-0.018</td>
</tr>
<tr>
<td>Microbial biomass C</td>
<td>+0.175</td>
<td>+0.584</td>
<td>-0.010</td>
</tr>
<tr>
<td>Microbial biomass N</td>
<td>+0.352</td>
<td>+0.080</td>
<td>-0.088</td>
</tr>
</tbody>
</table>

% of variance          | 73         | 8          | 6          |
4.4.4 Relationship between weed species populations and soil properties

A high population of *D. sanguinalis* was significantly associated with soils that exhibited high bulk density ($r^2 = 0.51$) (Table 4.4). Conversely, high soil bulk density suppressed populations of broad-leafed weeds such as *A. conyzoides*, *B. pilosa*, *C. benghalensis* and *L. martincensis* ($r^2 = -0.45$ to -0.63). High ECEC and exchangeable Ca and Mg in soils induced high populations of *A. conyzoides*, *B. pilosa*, *C. benghalensis*, *E. indica* and *L. martincensis* ($r^2 > 0.55$). On the contrary, soils with low ECEC and exchangeable Ca and Mg had high populations of *R. scabra* and *M. ripens*, with $r^2$ ranging from -0.45 to -0.51.

High available P in soils induced high populations of *A. conyzoides* *E. indica* and *C. benghalensis*. Conversely, *Hibiscus meuusei* and *R. scabra* thrived better on soils with low available P levels. Populations of *A. conyzoides*, *C. benghalensis* and *E. indica* showed a strong correlation ($r^2 > 0.60$) with soil mineralizable N. However, low soil mineralizable N was associated with dense populations of *R. scabra* and *M. ripens*. Populations of *A. hispidum* were not significantly influenced by any soil property. Exchangeable K, soil organic C and pH did not influence weed populations.
Table 4. Correlation between weed species biomass productivity and soil properties on farmers' fields in Goto, Hwedza, Zimbabwe

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td><em>Acanthospermum hispidum</em></td>
<td>-0.18</td>
<td>0.16</td>
<td>0.20</td>
<td>0.08</td>
<td>0.27</td>
<td>0.28</td>
<td>-0.05</td>
<td>0.34</td>
<td>0.29</td>
<td>0.22</td>
<td>0.18</td>
</tr>
<tr>
<td><em>Ageratum conyzoides</em></td>
<td>-0.51</td>
<td>0.29</td>
<td>0.55</td>
<td>0.13</td>
<td>0.62</td>
<td>0.79</td>
<td>-0.04</td>
<td>0.68</td>
<td>0.13</td>
<td>0.68</td>
<td>0.12</td>
</tr>
<tr>
<td><em>Bidens pilosa</em></td>
<td>-0.63</td>
<td>0.44</td>
<td>0.65</td>
<td>0.24</td>
<td>0.67</td>
<td>0.63</td>
<td>-0.18</td>
<td>0.39</td>
<td>0.32</td>
<td>0.55</td>
<td>0.11</td>
</tr>
<tr>
<td><em>Commelina benghalensis</em></td>
<td>-0.62</td>
<td>0.30</td>
<td>0.58</td>
<td>0.08</td>
<td>0.67</td>
<td>0.84</td>
<td>-0.06</td>
<td>0.76</td>
<td>0.14</td>
<td>0.73</td>
<td>0.25</td>
</tr>
<tr>
<td><em>Cynodon dactylon</em></td>
<td>-0.03</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td><em>Cyperus esculentus</em></td>
<td>0.03</td>
<td>0.21</td>
<td>0.41</td>
<td>0.03</td>
<td>0.11</td>
<td>0.38</td>
<td>0.47</td>
<td>0.25</td>
<td>0.15</td>
<td>0.47</td>
<td>0.18</td>
</tr>
<tr>
<td><em>Digitaria sanguinalis</em></td>
<td>0.51</td>
<td>0.42</td>
<td>0.24</td>
<td>0.02</td>
<td>0.14</td>
<td>0.43</td>
<td>0.22</td>
<td>0.35</td>
<td>0.04</td>
<td>0.17</td>
<td>0.34</td>
</tr>
<tr>
<td><em>Eleusine indica</em></td>
<td>-0.38</td>
<td>0.21</td>
<td>0.36</td>
<td>0.07</td>
<td>0.24</td>
<td>0.26</td>
<td>0.05</td>
<td>0.61</td>
<td>0.14</td>
<td>0.65</td>
<td>0.19</td>
</tr>
<tr>
<td><em>Eragrostis minor</em></td>
<td>-0.23</td>
<td>0.36</td>
<td>0.51</td>
<td>-0.11</td>
<td>0.25</td>
<td>0.18</td>
<td>-0.18</td>
<td>0.14</td>
<td>-0.48</td>
<td>0.43</td>
<td>0.34</td>
</tr>
<tr>
<td><em>Hibiscus meuesei</em></td>
<td>-0.01</td>
<td>0.00</td>
<td>0.04</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.03</td>
<td>-0.63</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td><em>Leucas martinicensis</em></td>
<td>-0.45</td>
<td>0.21</td>
<td>0.57</td>
<td>0.11</td>
<td>0.64</td>
<td>0.68</td>
<td>-0.05</td>
<td>0.66</td>
<td>0.14</td>
<td>0.65</td>
<td>0.26</td>
</tr>
<tr>
<td><em>Melinis repens</em></td>
<td>0.23</td>
<td>-0.11</td>
<td>-0.51</td>
<td>-0.04</td>
<td>-0.56</td>
<td>-0.51</td>
<td>0.08</td>
<td>-0.40</td>
<td>-0.09</td>
<td>-0.51</td>
<td>-0.18</td>
</tr>
<tr>
<td><em>Richardia scabra</em></td>
<td>0.36</td>
<td>-0.19</td>
<td>-0.58</td>
<td>-0.03</td>
<td>-0.38</td>
<td>-0.50</td>
<td>0.04</td>
<td>-0.51</td>
<td>-0.07</td>
<td>-0.52</td>
<td>-0.29</td>
</tr>
<tr>
<td><em>Setaria pumila</em></td>
<td>-0.03</td>
<td>0.28</td>
<td>-0.42</td>
<td>0.02</td>
<td>0.19</td>
<td>-0.47</td>
<td>0.03</td>
<td>-0.23</td>
<td>-0.09</td>
<td>0.02</td>
<td>-0.31</td>
</tr>
</tbody>
</table>
4.4.5 Spatial distribution of productive and degraded fields

Percentage land area under productive fields ranged from 31% (RG3 farms) to 48% (RG2 farms) (Table 4.6). RG1 and RG3 farms had the largest percentage land area under degraded to severely degraded fields. Across resource groups, combined degraded and severely degraded fields ranged from 33% (RG2) to 44% (RG3) of the cropped area. There were no significant differences in NDVI reflectance values among fields in different productivity classes for both the January and February 2013 images. The NDVI reflectance values averaged 0.15 and 0.32 for the January and February 2013 images, respectively (Table 4.7 and Figure 4.6).

Table 4.5 Percentage area (%) covered by fields under different productivity classes for farmers of varying resource endowment in Goto, Hwedza, Zimbabwe.

<table>
<thead>
<tr>
<th></th>
<th>Resource-endowed (n = 22)</th>
<th>Resource-intermediate (n = 63)</th>
<th>Resource-constrained (n = 45)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productive</td>
<td>39</td>
<td>48</td>
<td>31</td>
</tr>
<tr>
<td>Moderately productive</td>
<td>19</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>Degraded</td>
<td>30</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td>Severely degraded</td>
<td>12</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Total area of mapped fields (km²)</td>
<td>0.21</td>
<td>0.38</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 4.6 Normalized difference vegetation indices for fields under different productivity classes in Goto, Hwedza, Zimbabwe.

<table>
<thead>
<tr>
<th></th>
<th>January 2013</th>
<th>February 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productive</td>
<td>0.14</td>
<td>0.32</td>
</tr>
<tr>
<td>Moderately productive</td>
<td>0.14</td>
<td>0.33</td>
</tr>
<tr>
<td>Degraded</td>
<td>0.15</td>
<td>0.33</td>
</tr>
<tr>
<td>Severely degraded</td>
<td>0.15</td>
<td>0.32</td>
</tr>
<tr>
<td>SED</td>
<td>0.06</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Figure 4.5 Normalized difference vegetation index (NDVI) values for the surveyed area for (a) January and (b) February 2014, Goto ward, Hwedza. Blue = water bodies; Green = less vigorous vegetation; Orange and red = highly vigorous vegetation.
4.5 Discussion

Farmers designated croplands into different productivity classes based on indicator weeds, crop performance and soil physical attributes indicating their knowledge and experience of the soil environment. The perceived dominance of broad-leafed weeds on productive soils, as opposed to the high prevalence of grass-weeds on degraded soils, corroborates similar perceptions in other parts of SSA (Corbeels et al., 2000; Mairura et al., 2008). Maize grain yield was highly prioritized in classifying soils into different productivity categories most likely because of the importance of the crop in household food security in smallholder farming areas in Zimbabwe. In a related study in Northern Ethiopia, farmers used teff (Eragrostis tef) grain yield, a staple crop in the area, to classify soils into high, medium and low fertility (Tesfahunegn et al., 2011). The need for more draught power and the formation of more clods on productive than on degraded soils indicate farmers' knowledge of soil aggregation and its implications on workability. Soil physical attributes such as structure and colour have previously been used by farmers to indicate soil quality (Mtambanengwe and Mapfumo, 2005; Barrera-Bassols et al., 2009). The farmers also highlighted high presence of macro-fauna such as earthworms and millipedes on productive soils supporting perceptions in other tropical areas (Morales and Perfecto, 2000; Pauli et al., 2012).

The higher weed diversity on productive and moderately productive fields compared with the degraded and severely degraded ones provides evidence of the direct link between soil quality attributes and patterns in plant diversity and natural succession trends at field level. Native weeds can therefore be used as robust indicators of changes in soil quality as they respond to subtle alterations in soil properties and processes (Paniagua et al., 1999; Zhao et al., 2000).
Consistent with results from this study, *B. pilosa* and *L. martincensis* have also been found to dominate fertile soils, while *M. repens* and *R. scabra* were reported to be more abundant on nutrient-depleted soils (Mabasa and Nyahunzvi, 1995; Mairura *et al*., 2008). *Eleusine indica* dominated productive fields of RG1 and RG2 farmers most likely because of high rates of cattle manure addition on these fields. The weed species has been commonly found in manured fields (Makanganise *et al*., 1999). The overall reduction in weed diversity with increased soil degradation observed in this study indicates that croplands under current smallholder farming have lost significant weed biodiversity given the large area occupied by degraded soils.

Most soil bio-chemical properties deteriorated from productive to severely degraded croplands, indicating the influence of organic matter and nutrient resource allocation strategies to different fields. Farmers often apply high amounts of organic materials and mineral fertilizers to most-productive fields with little or no nutrient addition to least-productive fields (Mtambanengwe and Mapfumo, 2005; Zingore *et al*., 2007). The high ECEC and exchangeable Ca and Mg on productive soils of RG1 farmers could be explained by the high addition of cattle manure as these farmers often have large cattle heads (Zingore *et al*., 2008). Lack of differences in exchangeable K among soil productivity classes could be explained by availability of the nutrient element in granitic parent material from which the soils are derived (Nyamapfene, 1991). Available P and exchangeable Ca were below critical limits for optimum crop production on sandy soils in Zimbabwe on both productive and degraded croplands suggesting that soil fertility management technologies should firstly target these nutrients. Based on PCA, soil bio-chemical properties (available P, mineralizable N, exchangeable bases, microbial biomass N and organic C) were the most important
parameters influencing productivity confirming earlier findings in similar communities in Zimbabwe (Mugwira and Nyamangara, 1988; Mtambanengwe and Mapfumo, 2005).

Forty percent of the surveyed cropped area was considered degraded to severely degraded by farmers, concurring with previous assessments that degraded soils occupy a significant area on African smallholder farms (Tittonell, 2008; Ebanyat, 2009). That RG1 and RG3 farms had the largest area under degraded fields indicates that, overall, soil fertility management practices on smallholder farms are extractive. Thus, there is need for more investments in fertilizer and organic matter inputs to combat soil degradation on smallholder farms. The lack of differences in NDVI values among fields belonging to different productivity classes observed in this study suggest that such an index cannot be employed to discern soil productivity at field-level. Yet, crop growth and vigour is known to vary across the fields at local-scale (e.g. Mtambanengwe and Mapfumo, 2005; Tittonell et al., 2005). Landsat images have a spatial resolution of approximately 30 m, therefore covering an area of 0.9 ha (Wu, 2004; Obade and Lal, 2013). However, on smallholder farms in Zimbabwe fields can be as small as 0.2 ha, and often contiguous (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007). This could have resulted in overlaps in NDVI values across fields. Previous studies that have exclusively used NDVI reflectance values to assess soil degradation (e.g. Vlek et al., 2008) could have, therefore, under- or over-estimated the extent of degradation of croplands in smallholder farming areas of SSA. Using digital soil mapping and remote sensing to quantify soil organic C on farmers' fields in Eastern Zimbabwe, van Apeldoorn et al. (2014) also observed no differences among the fields despite known soil fertility gradients in the area (Zingore et al., 2007). These results call for further development of remote sensing
and GIS tools for local-level assessment of soil degradation. The advent of hyperspectral remote sensing tools with better resolution is key to this end (Adam et al., 2009).

The relationship between weed species biomass and soil properties observed in this study provides a basis for developing a scheme to assess soil degradation and aid farmer decision-making on potential rehabilitation options at field and farm levels. Weeds were identified by farmers to be one of the key indicators of soil productivity. Furthermore, there were consistencies between most of the indicator weed species mentioned by the farmers and field assessments. Biomass of *A. conyzoides*, *B. pilosa*, *C. benghalensis* and *L. martincensis* showed a strong positive correlation with soils rich in ECEC, exchangeable Ca and Mg, available P and mineralizable N. Conversely, the same species showed a strong negative correlation with soil bulk density. These results imply that soils dominated by these weeds had appreciable levels of biochemical fertility and a good structure. Such soils, the majority which were classified as productive by the farmers, would therefore require maintenance addition of mineral fertilizers and organic materials to preserve the necessary biochemical fertility and physical structure to support crop production.

Based on both FPRA and field measurements, *H. meeusei* typified moderately productive soils. Biomass of *H. meeusei* showed a strong positive correlation with low available P and exchangeable bases, a result reported on similar soils in Zimbabwe (Makanganise et al., 1999). *H. meeusei* did not dominate productive soils mostly likely because it was out-competed by other broad-leafed weeds such as *B. pilosa* and *C. benghalensis*. However, further detailed studies are required to ascertain this pattern. The dominance of *H. meeusei* on the moderately productive soils apparently indicates chemical degradation. Such soils would
thus be rehabilitated through high addition of liming materials such as termitaria, cattle manure and dolomitic lime, and P-based mineral fertilizers.

Biomass produced by *R. scabra* and *M. ripens* negatively correlated with ECEC, exchangeable Ca and Mg, mineralizable N and available P. This result confirms previous findings that these weed species are indicative of low soil nutrient levels (Mabasa et al., 1995; Agronomy Institute, 1998; Mairura et al., 2008). Apart from *R. scabra* and *M. ripens*, the degraded and severely degraded soils were also dominated by *D. sanguinalis*, a weed species that positively correlated well with soil bulk density. An ecological study of *D. sanguinalis* also showed that the weed species is most prevalent on shallow and highly compacted soils (Aldrich, 1984). Croplands dominated by high populations of *D. sanguinalis*, *R. scabra* and *M. ripens* would thus point to both biochemical and physical soil degradation. Farmers could rehabilitate such croplands through repeated addition of organic materials, such as cattle manure and woodland litter, to build C, and mineral fertilizers to address Ca, Mg and P deficiencies. To reverse physical degradation, such soils may require deep ploughing to break the compacted plough pan as well as putting in place soil and water conservation structures such as contours and ridges to curb soil erosion.

### 4.6 Conclusions

Farmers delineated croplands as productive, moderately productive, degraded and severely degraded on the basis of dominant plant species and soil physical attributes, and these, in turn, can inform decision-making by land managers to target rehabilitation options. Forty two percent of cropping land can be classified as degraded to severely degraded, with the
distribution skewed towards RG1 and RG3 farmers. Properties of soils sampled from farmers' fields deteriorated from productive to severely degraded, and from RG1 to RG3. Based on PCA of soil properties, mineral N, exchangeable Ca and Mg, and available P were the most important parameters indicating that base nutrients, N and P-based mineral fertilizers and organic nutrient resources remain key to sustaining crop productivity of sandy soils. Overall, laboratory-based soil physico-chemical and biological properties, and most of the weed species closely matched farmer categorization of croplands suggesting that ethnopedology approaches could contribute to assessment of soil degradation in African smallholder farms. The relationship between weed species populations and soil properties observed in this study provides a basis for developing a scheme to assess soil degradation and aid farmer decision-making on rehabilitation options at field and farm levels.
CHAPTER 5

Rehabilitating degraded soils for increased crop productivity on smallholder farms in Eastern Zimbabwe

5.1 Abstract

Soil degradation is a major threat to Southern Africa's agricultural production. Crops show generally weak responses to mineral fertilizers on degraded soils. A three-year study was conducted on smallholder farms in Eastern Zimbabwe to explore entry points for rehabilitating degraded croplands using principles of ISFM. The ISFM options involved nitrogen-fixing herbaceous legumes planted in the first year, with subsequent addition of cattle manure in the second year. In the third year, the influence of the ISFM options on maize productivity and changes in soil biological activity were then evaluated. Phosphorus was applied every year under each sequence. A comparison of reported soil physical and chemical figures for productive sandy soils in Zimbabwe and the experimental sites confirmed degradation of the latter. Above-ground biomass C and N accumulation were 3038 kg ha$^{-1}$ and 203 kg ha$^{-1}$, respectively, under 1-year indigenous legume fallow (indifallow) against 518 kg C ha$^{-1}$ and 14 kg N ha$^{-1}$ under 1-year natural fallow. Two-year indifallow produced approximately three times the biomass N attained under 2-year natural fallow. When all the treatment plots were planted to a maize test crop in the third year, herbaceous legume-based sequences showed the highest response to mineral fertilizer N compared with natural fallow-based sequences and continuous fertilized maize. Following addition of 120 kg N ha$^{-1}$ of mineral fertilizer, a regression analysis of maize yields against mineral N fertilizer showed a maximum yield of 2.5 t ha$^{-1}$ under the herbaceous legume-based sequences against 1 t ha$^{-1}$ under continuous fertilized maize and natural fallow-based options. 'Sunnhemp-start', a Crotalaria juncea L. (sunnhemp)-based sequence, and 'Indifallow-start 1', an indigenous legume-based sequence, gave the highest microbial biomass C (MBC) of 243 mg kg$^{-1}$ soil compared with 187 mg kg$^{-1}$ soil under continuous maize. Microbial biomass N showed a similar trend. Under 'Sunnhemp-start' and 'Indifallow-start 1', MBC to organic C ratio averaged 7; about one and half times more than under natural fallow-based sequences and continuous fertilized maize. Consistent with microbial biomass, soil carbon dioxide (CO$_2$) emission under 'Sunnhemp-start' and 'Indifallow-start 1' was 22% higher than under natural fallow-based sequences. Continuous maize treatments gave higher metabolic quotients ($q$CO$_2$) than legume-based sequences, indicating a lower microbial efficiency under the former. Short-term restoration of productivity of degraded sandy soils should focus on high quality organic resource application and P fertilization to stimulate microbial activity and induce responses to mineral fertilizers. When coupled to P fertilization, herbaceous legume-

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based ISFM sequences provide a potential entry point for reversing soil degradation and offer opportunities for increasing crop productivity in dominant smallholder farming systems of Zimbabwe and other parts of Southern Africa.

5.2 Introduction

Degradation of arable soils presents a major challenge for sustainable crop production in smallholder farming systems of SSA, including Southern Africa (Scherr, 2000; Muchena et al., 2005). Between 1982 and 2002, 10% of the agricultural land in SSA lost its productivity due to human-induced degradation (Vlek et al., 2008). Most of the degraded soils have been shown to exhibit a general lack of crop yield response to mineral fertilizer addition. While degradation of these croplands is sometimes physical e.g. presence of rills and gullies (e.g., Kangalawe et al., 2008; Guto et al., 2011), their non-responsiveness to mineral fertilizer addition is largely due to deterioration of chemical and biological properties (Tittonell et al., 2012). Most of such soils are characterized by low organic matter contents, low biological activity and severe macro- and micronutrient deficiencies (Mtambanengwe and Mapfumo, 2005, Zingore et al., 2008). Given the growing demands for food and feed production against a changing climate, interventions are critically required to rehabilitate degraded soils and arrest production practices that are based on extensification. Studies have shown that, with proper management of cropping sequences and consistent use of organic materials and mineral fertilizers, sandy soils can support maize grain yields of between 3 t ha\(^{-1}\) in the short-term (Mtambanengwe et al., 2006) and up to 5 t ha\(^{-1}\) in the long-term (Rusinamhodzi et al., 2013; Nezomba et al., 2015a). This therefore offers prospects that degraded sandy soils can be rehabilitated.
Addition of livestock manure to build SOM and rectify multiple nutrient deficiencies is one option recommended for rehabilitating degraded soils (Mtambanengwe and Mapfumo, 2008; Zingore et al., 2008). However, most smallholder farmers cannot obtain sufficient manure due to low livestock numbers, and are therefore unable to maintain critical SOC levels required to sustain soil productivity (Mtambanengwe and Mapfumo, 2005). This therefore calls for identification of complementary options to rehabilitate these degraded soils. In Zimbabwe, non-cultivated N₂-fixing herbaceous indigenous legumes were found to generate substantial biomass on nutrient-depleted soils that have < 10% clay, < 5 ppm available P, < 0.4% organic C (Mapfumo et al., 2005). The non-cultivated N₂-fixing indigenous legumes, which have hitherto been regarded by famers simply as weeds, are native to Zimbabwe and similar agro-ecologies of Southern Africa (Mapfumo et al., 2005). Due to their high adaptability to nutrient-depleted soils and variable rainfall regimes, and ability to biologically fix N, the indigenous legumes are a potential alternative source of N to increase cereal productivity in smallholder farming communities in Zimbabwe (Mapfumo et al., 2005; Nezomba et al., 2010). The legumes are different from the commonly used green manure cover crops (GMCC), as the latter are not only limited to N₂-fixing legumes, but include other crops that provide soil cover to reduce erosive forces (Abayomi et al., 2001), and smother weeds (Versteeg et al., 1998).

While the herbaceous indigenous legumes could produce considerable biomass on degraded soils, P fertilization is required to maximize biomass productivity, given the inherent low P levels in granitic sandy soils predominating in smallholder farming communities in Southern Africa (Hartemink and Huting, 2008). It was envisaged that the establishment of these legumes on degraded soils could enable crops to respond better to subsequent applications of
the small amounts of organic and inorganic nutrient resources commonly available to farmers. The underlying hypothesis of this Chapter was that biomass generated by P-fertilized N\textsubscript{2}-fixing herbaceous legumes with subsequent addition of cattle manure can stimulate soil biological processes towards restoration of degraded sandy soils. This approach was tested using the non-cultivated N\textsubscript{2}-fixing indigenous legumes of the genera *Chamaecrista*, *Crotalaria*, *Eriosema*, *Indigofera*, *Neonotonia* and *Tephrosia*, and a green-manure legume, *Crotalaria juncea* L. (sunnhemp). It was also envisaged that such herbaceous legume-based ISFM sequences could increase the responsiveness of degraded soils to mineral fertilizer. The main objective of the Chapter was to investigate potential entry points for rehabilitating degraded croplands using principles of ISFM on smallholder farms in Eastern Zimbabwe. The specific objectives were to: (i) assess the effect of indigenous herbaceous legume fallows (indifallows) on above-ground C and N productivity on degraded soils, (ii) determine maize grain yield responses to mineral N fertilizer under indigenous legume-based ISFM sequences and (iii) determine the influence of indigenous legume-based ISFM sequences on changes in soil microbial biomass and basal respiration.

### 5.3 Materials and methods

#### 5.3.1 Selection of experimental fields

The study was carried out between 2009 and 2012 in Nyahava (18° 13′S; 32° 22′E) and Goto (18° 41′S; 31° 42′ E) smallholder farming areas in Eastern Zimbabwe (Section 3.1). Prior to the 2009/2010 cropping season, FPRA were employed to investigate farmers' knowledge of soil degradation (Chapter 4). The local indicators of degraded croplands were then used to
identify fields for experimentation. In Nyahava, local indicators of soil degradation used to select the field sites were based on findings from a previous study in the same area (Mtambanengwe and Mapfumo, 2005). Four experimental sites were selected with the assistance of farmers and extension in Nyahava, and six in Goto. The experimental fields had similar catenary positions, and slope and history of management.

5.3.2. Establishment of indigenous legume-based ISFM sequences

At each field site, soils were first sampled at 0-20 cm depth and subsequently analyzed for total C, N, available P, pH, exchangeable bases, exchangeable acidity, ECEC, mineral N, texture and bulk density (Table 3.1). In the first cropping season, fields were tilled once to the 20 cm depth soon after the first effective rains in November 2009 using an animal-drawn mouldboard plough. At ploughing, there were negligible amounts of crop residues and weeds on the soil surfaces from previous season, and this was mainly attributed to free animal grazing during the dry season (Mtambanengwe and Mapfumo, 2005). At each experimental site, a total of seven plots, each measuring 15 m x 10 m, were demarcated. Two of the plots were put under indigenous legumes, with one intended for a 1-year fallow and the other for a 2-year fallow, resulting in the following treatments: (i) 1-year indifallow and (ii) 2-year indifallow. The 1-year indifallow and 2-year indifallow treatments initiated the 'Indifallow-start 1’ and 'Indifallow-start 2’ sequences, respectively. The next 2 plots were left under natural fallow to allow natural vegetation (mostly grasses) to regenerate on the ploughed fields for 1 and 2 years, giving (iii) 1-year natural fallow ('Natural fallow-start 1’) and (iv) 2-year natural fallow ('Natural fallow-start 2’) treatments, respectively. The other 2 plots were
allocated to (v) continuous fertilized maize and (vi) continuous unfertilized maize. The remaining plot was planted to a (vii) 1-year sunnhemp fallow as a green manure legume to provide for the 'Sunnhemp-start' sequence.

The treatments were randomly assigned to plots at each of the experimental sites and replicated across the farms. With the exception of continuous unfertilized maize, basal P fertiliser was added in each plot at 26 kg ha\(^{-1}\) in a PKS blend formulation (32% P\(_2\)O\(_5\): 16% K\(_2\)O: 5% S) before planting. A medium maturing maize variety, SC 513 (137 days to maturity), was planted in the continuous maize plots at a spacing of 0.75 m (inter-row) and 0.3 m (within rows) to attain a population density of approximately 44000 plants ha\(^{-1}\). The continuous fertilized maize crop was top-dressed with ammonium nitrate (34.5% N) at 120 kg N ha\(^{-1}\) split-applied at 3, 6 and 9 weeks after emergence (WAE). The maize plots were kept weed-free through hand hoe weeding. In the succeeding seasons, the treatments were allocated to the respective sequences as shown in Table 5.1. The experimental fields were not protected from free grazing by livestock during the dry season to mimic farmer management practices. Cattle manure was applied at 10 t ha\(^{-1}\) by broadcasting, and incorporated into soil before maize planting. The manure was sub-sampled and analyzed for total N, P, Mg, Ca and K (Table 3.1). Tillage was done as previously described.
Table 5. Sequencing framework ISFM options on degraded sandy soils on smallholder farms in Zimbabwe

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N P</td>
</tr>
<tr>
<td>‘Indifallow-start 1’</td>
<td>Indifallow</td>
<td>Maize + cattle manure + mineral fertilizer N and P</td>
<td>Maize + mineral fertilizer N and P</td>
<td>310 94</td>
</tr>
<tr>
<td>‘Sunnhemp-start’</td>
<td>Sunnhemp fallow</td>
<td>Maize + cattle manure + mineral fertilizer N and P</td>
<td>Maize + mineral fertilizer N and P</td>
<td>310 94</td>
</tr>
<tr>
<td>‘Natural fallow-start 1’</td>
<td>Natural fallow</td>
<td>Maize + cattle manure + mineral fertilizer N and P</td>
<td>Maize + mineral fertilizer N and P</td>
<td>310 94</td>
</tr>
<tr>
<td>‘Indifallow-start 2’</td>
<td>2-year indifallow</td>
<td></td>
<td></td>
<td>120 52</td>
</tr>
<tr>
<td>‘Natural fallow-start 2’</td>
<td>2-year natural fallow</td>
<td></td>
<td></td>
<td>120 52</td>
</tr>
<tr>
<td>Fertilized maize</td>
<td>Fertilized maize</td>
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<td>Fertilized maize</td>
<td>360 78</td>
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<td>Unfertilized maize</td>
<td>Unfertilized maize</td>
<td>Unfertilized maize</td>
<td>Unfertilized maize</td>
<td>0 0</td>
</tr>
</tbody>
</table>

*Cumulative N and P added as mineral fertilizer and cattle manure over the 3-year period; The grey shade indicates 2-year fallow.

Drawing on past studies (Mapfumo et al., 2005; Nezomba et al., 2010), indifallows were established by broadcasting seeds of different indigenous legume species in mixtures. The species were *Chamaecrista mimosoides* Greene., *Crotalaria laburnifolia* (L.), *C. ochroleuca* G. Don, *C. cylindrostachys* Welw. ex Baker, *C. pallida* (L.), *C. glauca* Willd., *Eriosema ellipticum* Welw. ex Baker, *Indigofera arrecta* Hochst. ex A. Rich., *I. astragalina* DC., *Macrotyloma daltonii* (Webb) Verdc., *Neonotonia wightii* (Wight & Arn.) J.A. Lackey, *Tephrosia radicans* Welw. ex Baker, *T. purpurea* Pers. and *T. longipes* Meisn. The seed mixes were planted at 120 seeds m$^{-2}$ species$^{-1}$ on the ploughed fields. The seed rate was calculated using seed number to mass ratios (Tauro et al., 2009). The legume seeds had been collected by farmers from fallowed fields as previously detailed in Mapfumo et al. (2005),
and were not inoculated before planting. The sunnhemp mixed fallow was established by broadcasting sunnhemp seed at 2 g m\(^{-2}\). Sunnhemp is a green manure crop being promoted by SOFECISA in the study areas (Mtambanengwe and Mapumo, 2009).

5.3.3 Quantification of biomass productivity and species abundance under fallows

Above-ground biomass productivity of indifallows, sunnhemp fallow and natural fallows was quantified using a 1m\(^2\) quadrat (Mapfumo et al., 2005) 4 months (peak growth) and 11 months (late dry season) after fallow establishment in the case of 1-year fallows (2009/10 season), and also 15 months after establishment in the case of 2-year fallows (2010/11 season). Below-ground biomass in fallow treatments was not quantified in this study although roots are also known to influence soil biological activity and productivity of rotational cereals. The quadrat was randomly thrown on three positions in each plot and the contained biomass cut from just above the soil level using a sickle. The harvested plants were separated into individual species biomass under shade and oven-dried at 60\(^{\circ}\) C to determine dry matter. Relative species abundance was calculated by expressing the mass of each species as a percentage of the total biomass productivity as follows:

\[
\text{Species abundance} = \frac{\text{Species biomass (kg/ha)}}{\text{Total biomass productivity (kg/ha)}} \times 100 \quad \text{Equation 5.1}
\]

Total biomass from each quadrat was ground on a Wiley Mill and sub-sampled for total N analysis (Table 3.1). Total fallow N productivity was then calculated by multiplying the tissue N concentration by the corresponding biomass, while total fallow C productivity was estimated by multiplying total biomass by 0.45. A previous study on similar soils in
Zimbabwe showed above ground biomass of indigenous legumes, sunnhemp, natural grasses and broad leaf weeds to contain 45% C (Nezomba et al., 2009).

5.3.4 Determination of maize N response under the different treatments

During the third cropping season (2011/2012), all the treatments were planted to a maize test crop (Table 5.1). Two weeks before planting the maize crop, all above-ground biomass in the fallows were incorporated to a depth of 20 cm using a mouldboard plough. Basal P fertilizer was applied across all the treatments at 26 kg ha\(^{-1}\). Maize (SC 513) was planted at a population density of 44,000 plants ha\(^{-1}\). To determine maize responses to mineral N fertilizer, N was applied at 0, 35, 70, 90 and 120 kg ha\(^{-1}\) in sub-plots measuring 3 m x 10 m under each of the treatments with the exception of the continuous unfertilized maize treatment. At physiological maturity, maize ears (grain + cob) were harvested from net plots of 1.5 m x 9.4 m (2 middle rows) and grain yield quantified at 12.5% moisture content.

5.3.5 Determination of soil microbial biomass, basal respiration and total C

To assess the effects of the different sequences on changes in soil microbiological properties and total organic C, soil samples were collected at 0-10 and 10-20 cm depths from plots receiving 120 kg N ha\(^{-1}\) and the continuous unfertilized control during the 2011-12 cropping season at 3 and 6 weeks after planting (WAP) of maize. The samples were analysed for microbial biomass C and N, basal respiration and total organic C (Table 3.1). Soil basal
respiration was determined only on soils sampled 6 weeks after maize planting. The CO$_2$-C released during soil basal respiration was quantified on days 1, 4, 8, 16 and 21, and the amounts added to obtain the total CO$_2$-C evolved. Metabolic quotient ($q$CO$_2$), a measure of efficiency of the microbial community, was calculated by dividing the amount of CO$_2$-C evolved on the first day of incubation by microbial biomass C (Anderson and Domsch, 1990).

5.3.6 Data analyses

Statistical differences in fallow C and N productivity and maize yields were assessed through ANOVA, with field sites (blocks) and the ISFM options considered as fixed factors. The single and interactive effects of ISFM options, soil depth and time of sampling on soil microbial biomass, basal respiration and metabolic quotient were also assessed through ANOVA. All the factors were considered fixed. Mean separation was done using the Turkey's Test at $P < 0.05$. Maize grain yield responses to mineral N fertilizer were calculated using the exponential model in regression analysis as follows:

$$Y_x = Y_0 + \Delta Y_{\text{max}} (1 - \exp(-kx))$$  \hspace{1cm} \text{Equation 5.2}

where $Y_x$ is the grain yield (kg ha$^{-1}$) at particular rate (x) of N,

$Y_0$ the yield at zero N (kg ha$^{-1}$), $\Delta Y_{\text{max}}$ the maximum yield increase from the initial (kg ha$^{-1}$) and $k$ is the rate constant (kg$^{-1}$) or a specific responsiveness factor.
5.4 Results

5.4.1 Rainfall distribution and chemical properties of cattle manure

Total seasonal rainfall received during the experimental period averaged 686 mm and 745 mm in Goto and Nyahava, respectively (Figure 5.1). Within-season distribution varied strongly, particularly in Goto. Overall, across sites and seasons (years), the cattle manure used in the experiments had the following properties: total N = 0.7%, total P = 0.16%, total Mg = 0.1%, total Ca = 0.3% and total K = 0.5% (data not shown).

Figure 5.1 Rainfall distribution during the experimental period.
5.4.2 Soil properties on degraded croplands

Overall, soil chemical properties on the degraded field sites selected for experimentation were lower than reported values for productive soils of similar textural class (Table 5.2). Total C and N on productive soils, based on studies in similar smallholder farming areas in Zimbabwe, were between 2 and 3 times, respectively, more than on the degraded soils.

Table 5. 2 Initial physical and chemical characteristics of soils (0-20 cm) on degraded fields in Goto and Nyahava smallholder farming areas in Zimbabwe. Figures in parentheses denote standard error of mean (SEM).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goto (n=6)</th>
<th>Nyahava (n=4)</th>
<th>1Productive sandy soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay (%)</td>
<td>8 (0.2)</td>
<td>9 (0.1)</td>
<td>8 (0.3)</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>81 (2)</td>
<td>77 (3)</td>
<td>87 (2)</td>
</tr>
<tr>
<td>Organic C (%)</td>
<td>0.3 (0.05)</td>
<td>0.4 (0.03)</td>
<td>0.7 (0.04)</td>
</tr>
<tr>
<td>Total N (%)</td>
<td>0.02 (0.007)</td>
<td>0.03 (0.005)</td>
<td>0.07 (0.002)</td>
</tr>
<tr>
<td>Available P (ppm)</td>
<td>4 (2)</td>
<td>4 (1)</td>
<td>9 (2)</td>
</tr>
<tr>
<td>pH (0.01M CaCl₂)</td>
<td>4.1 (0.11)</td>
<td>4.5 (0.13)</td>
<td>5.4 (0.12)</td>
</tr>
<tr>
<td>Mineral N (mg kg⁻¹)</td>
<td>17 (1)</td>
<td>21 (4)</td>
<td>22 (3)</td>
</tr>
<tr>
<td>Exc. Ca (cmol (c) kg⁻¹)</td>
<td>0.4 (0.02)</td>
<td>0.4 (0.02)</td>
<td>3.2 (0.01)</td>
</tr>
<tr>
<td>Exc. Mg (cmol (c) kg⁻¹)</td>
<td>0.3 (0.01)</td>
<td>0.2 (0.01)</td>
<td>0.9 (0.02)</td>
</tr>
<tr>
<td>Exc. K (cmol (c) kg⁻¹)</td>
<td>0.2 (0.001)</td>
<td>0.2 (0.001)</td>
<td>1.0 (0.001)</td>
</tr>
<tr>
<td>Exc. Al and H (cmol (c) kg⁻¹)</td>
<td>0.4 (0.002)</td>
<td>0.2 (0.001)</td>
<td>0.2 (0.003)</td>
</tr>
<tr>
<td>ECEC (cmol (c) kg⁻¹)</td>
<td>2.8 (0.03)</td>
<td>3.1 (0.08)</td>
<td>4.6 (0.04)</td>
</tr>
<tr>
<td>Bulk density (kg m⁻³)</td>
<td>1700 (56.6)</td>
<td>1750 (65.8)</td>
<td>1640 (48.9)</td>
</tr>
</tbody>
</table>

1Average values for productive sandy soils obtained from studies conducted in smallholder farming areas in Zimbabwe (Mugwira and Nyamangara, 1988; Mtambanengwe and Mapfumo, 2005; Chikuvire et al., 2007; Zingore et al., 2007; Masvaya et al., 2010; Rusinamhodzi et al., 2013; Nezomba et al., 2015a). Figures in parentheses denote standard error of mean.
Available P on the degraded soils was 4 ppm compared with 9 ppm reported on productive sandy soils in Zimbabwe. ECEC, and exchangeable Ca and Mg from the degraded soils were also lower than values obtained for productive sandy soils in similar areas. Bulk density on the degraded soils was 6% higher than the average value obtained for productive sandy soils in Zimbabwe.

5.4.3 Species abundance and biomass productivity under fallows

In both Goto and Nyahava, 1-year indifallow was dominated by annual legume species, with *Crotalaria laburnifolia* and *C. ochroleuca* contributing > 50% of the total system biomass (Figures 5.2 and 5.3). Under 1-year sunnhemp fallow, sunnhemp constituted more than 75% of the biomass. In the 2-year indifallow, most of the system biomass was, however, contributed by non-leguminous species such as *Setaria pumila* (25% in Goto and 26% in Nyahava) and *Cynodon dactylon* (33% in Goto and 27% in Nyahava).

![Bar chart showing relative species abundance under indifallows and sunnhemp fallow in Goto, Hwedza, Zimbabwe. Vertical bar represents least significant difference (LSD).](attachment:image.png)
Across sites, the 1-year indifallow produced an average of 10 t ha\(^{-1}\) above-ground biomass compared with 2.8 t ha\(^{-1}\) under natural fallow (data not shown), translating to significantly \((P < 0.05)\) higher above-ground biomass C and N accumulation than in natural fallow (Fig. 5.4a-d). Under high rainfall in Goto, 1-year indifallow yielded 3195 and 1994 kg C ha\(^{-1}\) at peak growth (16 weeks) and late dry season (44 weeks), respectively, against 540 and 270 kg C ha\(^{-1}\) under natural fallow. With respect to N, the 1-year indifallow gave 213 kg N ha\(^{-1}\) at peak growth compared with 14 kg N ha\(^{-1}\) generated in the natural fallow. A similar result was observed under medium-high rainfall conditions in Nyahava. There were no significant \((P > 0.05)\) differences in biomass C and N productivity between 1-year indifallow and 1-year sunnhemp fallow. Two-year indifallow accumulated less biomass C and N than 1-year indifallow as the total biomass under the former was only contributed by biennial indigenous legume species and grass species. However, the 2-year indifallow produced approximately two times the biomass C and N attained under 2-year natural fallow (Figure 5.4e-f).
Figure 5. Above-ground biomass C and N produced under 1-year fallows (a,b,c,d), and 2-year fallows (e, f) on degraded soils in smallholder farming areas in Zimbabwe. Bars indicate standard error of differences of means (SEDs) for a = Goto; b = Nyahava.
5.4.4 Maize response to mineral N fertilizer under ISFM sequences

In both Goto and Nyahava, maize under continuous mineral fertilizer yielded no more than 1.2 t ha\(^{-1}\) of grain in the first two cropping seasons (Figure 5.5). Unfertilized maize gave an average grain yield of 0.4 t ha\(^{-1}\) over the same period. In the third cropping season in Nyahava, maize grown after 'Indifallow-start 1' showed the greatest response to mineral N fertilizer \((R^2 = 0.65; P < 0.001)\) compared with 'Natural fallow-start 1' \((R^2 = 0.35; P = 0.01)\), 'Natural fallow-start 2' \((R^2 = 0.43; P = 0.09)\) and continuous fertilized maize \((R^2 = 0.4; P = 0.005)\) (Figure 5.6).

![Diagram showing maize productivity under continuous fertilized and unfertilized treatments in the first (2009-2010) and second (2010-2011) seasons on degraded soils in smallholder farming areas of Zimbabwe. Error bars represent standard error on means (SEMs).](image-url)

Figure 5.5 Maize productivity (t ha\(^{-1}\)) under continuous fertilized and unfertilized treatments in the first (2009-2010) and second (2010-2011) seasons on degraded soils in smallholder farming areas of Zimbabwe. Error bars represent standard error on means (SEMs).
In Goto in the third year, 'Indifallow-start 2' gave the highest response to mineral N fertilizer ($R^2 = 0.54$), with all the other sequences recording $R^2$ of $< 0.5$ (Figure 5.7). Overall, maize yield responses to mineral N were lower in Goto than in Nyahava due to a prolonged mid-season dry spell, which coincided with silking and grain filling stages.

Figure 5.6 Maize grain yield responses to mineral N fertilizer under different ISFM sequences on degraded soils in the third (2011-2012) cropping season in Nyahava smallholder farming area in Zimbabwe. The lines represent the fitted exponential functions.
Figure 5. Maize grain yield responses to mineral N fertilizer under different ISFM sequences on degraded soils in the third (2011-2012) cropping season in Goto smallholder farming area in Zimbabwe. The lines represent the fitted exponential functions.

In Nyahava, the model predicted an average maximum grain yield ($Y_{max}$) of 4 t ha$^{-1}$ under 'Indifallow-start 1' and 'Sunnhemp-start'; three times the predicted yields under natural fallow-based sequences and continuous fertilized maize (Table 5.3). However, because of the low
yields in Goto, the model estimated a maximum grain yield of less than 2 t ha$^{-1}$ across all treatments.

Table 5. 3 Regression model parameters for maize responses to different rates of mineral N fertilizer under ISFM sequences on degraded soils in Goto and Nyahava smallholder communities in Zimbabwe

<table>
<thead>
<tr>
<th>Site/Treatment</th>
<th>$Y_0$ (t ha$^{-1}$)</th>
<th>$Y_{\text{max}}$ (t ha$^{-1}$)</th>
<th>-k</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nyahava</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'Indifallow-start 1'</td>
<td>0.7</td>
<td>3.9</td>
<td>0.0080</td>
</tr>
<tr>
<td>'Natural fallow-start 1'</td>
<td>0.4</td>
<td>1.2</td>
<td>0.0098</td>
</tr>
<tr>
<td>'Sunnhemp-start'</td>
<td>0.7</td>
<td>4.1</td>
<td>0.0009</td>
</tr>
<tr>
<td>'Indifallow-start 2'</td>
<td>0.5</td>
<td>3.1</td>
<td>0.0030</td>
</tr>
<tr>
<td>'Natural fallow-start 2'</td>
<td>0.4</td>
<td>0.9</td>
<td>0.0087</td>
</tr>
<tr>
<td>Continuous fertilized maize</td>
<td>0.4</td>
<td>1.7</td>
<td>0.0027</td>
</tr>
<tr>
<td><strong>Goto</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'Indifallow-start 1'</td>
<td>0.5</td>
<td>0.9</td>
<td>0.0082</td>
</tr>
<tr>
<td>'Natural fallow-start 1'</td>
<td>0.2</td>
<td>0.7</td>
<td>0.0204</td>
</tr>
<tr>
<td>'Sunnhemp-start'</td>
<td>0.6</td>
<td>1.8</td>
<td>0.0027</td>
</tr>
<tr>
<td>'Indifallow-start 2'</td>
<td>0.4</td>
<td>1.4</td>
<td>0.0065</td>
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<tr>
<td>'Natural fallow-start 2'</td>
<td>0.3</td>
<td>0.6</td>
<td>0.0115</td>
</tr>
<tr>
<td>Continuous fertilized maize</td>
<td>0.3</td>
<td>0.6</td>
<td>0.0049</td>
</tr>
</tbody>
</table>

5.4.5 Soil microbial biomass under the different treatments

Overall in Goto, microbial biomass was not significantly different among treatments at 3 WAP of the maize test crop, but had significantly increased at 6 WAP (Table 5.4). At 6 WAP (0-10 cm), 'Indifallow-start 1' and 'Indifallow-start 2' gave > 235 mg kg$^{-1}$ of microbial biomass C (MBC) compared with < 200 mg kg$^{-1}$ under continuous fertilized maize. A similar trend was recorded from soils sampled from the 10-20 cm depth. Overall, 'Sunnhemp-start' gave the highest MBC across treatments. Microbial biomass C to organic C ratios were highest under 'Indifallow-start 1' and 'Sunnhemp-start' both 3 and 6 WAP. For example, at 3
WAP, 'Sunnhemp-start' gave a microbial biomass C to organic C ratio of 5.6 (0-10 cm) compared with < 4.4 under natural fallow-based sequences across sampling depths. At 6 WAP (0-10 cm), microbial biomass N (MBN) were > 30 mg kg\(^{-1}\) under 'Indifallow-start 1' and 'Sunnhemp-start' against < 20 mg kg\(^{-1}\) under 'Natural-fallow start 2' and continuous maize treatments.

At Nyahava in the 0-10 cm depth (3 WAP), MBC did not differ significantly among treatments (Table 5.5). Although MBC was slightly lower in 10-20 cm depth than the upper layer, still there were no significant differences across the treatments. MBC had, however, markedly increased at 6 WAP in both the 0-10 cm and 10-20 cm depths, particularly under 'Indifallow-start 1', 'Indifallow-start 2' and 'Sunnhemp-start 1'. 'Indifallow-start 1' gave the highest microbial biomass C to organic C ratios at both 3 and 6 WAP, and at 0-10 cm and 10-20 cm depths. MBN was not significantly different among treatments 3 WAP (0-10 cm), with 'Indifallow-start 1' and 'Natural fallow-start 2' giving the highest and least values, respectively. In the 10-20 cm depth, 'Indifallow-start 1' consistently gave the highest MBN. MBN had increased in all the treatments 6 WAP in both the 0-10 cm and 10-20 cm depths, with the exception of continuous unfertilized maize. 'Indifallow-start 1' (0-10 cm) gave approximately 3 times the MBN recorded under 'Natural fallow-start 2' and continuous fertilized maize.
Table 5. Soil organic C, and microbial biomass C and N under different ISFM options on degraded soils at 3 and 6 weeks after planting of maize in Goto smallholder farming area during the 2011/2012 season cropping season.

<table>
<thead>
<tr>
<th>Sampling depth/Treatment</th>
<th>3WAP</th>
<th></th>
<th>6WAP</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MBC</td>
<td>MBN</td>
<td>Soil organic C</td>
<td>MBC</td>
</tr>
<tr>
<td></td>
<td>(mg kg(^{-1}))</td>
<td>(mg kg(^{-1}))</td>
<td>(t ha(^{-1}))</td>
<td>(mg kg(^{-1}))</td>
</tr>
<tr>
<td>0-10 cm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>'Indifallow-start 1'</td>
<td>185</td>
<td>9.2</td>
<td>5.1</td>
<td>4.7</td>
</tr>
<tr>
<td>'Natural fallow-start 1'</td>
<td>179</td>
<td>11.6</td>
<td>5.3</td>
<td>4.4</td>
</tr>
<tr>
<td>'Sunnhemp-start'</td>
<td>196</td>
<td>11.3</td>
<td>5.4</td>
<td>5.6</td>
</tr>
<tr>
<td>'Indifallow-start 2'</td>
<td>186</td>
<td>11.5</td>
<td>5.4</td>
<td>4.3</td>
</tr>
<tr>
<td>'Natural fallow-start 2'</td>
<td>172</td>
<td>10.8</td>
<td>5.5</td>
<td>3.9</td>
</tr>
<tr>
<td>Continuous fertilized maize</td>
<td>188</td>
<td>9.9</td>
<td>5.4</td>
<td>4.4</td>
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<tr>
<td>Continuous unfertilized maize</td>
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<td>10.1</td>
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<td>10-20 cm</td>
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<td>4.3</td>
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<td>4.4</td>
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<td>'Natural fallow-start 2'</td>
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<td>5.0</td>
<td>3.2</td>
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<td>Continuous fertilized maize</td>
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<td>8.6</td>
<td>5.1</td>
<td>3.9</td>
</tr>
<tr>
<td>Continuous unfertilized maize</td>
<td>182</td>
<td>8.4</td>
<td>5.1</td>
<td>3.8</td>
</tr>
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Statistical significance:

<table>
<thead>
<tr>
<th></th>
<th>MBC</th>
<th>MBN</th>
<th>Soil organic C</th>
<th>MBC/Organic C</th>
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<tbody>
<tr>
<td>Treatment</td>
<td>*</td>
<td>ns</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>*</td>
<td>*</td>
<td>ns</td>
<td>*</td>
</tr>
<tr>
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<td>*</td>
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<td>*</td>
</tr>
<tr>
<td>Depth x Treatment</td>
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<td>ns</td>
<td>ns</td>
<td>*</td>
</tr>
<tr>
<td>Time x Depth x Treatment</td>
<td>*</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
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</table>

§ Significantly different at *p < 0.05; ns= not significant; MBC= microbial biomass carbon; MBN= microbial biomass nitrogen
Table 5. Soil organic C, and microbial biomass C and N under different ISFM options on degraded soils at 3 and 6 weeks after planting of maize in Nyahava smallholder farming area during the 2011/2012 season cropping season.

<table>
<thead>
<tr>
<th>Sampling depth/Treatment</th>
<th>0-10 cm</th>
<th>10-20 cm</th>
<th>3WAP</th>
<th>6WAP</th>
<th>3WAP</th>
<th>6WAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MBC (mg kg⁻¹)</td>
<td>MBN (mg kg⁻¹)</td>
<td>Soil organic C (t ha⁻¹)</td>
<td>MBC/Organic C (%)</td>
<td>MBC (mg kg⁻¹)</td>
<td>MBN (mg kg⁻¹)</td>
</tr>
<tr>
<td>0-10 cm</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'Indifallow-start 1'</td>
<td>183</td>
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<td>11.3</td>
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<td>2.6</td>
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<td>5.3</td>
<td>2.5</td>
<td>142</td>
<td>7.9</td>
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Statistical significance:

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<th>MBN</th>
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<th>MBC/Organic C</th>
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<tr>
<td>Time x Depth x Treatment</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

§ Significantly different at *p < 0.05; ns= not significant; MBC= microbial biomass carbon; MBN= microbial biomass nitrogen
5.4.6 Soil CO₂-C emission and metabolic quotient under ISFM sequences

Basal respiration was higher in soils collected from the 0-10 cm depth than 10-20 cm for most of the treatments (Figure 5.8). In Goto, 'Indifallow-start 1' (157 mg CO₂-C kg⁻¹ soil) and 'Sunnhemp-start' (163 mg CO₂-C kg⁻¹ soil) gave the greatest CO₂-C emissions (Figure 5.8a). Continuous maize treatments and 'Natural fallow-start 2' released < 115 mg CO₂-C kg⁻¹ soil. In Nyahava (0-10 cm), 'Indifallow-start 1' and 'Sunnhemp-start' consistently released the most CO₂-C compared with the continuous maize treatments (Figure 5.8b).

Natural fallow-based sequences and continuous maize gave higher metabolic quotients ($q_{CO₂}$) than legume-based sequences (Figure 5.9). In Goto (0-10 cm), $q_{CO₂}$ was approximately 0.1 mg CO₂-C g⁻¹ microbial C day⁻¹ under 'Indifallow-start 1', 'Sunnhemp-start' and 'Indifallow-start 2', but doubled under continuous maize and natural fallow-based sequences (Figure 5.9a). A similar trend was recorded for the 10-20 cm depth. The $q_{CO₂}$ patterns of soils from Nyahava were consistent with those from Goto (Figure 5.9b).
Figure 5. Total CO$_2$-C released from degraded soils under different ISFM options in (a) Goto and (b) Nyahava smallholder farming areas, Zimbabwe. Bars indicate standard error of differences of means (SEDS) for $a =$ ISFM option; $b =$ depth
Figure 5. 9 Soil metabolic quotient (qCO₂) under different ISFM options in (a) Goto and (b) Nyahava smallholder farming areas, Zimbabwe. Bars indicate standard error of differences of means (SEDs) for a = ISFM option; b = depth

5.5 Discussion

Degraded soils often support low net primary productivity levels, typically around 2 t ha⁻¹ year⁻¹, preventing the restoration of their organic matter content and physico-chemical fertility (Lal, 2006b).
In this study, 1-year indifallow and 1-year sunnhemp fallow produced > 10 t ha\(^{-1}\) of above-ground biomass on nutrient-depleted soils, while 1-year natural fallow accumulated < 3 t ha\(^{-1}\). The high amounts of C and N measured under 1-year indifallow and 1-year sunnhemp fallow were due to the biomass contributed by legume species. The lower biomass productivity in 2-year indifallow than under 1-year indifallow was as a result of reduced legume biomass in the second year. Annual legume species such as *C. laburnifolia* and *C. ochroleuca*, which contributed most of the shoot biomass under 1-year indifallow, did not re-establish well in the second year due to the dominance of grass species. Consequently, most of the legume biomass under 2-year indifallow was contributed by biennial legume species such as *I. arrecta* and *E. ellipticum*. Although biomass productivity of the predominantly grass weeds and biennial legume species under 2-year indifallow could not match productivity under the 1-year indifallow, the biomass productivity was better than leaving the soils under a 2-year natural fallow.

Herbaceous legumes therefore offer better prospects for generating high initial above-ground biomass on degraded soils than natural fallowing. Although the measured data in this study were based on shoot biomass yields, basing on commonly known shoot to root ratios of grasses and herbaceous legumes (Bolinder et al., 2002; Pang et al., 2011), it is likely that the legume-based fallows also generated more below-ground biomass than the natural fallows. Working in Zimbabwe, Chikowo et al. (2004b) reported that *Cajanus cajan*, a herbaceous N\(_2\)-fixing legume, yielded 2 t ha\(^{-1}\)year\(^{-1}\) in root biomass in the 0-20 cm depth.

The high microbial biomass attained under 'Sunnhemp-start' and 'Indifallow-start 1' suggest that the legumes biomass generated in the first year and cattle manure applied in the second year provided
labile C and N to stimulate soil microbial activity. Inclusion of legumes in cereal-based cropping systems has been shown to increase microbial biomass (Yusuf et al., 2009; Silva et al., 2010). 'Indifallow-start 2' gave superior microbial biomass than 'Natural-fallow-start 2' implying that mixtures of legume biomass and grass weeds generated under 2-year indifallow in the preceding years provided better microbial substrates compared with the predominantly grass weeds under 2-year natural fallow. The ratio of microbial biomass C to total SOC was highest under 'Sunnhemp-start' and 'Indifallow-start 1' indicating greater biological activity that would suggest a faster soil rehabilitation potential as compared with the other sequences (Sparling, 1992). Consistent with microbial biomass, soil basal respiration was also highest under 'Sunnhemp-start' and 'Indifallow-start 1' reflecting the superior microbial activity (Franchini et al., 2007). Stressful soil environments such as those associated with nutrient depletion and contamination often lead to a decrease in microbial efficiency, which translates into increased qCO₂ as microbes spend more energy on maintaining metabolic activity than in accumulating biomass (Wardle and Ghani, 1995; Hu et al., 2010). The lower metabolic quotient (qCO₂) obtained under legume-based sequences therefore indicated more available C and thus less microbial stress compared with natural fallow-based sequences and continuous maize treatments.

The higher maize response to mineral N fertilizer under the legume-based ISFM sequences could be explained by increased soil N availability through addition of legume biomass and cattle manure. Besides above-ground legume biomass, the increased N under the legume-based ISFM sequences could also be attributed to mineralization of legume roots, nodules and other N compounds deposited in the rhizosphere. Below-ground legume N has been found to contribute between 3-15% of the N taken up by three successive rotational cereal crops (Glasener et al., 2002; Peoples et al., 2009). While organic matter turnover rates are high in tropical environments, particularly on sandy soils
(Chivenge et al., 2007), some of the biomass accumulated under these sequences could also have temporarily immobilized the fertilizer N and released it in synchrony with crop demand (Gentile et al., 2009). Moreover, the organic materials can contribute to increased water capture (Dunjana et al., 2012). Similar mechanisms were less pronounced under natural fallow-based sequences because of the low organic matter accumulation. First, the natural fallows produced lower shoot biomass than the legume-based fallows. Second, most of the grass biomass produced under natural fallows were grazed by livestock during the dry season given that the experimental field sites were not fenced. On the contrary, indigenous legumes and sunnhemp contributed high quantities of biomass under the legume-based fallow systems because they are non-palatable.

Other possible factors contributing to the high maize yields attained under 'Indifallow-start 1' and 'Sunnhemp-start' include provision of multiple nutrients and acidity regulation effects through the addition of cattle manure (Zingore et al., 2008). Farmers are less likely to get a significant crop yield penalty by fallowing their degraded fields under herbaceous legumes over 1 or 2 cropping seasons. As shown in this study, continuously cropped maize on the degraded fields, even with recommended N and P fertilization, gave low grain yields. This therefore suggests the need for organic matter management strategies and balanced fertilization to address multiple nutrient deficiencies often associated with such soils (Tittonell et al., 2008; Rusinamhodzi et al., 2013).

The legume-based ISFM sequences were able to stimulate soil biological activity and increase maize response to mineral N fertilizer on degraded croplands in the short-term (3 years). This indicates that there is scope for long-term assessment of the sustainability of these crop yield responses allowing for the effects of seasonal rainfall variability on these sequences. Past studies have shown that extreme conditions of poor soil fertility critically undermine initial efforts to introduce common grain
legume-based rotations to enhance productivity of cereals (Mapfumo et al., 1999; Ncube et al., 2007). This study therefore suggests that these experiments on ISFM-based sequences could open new opportunities for analysing trade-offs related to farmer decisions on introduction of new cropping systems to address persistent problems of declining soil productivity, land degradation and increased climate variability. In order to reduce the risk associated with fertilizer use under erratic rainfall conditions, options such as staggered planting with different crop types and varieties and split application of the fertilizers in response to soil moisture conditions have generally been recommended for smallholder farmers (Piha, 1993; Rurinda et al., 2013). However, the entry point for sufficiently stimulating crop response to the external inputs has been a major constraining factor.

A combination of high initial biomass productivity, stimulation of soil biological activity and better responses to mineral N fertilizer presents herbaceous legume-based ISFM sequences as potential entry points for 'kick-starting' rehabilitation of degraded sandy soils. The high biomass productivity of the indigenous legumes under indifallows was mainly attributed to the use of sufficiently high plant population densities, their inherent ecological adaptability, and notably P fertilization. Nevertheless, fertilization of non-food legumes often presents a dilemma for resource-constrained smallholder farmers due to lack of direct food benefits (Mtambanengwe and Mapfumo, 2009). However, given the large spatial extent of degraded soils under smallholder cropping in Africa (Eswaran et al., 2005) and that farmers are already abandoning these nutrient depleted soils due to weak responses of main crops to external fertilization (Mapfumo et al., 2005), this study adds a new dimension to future economic considerations and trade-off analyses. Applying P fertilizer to indigenous legumes and sunnhemp may not only lead to maximization of biomass and N accumulation by the legumes (Giller and Cadisch, 1995; Mapfumo, 2011), but also presents a
strategy for building P stocks in these degraded sandy soils. The retention of the legume biomass *in-situ* under the fallows coupled with the low mobility of P imply that there is minimal loss of the nutrient, and the rotational crops could in turn benefit from the residual P, provided it is not fixed into non-available forms. Programs focusing on enhancing fertilizers to smallholder farmers (e.g. subsidies or handouts by NGOs) could consider this new dimension in soil fertility management, which can bring large areas of arable land back to production. The indigenous legumes offer an alternative option for farmers as they still yielded > 5 t ha\(^{-1}\) of above-ground biomass without P fertilization (Nezomba *et al*., 2010). Future studies could also explore intercropping of indigenous legumes with small grain cereal crops such as *Eleusine coracana* L. (finger millet). Finger millet can give reasonable yields with minimum weeding, and is adapted to low soil moisture conditions (Frere, 1984) implying less competition for water with the indigenous legumes.

Although they have a direct food value, commonly grown grain legumes such as cowpea and groundnut are less likely to 'kick-start' rehabilitation of these degraded soils because of low biomass productivity (Mapfumo, 2011). Most grain legumes also have high N grain harvest indices and are grazed by livestock during the dry season such that their overall contribution to organic N on fields can be negligible (Baudron *et al*., 2012b). However, adoption of indigenous legumes and sunnhemp could still be hindered by lack of an established seed market as well as farmers' preference for grain legumes because of their nutritional value (Drechesel *et al*., 1996; Amede, 2003; Kamanga *et al*., 2014). While farmers could easily collect seed of indigenous legumes from fallowed fields and the wild with minimal training on identification methods (Mapfumo *et al*., 2005), germplasm of legume cover crops such as sunnhemp largely remain inaccessible to most farmers (Mtambanengwe and Mapfumo, 2009; Snapp *et al*., 2002). For farmers to employ herbaceous legume-based ISFM
sequences in rehabilitating degraded soils, access to affordable herbaceous legume seed and NPK fertilizers are therefore important.

5.6 Conclusions

Seeding of indigenous legumes and sunnhemp on degraded sandy soils, with P fertilization, led to more above-ground biomass C and N production than leaving the fields to natural fallow. The predominantly legume biomass produced under indifallow and sunnhemp fallow in combination with cattle manure increased soil biological activity (microbial biomass and basal respiration) and the responsiveness of the degraded soils to mineral N fertilizer. These results imply that most degraded soils may not respond to mineral fertilizer addition without management options that stimulate biological activity. Further complementary studies could focus on the influence of the different ISFM sequences on changes in fungi and bacteria populations, their diversity and other soil microbes as this is key to informing the rehabilitation process. Maize grain yield response to mineral fertilizer N was higher under herbaceous legume-based ISFM sequences compared with mineral fertilizer only. The study showed that soils that are perceived to be degraded by famers have not yet reached 'the point of no return', and herbaceous legume-based ISFM sequences are potential entry points for 'kick-starting' rehabilitation of such soils. Yet, in many smallholder farming areas in Southern Africa, putting the degraded soils to non-cropping land uses is likely to be constrained by limited arable land against a rising population and lack of alternative livelihood options to diversify out of crop production.
CHAPTER 6

Sequencing ISFM options for sustainable crop intensification by different categories of smallholder farmers in Zimbabwe

6.1 Abstract

Research has proved that ISFM can increase crop yields. However, its uptake by smallholder farmers in Africa is often constrained by lack of technical guidelines on effective starting points and how the different ISFM options can be combined to increase crop productivity on a sustainable basis. A four-year study was conducted on sandy soils (< 10 % clay) on smallholder farms in Eastern Zimbabwe to assess how sequencing of different ISFM options may lead to increases in soil nutrients, enhanced efficiency of resource use and increase crop yields at field scale. The sequences were primarily based on low quality organic resources, nitrogen-fixing green manure and grain legumes, and mineral fertilizers. To enable comparison of legume and maize grain yields among treatments, yields were converted to energy (kilocalories) and protein (kgs) equivalents.

In the first year, ‘Manure-start’, a cattle manure-based sequence, yielded 3.4 t ha⁻¹ of maize grain compared with 2.5 and 0.4 t ha⁻¹ under a woodland litter-based sequence ‘Litter-start’ and continuous unfertilized maize control, respectively. The ‘Manure-start’ produced 12 x 10⁶ kilocalories (kcal); significantly (P < 0.05) out-yielding ‘Litter-start’ and a fertilizer-based sequence (‘Fertilizer-start’) by 50%. A soyabean-based sequence, ‘Soya-start’, gave the highest protein production of 720 kg against < 450 kg for the other sequencing treatments.

In the second year, the sequences yielded an average of 5.7 t ha⁻¹ of maize grain, producing over 19 x 10⁶ kcal and 400 kg of protein. Consequently, the sequences significantly out-performed farmers’ designated least-productive fields by ~ five-fold. In the third year, ‘Soya-start’ gave the highest maize grain yield of 3.7 t ha⁻¹; translating to 1.5 and 3 times more calories than under farmers’ designated most- and least-productive fields, respectively. In the fourth year, ‘Fertilizer-start’ produced the highest calories and protein of 14 x 10⁶ kcal and 340 kgs, respectively. Cumulatively over four years, ‘Manure-start’ and ‘Soya-start’ gave the highest calories and protein, out-performing farmers’ designated most- and least-productive fields. Crotalaria juncea L. (sunnhemp)-based sequences, ‘Sunnhemp-start’ and ‘Fertilizer-start’, recorded the highest gains in available P of ~ 4 mg kg⁻¹ soil over the four-year period. Assessment of P agronomic efficiencies showed significantly more benefits under the ISFM-based sequences than under farmers’ designated most- and least-productive fields. Based on costs of seed, nutrients and labour, ‘Soya-start’ gave the best net present value over the four years, while ‘Fertilizer-start’ was financially the least attractive. Overall, the ISFM-based sequences were more profitable than fields designated as most- and least-

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productive by farmers. ISFM-based sequences can provide options for farm-level intensification by different categories of smallholder farmers in Southern Africa through (i) building P stocks on sandy soils, (ii) increasing crop yields and significantly contributing to farm-level calorie and protein production, and (iii) increasing returns to seed, nutrients and labour investments. These findings have strong implications for development of decision support tools for farmers with different access patterns to crop nutrient resources, but requiring options for restoring productivity of their degraded fields.

6.2 Introduction

Despite persistent low maize and grain legume yields, most smallholder farmers in Southern Africa are highly depended on locally-grown crops to meet their food requirements as opportunities to purchase food from external markets are limited. Maize in the region accounts for up to 50% of calories consumed on smallholder farms (SADC FANR, 2007). While maize is allocated to most of the arable land (often >80%) as a staple crop, rotations and intercrops with grain legumes such as soyabean, groundnut and cowpea are commonly practiced (Shumba, 1983; Franke et al., 2014). The rotations and intercrops help to control diseases and pests, diversify household diets, and reduce risk of crop failure (Giller and Cadisch, 1995; Rusinamhodzi et al., 2012). Besides providing a cheap source of protein, grain legumes also significantly contribute to calorie needs of African smallholder farmers as they are usually processed into various edible products on-farm (Mpepereki et al., 2000; Ashaye et al., 2005). However, both maize and grain legume yields rarely exceed 1 t ha\(^{-1}\), largely due to poor and declining soil fertility (Mapfumo and Giller, 2001). With diminishing opportunities for agricultural expansion into new areas, there is a need to focus on intensifying production on existing croplands. This also inevitably calls for restoration of land currently abandoned by farmers due to loss of soil productivity.
In response to problems of nutrient scarcity as well as addressing environmental concerns on smallholder farms, the last two decades have seen soil fertility studies focusing on ISFM (Buresh et al., 1997a; Vanlauwe et al., 2001a). Despite studies providing empirical evidence that ISFM technologies can increase crop yields (e.g. Vanlauwe et al., 2001a; Gentile et al., 2009), there has been little uptake by farmers. In Zimbabwe, for instance, smallholder farmers have used between 20-100 kg of mineral N fertilizer and 0-10 t of cattle manure per farm per year (Zingore, 2006; Mtambanengwe and Mapfumo, 2008). The disparities in quantity and quality of the nutrient resources are generally a function of farmer resource endowment (Mapfumo and Mtambanengwe, 2005), suggesting the need to package ISFM options in response to these farmer categories.

Increasingly, there are clear demands for intensification of legume-cereal cropping systems, but still lacking are the technical options for addressing fundamental challenges of poor and diminishing soil fertility. Under current smallholder cropping in Southern Africa, nutrients are often applied to maize, with legumes only benefiting from residual fertility in a rotation (Waddington and Karigwindi, 2001). However, there is evidence of better crop yields when P containing basal fertilizers are applied to the legume crop (Chikowo et al., 1999; Kanonge et al., 2009). These findings show a need for medium to long-term studies to assess how different combinations of ISFM technology components can be sequenced across temporal scales to build soil productivity and increase efficiency of resource use.

Smallholder farmers have been shown to cumulatively build soil fertility of specific fields or sections within fields through preferential allocation and loading of nutrients to these croplands (Mtambanengwe and Mapfumo, 2005; Zingore, 2006), and this is often exemplified by fields close to homesteads. However, such fields are usually too small to significantly contribute to aggregate
farm-level crop yields (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2011). Failure to allocate nutrient inputs to the remaining fields has often resulted in farmers abandoning such lands or aggravating degradation processes through mining of soil nutrients. Efforts to address this challenge through alternative technical approaches such as CA have in turn been undermined by poor soil fertility. The short to medium yield benefits of CA have often been too low to attract farmers’ interest and commitment (Tittonell et al., 2012). In order to increase farm-level crop yields and meet demands for household food and income, it is imperative to explore options for building soil fertility over relatively shorter periods compared with current farmer strategies.

In this Chapter, it was hypothesized that systematic sequences of ISFM options cumulatively enhance efficient use of the limited nutrient resources available to farmers, significantly increasing maize and grain legume yields and contributing to calorie and protein production by different categories of households. The study therefore sought to evaluate the influence of sequences of different ISFM options on crop productivity and calorie and protein production, and resource use efficiencies on smallholder farms in Eastern Zimbabwe. Specific objectives were to: (i) determine the effectiveness of different ISFM options as entry points for enhancing crop yields, and the subsequent calorie and protein production, (ii) quantify changes in available P under different ISFM sequences and (iii) assess profitability of different sequences of ISFM options.
6.3 Materials and methods

6.3.1 Prioritizing ISFM options with communities

The study was conducted between 2005 and 2011 in Hwedza District and Chinyika Resettlement Area in Makoni District over four years as part of adaptive ISFM research initiatives by SOFECSA (www.sofecsa.org). The study sites are described in Section 3.1. This study built on SOFECSA’s operational framework designed to promote ISFM technology options that enhance intensity and efficiency of use of mineral and organic fertilizer combinations by different categories of smallholder farming households across agro-ecological zones of Southern Africa (Mapfumo, 2009a). In 2005, FPRA that included key informant interviews, FGDs and community meetings were used to (i) identify soil fertility management practices employed by farmers in maize and legume production, (ii) establish levels of organic and inorganic nutrient inputs applied and (iii) commonly practiced cropping sequences. A major result of the participatory work was the identification of three soil fertility management regimes by farmers of different resource groups (Table 6.1). While there was little diversity in the identified ISFM options, the farmers highlighted that the intensity of use of both organic and inorganic fertilizers was dictated by farmer resource endowment. Different farmer resource groups were therefore envisaged to prefer specific sequencing options.

6.3.2 Rationale for sequencing of ISFM options

Building on findings from the participatory enquiry (Table 6.1) and related studies on soil fertility gradients and nutrient resource allocation on smallholder farms (Mtambanengwe, 2006; Zingore, 2006), five major ISFM options were identified for sequencing. This study advances the sequencing
concept to enhance the value of ISFM in sustainable crop intensification on smallholder farms, drawing on intimate knowledge of farming systems in Southern Africa. Underpinning this concept is the requirement to build soil P through seasonal/annual P additions, coupled to external organic resource inputs to progressively enhance the functioning of microbial processes that drive efficiency of nutrient cycling, including improvement of N$_2$ fixation by legumes (Table 6.2). Different sequences of ISFM options, primarily defined by combined use of organic and inorganic nutrient sources, were premised to have dissimilar effects in ‘kick-starting’ soil biological processes that determine P accumulation and agronomic use efficiency of added nutrient (especially N), and subsequently on crop yields.

In advancing the sequencing concept in this study, N and P fertilization strategies were considered the major drivers for increasing crop productivity on nutrient-depleted granitic sandy soils on smallholder farms in Zimbabwe. Sandy soils in Zimbabwe are known to be inherently deficient in N and P (Grant, 1981; Mashiringwani, 1983) and characterised by low SOM (Mapfumo et al., 2007). Although research has also revealed deficiencies in Ca, Mg and micronutrients such as Zn (Tagwira, 1991; Mapfumo and Mtambanengwe, 2004; Manzeke et al., 2012), significant crop yield responses have mostly been realised following addition of N and P fertilizers (Piha, 1993; Manzeke et al., 2012). With adequate N and P fertilization, the sandy soils have been found to give grain yields of up to 4 t ha$^{-1}$ for maize and 2 t ha$^{-1}$ for soyabean (Piha, 1993; Kasasa et al., 1999).

In this study, amounts of total N and P required to attain the target yields were theoretically derived based on crop uptake requirements (Nijhof, 1987; Piha, 1993; Janssen, 2011). A tonne of maize grain and 1 t of stover remove approximately 20-30 kg N and 3-8 kg P from the soil, while 1 t of soyabean
grain removes 2-4 kg P. Soyabean stover was assumed to remove negligible soil P given that most of it decomposes *in-situ*, as most of the leaves are shed before harvesting is done. The underpinning principle in the sequences was to build soil P to enhance use efficiency of N supplied through organic resources and mineral fertilizers.

Table 6. Integrated soil fertility management (ISFM) regimes selected by smallholder farmers in Hwedza and Makoni, Zimbabwe.

<table>
<thead>
<tr>
<th>Farmer category*</th>
<th>Major attributes*</th>
<th>Selected integrated soil fertility management options</th>
</tr>
</thead>
</table>
| Resource-endowed (RG 1) | - High livestock ownership with >10 cattle and at least 2 oxen  
- Own farming implements e.g. a plough; an ox-drawn cart  
- Relatively high capacity to secure inputs  
- Frequently use hired labour | 1. **Livestock manure x mineral fertilizer on maize**: Cattle manure, inorganic basal P and top dressing N applied to the maize crop  
2. **Soyabean/Groundnut/Cowpea-maize rotations**: Inorganic basal P applied to both legume and maize, and top dressing N applied to the maize crop  
3. **Crotalaria juncea (L.) (Sunnhemp)-maize rotations**: Inorganic basal P applied to both legume and maize, and top dressing N applied to the maize crop |
| Intermediate (RG 2) | - Varying but limited resource ownership  
- Cattle ownership ≥4  
- Limited access to credit  
- No regular pattern for hiring-in or hiring-out labour | 1. **Livestock manure x mineral fertilizer on maize**: Cattle manure, inorganic basal P and top dressing N applied to the maize crop  
2. **Soyabean/Groundnut/Cowpea-maize rotations**: Inorganic basal P applied to both legume and maize, and top dressing N applied to the maize crop |
| Resource-constrained (RG 3) | - Major constraints include lack of farming implements; lack of draught power (0–3 cattle) and lack of cash to buy inputs  
- Generally have limited or no source of remittances  
- Often sell their labour to other two groups  
- Dominated by women, child-headed households and the aged | 1. **Woodland litter x mineral fertilizer on maize**: Woodland litter, inorganic basal P and top dressing N applied to the maize crop  
2. **Groundnut/Cowpea-maize rotations**: Inorganic basal P applied to both legume and maize, and top dressing N applied to the maize crop  
3. **Sunnhemp-maize rotations**: Inorganic basal P applied to both legume and maize, and top dressing N applied to the maize crop |

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* Adapted from Mtambanengwe and Mapfumo (2005)
Table 6.2 Sequencing framework of ISFM options on smallholder farms in Zimbabwe.

<table>
<thead>
<tr>
<th>Sequencing option</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Total N and P added† (kg ha⁻¹)</th>
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</thead>
<tbody>
<tr>
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<td>Maize under sunnhemp biomass (½ P rate +½ N rate)</td>
<td>Maize (¾ P rate + full N rate)</td>
<td>Soyabean (¾ P rate )</td>
<td>318</td>
</tr>
<tr>
<td>‘Fertilizer-start’</td>
<td>Maize + mineral fertilizer</td>
<td>Sunnhemp (½ P rate)</td>
<td>Maize (½ P rate + ½ N rate)</td>
<td>Maize (full fertilizer rates)</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>(full fertilizer rates )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>‘Soya-start’</td>
<td>Soyabean (full P rate)</td>
<td>Maize (¾ P rate + ¾ N rate)</td>
<td>Maize + cattle manure (¾ P rate + full N rate)</td>
<td>Maize (½ P rate + full N rate)</td>
<td>428</td>
</tr>
<tr>
<td>‘Manure-start’</td>
<td>Maize + cattle manure (full fertilizer rates)</td>
<td>Maize (½ P rate + full N rate)</td>
<td>Soyabean (¾ P rate)</td>
<td>Maize (½ P rate + full N rate)</td>
<td>458</td>
</tr>
<tr>
<td>‘Litter-start’</td>
<td>Maize + woodland litter (full fertilizer rates)</td>
<td>Maize (½ P rate + full N rate)</td>
<td>Soyabean (¾ P rate)</td>
<td>Maize (½ P rate + full N rate)</td>
<td>448</td>
</tr>
<tr>
<td>Unfertilized</td>
<td>Unfertilized soyabean</td>
<td>Unfertilized soyabean</td>
<td>Unfertilized soyabean</td>
<td>Unfertilized soyabean</td>
<td>16</td>
</tr>
<tr>
<td>soyabean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unfertilized</td>
<td>Unfertilized maize</td>
<td>Unfertilized maize</td>
<td>Unfertilized maize</td>
<td>Unfertilized maize</td>
<td>0</td>
</tr>
<tr>
<td>maize</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Full P rate for legumes = 26 kg P ha⁻¹; Full mineral fertilizer rates for maize = 26 kg P ha⁻¹ and 120 kg N ha⁻¹;

†Total N and P added as organic nutrient resources and mineral fertilizers. Total N and P in cattle manure and woodland litter were estimated based on Palm et al. (2001). Biomass productivity and N input from sunnhemp and soyabean on sandy soils were estimated according to Nezomba et al. (2008) and Kasasa et al. (1999).

The basis for applying different rates of mineral N and P fertilizer under the sequences was informed by conceptual N and P budgets (Table 6.3).
### Table 6.3 A summary of the conceptual rationale used for applying different rates of mineral N and P fertilizer under the ISFM sequences

<table>
<thead>
<tr>
<th>Sequencing option</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Sunnhemp-start'</td>
<td><em>(Year 1)</em>: Phosphorus-fertilized sunnhemp generates high amounts of organic N and C to stimulate biological activity on nutrient-depleted soils (Nezomba <em>et al</em>., 2008). <em>(Year 2)</em>: The subsequent maize crop benefits from some of the N generated by sunnhemp crop, and recycled P. <em>(Year 3)</em>: The maize crop benefits from residual P, but increased P fertilization is required to support high yields and build soil P stocks. <em>(Year 4)</em>: The soyabean crop require P fertilization to maximize yields while maintaining soil P stocks to benefit a subsequent cereal crop.</td>
</tr>
<tr>
<td>'Fertilizer-start'</td>
<td><em>(Year 1)</em>: Based on uptake requirements, some of the P applied to the maize crop remains in the soil P pool. <em>(Year 2)</em>: The rotational sunnhemp benefits from the residual P to increase biological N&lt;sub&gt;2&lt;/sub&gt;-fixation and biomass productivity. <em>(Year 3)</em>: The maize crop benefits from some of the N generated by the sunnhemp crop, and recycled P. <em>(Year 4)</em>: High P fertilization is required to build soil P and maximize maize yields.</td>
</tr>
<tr>
<td>'Soya-start'</td>
<td><em>(Year 1)</em>: Phosphorus-fertilized soyabean biologically fixes high amounts of N&lt;sub&gt;2&lt;/sub&gt; but most of the N is channelled to grain (Giller, 2001). <em>(Year 2)</em>: The rotational maize crop benefits from the residual P, but require substantial amounts of mineral N fertilizer to maximize yields. <em>(Year 3)</em>: Cattle manure adds P and provides labile C to increase soil biological activity. The cattle manure, however, immobilizes most of the N (Nyamangara <em>et al</em>., 2003) hence the need for substantial amounts of mineral N fertilizer to maximize maize yields. <em>(Year 4)</em>: The maize crop benefits from residual P, and N mineralized from the cattle manure, but high mineral N fertilizer is required to maximize yields.</td>
</tr>
<tr>
<td>'Manure-start'</td>
<td><em>(Year 1)</em>: Cattle manure provides labile C to increase soil biological activity but is a poor source of P and external supply of the nutrient is required. Most of the N in cattle manure is immobilized in the first year of application; hence the need for high amounts of mineral N fertilizer to enhance maize yields. <em>(Year 2)</em>: The maize crop benefits from residual P, and N mineralized from the cattle manure, but substantial mineral N fertilizer is required to attain high yields. <em>(Year 3)</em>: The soyabean crop benefits from residual P. <em>(Year 4)</em>: The maize crop benefits from residual P built over the preceding 3 years, but mineral N fertilizer is still required to maximize yields.</td>
</tr>
<tr>
<td>'Litter-start'</td>
<td><em>(Year 1)</em>: Woodland litter provides labile C to increase soil biological activity. Most of the N in the litter is immobilized in the year of application (Mtambanengwe and Kirchmann, 1995), hence the need for high amounts of mineral N fertilizer to maximize maize yields. <em>(Year 2)</em>: The maize crop benefits from N mineralized from the litter, but substantial mineral N fertilizer is required to attain high yields. <em>(Year 3)</em>: The soyabean crop benefits from residual P built over the preceding 3 years, but as for cattle manure substantial mineral N fertilizer is still required to maximize yields.</td>
</tr>
</tbody>
</table>

The conceptual rationale used for applying different rates of mineral N and P fertilizer under the ISFM sequences were based on: (i) estimated biomass productivity and quantities of N<sub>2</sub> fixed by soyabean and *Crotalaria juncea* (L.) (sunnhemp) on sandy soils (Kasasa *et al*., 1999; Nezomba *et al*.,
(ii) potential N and P supply from cattle manure and woodland litter (Palm et al., 2001); (iii) native soil N and P supply capacity (Janssen et al., 1990; Chikowo et al., 2010); (iv) estimated erosion and leaching losses from field measurements in Zimbabwe (Elwell and Stocking, 1988; Chikowo et al., 2004a) and (v) N and P removal in grain and stover (Nijhof, 1987; Palm et al., 2001; Janssen, 2011).

6.3.3 Selection of case study farms

Field experimentation sites were selected through FPRA, including community transect walks and key informant interviews. Given that previous studies in similar areas showed consistence between local and laboratory of indicators of soil productivity (Mtambanengwe and Mapfumo, 2005), the selection criteria also drew from farmers' local knowledge of indicators of nutrient-depleted (degraded) soils. In Makoni, experiments were established on three field sites during the 2005/2006 cropping season, while five sites were established in Hwedza in the 2007/2008 cropping season. The sites had similar soil texture, catenary position, slope and history of management, and fell into what farmers classified as least-productive ('poor') fields. All the sites had been under a continuous fertilized maize crop prior to establishment of the experiments. The sites also served as Learning Centres under the SOFECISA research for development initiatives (Mapfumo, 2009b; Mapfumo et al., 2013). Before establishment of experiments, soils (0-20 cm depth) were sampled from each site and analysed for total organic C, total N, available P, pH and texture (Table 3.1) The fields were then mouldboard-ploughed soon after the first effective rains.
In the first year of experimentation, all field sites had seven major treatments (Table 6.2): (i) Maize receiving mineral fertilizer only, (ii) Maize with mineral fertilizer + cattle manure, (iii) Maize with mineral fertilizer + composted woodland litter, (iv) Soyabean with basal P, (v) Sunnhemp with basal P, (vi) Continuous unfertilized maize and (vii) Continuous unfertilized soyabean. Both maize and legumes received basal P fertilizer at 26 kg P ha\(^{-1}\) as PKS blend (0% N: 32% P\(_2\)O\(_5\): 16% K\(_2\)O: 5% S). The maize was top-dressed at 120 kg N ha\(^{-1}\) using ammonium nitrate (34.5% N) applied in 3 splits: 30% at 2 weeks after emergency (WAE); 40% at 6 WAE and the remaining 30% at 9 WAE. In the succeeding seasons, the ISFM treatments were assigned as shown in Table 6.2. Cattle manure and woodland litter were applied at 7 t ha\(^{-1}\) and incorporated into soil. At each experimental field site, just before application during each cropping season, the cattle manure and woodland litter were each sub-sampled for determination of total N, P, Mg, Ca and K (Table 3.1).

Experimental treatments were replicated across farms, with gross plot sizes of 100 m\(^2\). Maize (SC 513) was planted at a population density 37000 plants ha\(^{-1}\). Legumes were planted at a spacing of 0.45 m inter-row and 0.15 m within rows. The experimental plots were kept weed-free through hand hoe weeding. In addition to the experimental field sites, the most ('rich')- and least ('poor')-productive maize fields belonging to host farmers and other households of similar resource endowment were monitored in Hwedza during the 2007/2008, 2008/2009 and 2009/2010 cropping seasons. As opposed to Makoni where smallholder farming only began after 1982 (Mtambanengwe and Mapfumo, 2005), Hwedza has >80 years of smallholder farming and therefore presented a good basis for comparing the performance of the sequences against long-term farmer soil fertility management practices. Data on quantities of nutrients (mineral fertilizers, manure and woodland litter) applied during each cropping season were collected through farm diaries, semi-structured
interviews and direct measurements. Where sub-samples of the organic resource inputs could not be collected for chemical quality determination, estimates were made from the organic resources database (Palm et al., 2001). The quantities of organic nutrients applied per field were given in local units, and these were converted to kg ha⁻¹ using known estimates (Mapfumo and Giller, 2001).

6.3.4 Determining crop productivity and nutritional value

Maize productivity was determined at physiological maturity (20 weeks after planting) from net plots measuring 3.6 m x 5 m. Three within-plot replicates were harvested per treatment and grain yield determined at 12.5% moisture content. The total dry matter yield was quantified after oven-drying of whole plant biomass to constant mass at 60°C. Sub-samples of grain and stover were ground and analyzed for total N and P (Table 3.1). Sunnhemp and soyabean biomass yields were quantified at peak flowering (16 weeks after planting) using a 1m² quadrat. Biomass present within three randomly located quadrats were cut at just above the soil level in each plot. The fresh biomass was initially air-dried under shade before oven-drying to constant weight at 60°C for dry matter determination. Soyabean grain and stover yields were quantified at physiological maturity (approximately 12 weeks after planting) from 3 replicate net plots measuring 1.8 m x 5 m each.

Energy derived from maize and soyabean grain were estimated by converting grain yields into kilocalories (kcal) using the ratios: 1 kg of maize grain = 3840 kcal (USDA, 1984) and 1 kg of soyabean grain = 4460 kcal (FAOSTAT, 2010). The yields were also converted to protein equivalents using protein content estimates of 8 and 40% for maize and soyabean grain, respectively (USDA, 1984; Blackman et al., 1992).
6.3.5 Soil sampling and analyses

After crop harvesting (in June of each season), soils (0-20 cm depth) were sampled from 10 randomly selected points in each plot. The sub-samples from each plot were thoroughly mixed before analysis. The samples were air-dried and passed through a 2 mm sieve, after which they were analysed for total organic C, total N, available P and pH (Table 3.1).

6.3.6 Estimating N and P agronomic efficiencies

In order to assess the cumulative effect of the different fertilization options on nutrient use efficiency under maize in the medium-term (after 4 years), agronomic N and P efficiencies were quantified based on nutrients applied in the fourth year. Preliminary analysis of the first three years data showed no definite patterns (data not shown). The agronomic N and P efficiencies were calculated by subtracting maize grain yield in unfertilized plots (controls) from yields in respective treatment plots, divided by the total amount of nutrient applied, thus

\[ X-\text{AE (kg grain kg X}^{-1}) = \frac{\text{Grain yield (treatment)} - \text{Grain yield (control)}}{\text{X applied}} \]  

Equation 6.1

where X is either N or P

Total N and P applied were calculated as the sum of (i) externally added nutrient in inorganic and organic fertilizers, (ii) in-situ dry season above ground biomass and (iii) root biomass of preceding crops. N and P inputs from externally added organic materials were quantified by multiplying the nutrient concentration by the quantity applied. Above ground biomass (mainly from remnants of crop
residues) from the experimental fields at the start of the cropping season were calculated on the basis that 1.7 t ha\(^{-1}\) biomass remains on field surfaces after dry season grazing by livestock (Mtambanengwe and Mapfumo, 2005). Root biomass of preceding maize and soyabean were estimated using root to shoot ratios of 0.2 (Balesdent and Balabane, 1992) and 0.1 (Sanders and Brown, 1976), respectively. The estimated N and P content in the root biomass were derived from the organic resources database. Senesced roots of annual crops such as maize and soyabean contain 0.8% N and 0.1% P (Palm et al., 2001).

6.3.7 Quantifying profitability of ISFM sequences

Economic profitability under ISFM sequences as well as on farmers' fields was quantified using gross margin analysis (Gittinger, 1984). Economic benefit per year was calculated as the difference between the field value of the output (grain yield) and the field value of inputs (seed, fertilizers and labour). The value of seed and fertilizers were obtained from the nearby district town at time of planting. Estimates of labour costs for land preparation, planting, fertilizer application, weeding and harvesting were collected through farm diaries and semi-structured interviews. The value of maize and soyabean grain were taken as the farm gate price at harvest. Input and output prices were taken as the averages of 2008/2009, 2009/2010 and 2010/2011 cropping seasons. This was because prices for early years of the study (between 2005 and 2007) were difficult to estimate due to hyperinflation in Zimbabwe. The value of cattle manure and woodland litter were estimated as the cost of labour for collecting the manure from kraals or litter from the woodlands and applying them to fields. The unit prices of the inputs and the outputs used in the gross margin analysis are presented on Table 6.4. For each sequence, a net present value (NPV) of yearly gross margins was computed by summing
discounted annual margins (Gittinger, 1984). The NPV is a financial performance indicator, which gives an absolute measure of the present worth of an income stream accruing to farmers (Gittinger, 1984).

Table 6. 4 Input and output prices used in gross margin analyses under different ISFM sequences in Makoni and Hwedza smallholder farming areas in Zimbabwe.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Unit</th>
<th>Cost (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize seed</td>
<td>US$ kg⁻¹</td>
<td>2.20</td>
</tr>
<tr>
<td>Soyabean seed</td>
<td>US$ kg⁻¹</td>
<td>1.63</td>
</tr>
<tr>
<td>Sunnhemp seed</td>
<td>US$ kg⁻¹</td>
<td>0.50</td>
</tr>
<tr>
<td>Ammonium nitrate</td>
<td>US$ kg⁻¹ N</td>
<td>1.75</td>
</tr>
<tr>
<td>PKS</td>
<td>US$ kg⁻¹ P</td>
<td>3.98</td>
</tr>
<tr>
<td>Labour for manure</td>
<td>US$ ha⁻¹</td>
<td>50.00</td>
</tr>
<tr>
<td>Labour for woodland litter</td>
<td>US$ ha⁻¹</td>
<td>55.00</td>
</tr>
<tr>
<td>§Labour for maize</td>
<td>US$ ha⁻¹</td>
<td>240.00</td>
</tr>
<tr>
<td>†Labour for legumes</td>
<td>US$ ha⁻¹</td>
<td>201.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Unit</th>
<th>Cost (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize grain</td>
<td>US$ t⁻¹</td>
<td>260.00</td>
</tr>
<tr>
<td>Soyabean grain</td>
<td>US$ t⁻¹</td>
<td>750.00</td>
</tr>
</tbody>
</table>

§Labour for maize: Land preparation = 4 man-days ha⁻¹, Planting = 10 man-days ha⁻¹, Inorganic fertilizer application = 4 man-days ha⁻¹, Weeding = 38 man-days ha⁻¹, Harvesting = 24 man-days ha⁻¹

†Labour for legumes: Land preparation = 4 man-days ha⁻¹, Planting = 14 man-days ha⁻¹, Inorganic fertilizer application = 1 man-day ha⁻¹, Weeding = 30 man-days ha⁻¹, Harvesting = 18 man-days ha⁻¹

Local daily casual worker rate = US$ 3.00 per day

6.3.8 Data analyses

Analysis of variance (ANOVA) was used to separate effects of different sequencing treatments on crop yields, and subsequent calorie and protein contribution. The statistical analyses was done using GENSTAT 13th Edition. ANOVA was also used to determine treatment differences with respect to N
and P agronomic use efficiencies, available P and gross margins. In years when soyabean was planted in two sequences only, Student $t$-Test was used to separate treatment effects. Mean separation was done using least significant difference (LSD) at $P < 0.05$. Relationships between pre-season available P and maize productivity were tested using linear regressions.

6.4 Results

6.4.1 Initial soil properties, chemical attributes of organic materials and rainfall distribution

Across the sites, the soils had a mean clay content of 9% (Table 6.5). Plant available P and organic C averaged 6 mg kg$^{-1}$ and 0.5%, respectively. However, soil pH was relatively higher in Hwedza (4.8) than in Makoni (4.5). Overall, cattle manure and woodland litter applied across seasons and experimental sites had total N of between 0.6 and 1.0%, while total P ranged from 0.14 to 0.22% (data not shown). Total Mg and K in cattle manure were 0.12% and 0.61%, respectively, while woodland litter contained 0.15% Mg and 0.18% K. Total annual rainfall received during the study period ranged from 648 mm (2007/2008 season) to 977 mm (2005/2006 season) for Makoni and 738 mm (2007/2008 season) to 892 mm (2010/2011 season) for Hwedza (Figure 6.1). The 2007/2008 and 2010/2011 seasons were characterized by poor rainfall distribution.
Table 6. 5 Physical and chemical characteristics of soils at 0-20 cm depth at establishment of experiments in Makoni and Hwedza smallholder farming areas in Zimbabwe

<table>
<thead>
<tr>
<th>Site/Farmer</th>
<th>Clay (%)</th>
<th>Sand (%)</th>
<th>Organic C (g kg(^{-1}))</th>
<th>Available P (mg kg(^{-1}))</th>
<th>pH (0.01M CaCl(_2))</th>
<th>Total N (g kg(^{-1}))</th>
<th>Ca cmol ((+)^{\text{+}}) kg(^{-1})</th>
<th>Mg cmol ((+)^{\text{+}}) kg(^{-1})</th>
<th>K cmol ((+)^{\text{+}}) kg(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Makoni</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mudange</td>
<td>7 (0.2)</td>
<td>89 (0.4)</td>
<td>3 (0.5)</td>
<td>4 (0.4)</td>
<td>4.1 (0.05)</td>
<td>0.2 (0.08)</td>
<td>0.7 (0.01)</td>
<td>0.5 (0.02)</td>
<td>0.2 (0.005)</td>
</tr>
<tr>
<td>Chikodzo</td>
<td>10 (0.6)</td>
<td>86 (1)</td>
<td>5 (0.4)</td>
<td>7 (0.2)</td>
<td>4.5 (0.12)</td>
<td>0.3 (0.02)</td>
<td>1.0 (0.02)</td>
<td>0.8 (0.04)</td>
<td>0.3 (0.004)</td>
</tr>
<tr>
<td>Chimbira</td>
<td>10 (0.4)</td>
<td>75 (0.6)</td>
<td>6 (0.5)</td>
<td>7 (0.6)</td>
<td>4.8 (0.13)</td>
<td>0.6 (0.01)</td>
<td>0.6 (0.03)</td>
<td>0.7 (0.03)</td>
<td>0.1 (0.003)</td>
</tr>
<tr>
<td><strong>Hwedza</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chiutsu</td>
<td>10 (0.1)</td>
<td>82 (0.2)</td>
<td>5 (0.1)</td>
<td>6 (0.5)</td>
<td>4.6 (0.02)</td>
<td>0.3 (0.05)</td>
<td>0.9 (0.03)</td>
<td>0.6 (0.02)</td>
<td>0.2 (0.001)</td>
</tr>
<tr>
<td>Chindove</td>
<td>7 (0.3)</td>
<td>89 (0.4)</td>
<td>4 (0.6)</td>
<td>5 (0.1)</td>
<td>4.9 (0.04)</td>
<td>0.4 (0.03)</td>
<td>0.7 (0.01)</td>
<td>0.3 (0.04)</td>
<td>0.3 (0.002)</td>
</tr>
<tr>
<td>Chiwaveshe</td>
<td>8 (0.2)</td>
<td>87 (0.7)</td>
<td>4 (0.2)</td>
<td>6 (0.2)</td>
<td>4.9 (0.03)</td>
<td>0.4 (0.07)</td>
<td>0.9 (0.02)</td>
<td>0.4 (0.01)</td>
<td>0.3 (0.001)</td>
</tr>
<tr>
<td>Goto</td>
<td>11 (0.4)</td>
<td>79 (0.1)</td>
<td>4 (0.2)</td>
<td>7 (0.3)</td>
<td>5.2 (0.02)</td>
<td>0.3 (0.01)</td>
<td>1.1 (0.04)</td>
<td>0.5 (0.03)</td>
<td>0.2 (0.003)</td>
</tr>
<tr>
<td>Nyakadzumbu</td>
<td>10 (0.1)</td>
<td>81 (0.2)</td>
<td>3 (0.1)</td>
<td>5 (0.3)</td>
<td>4.5 (0.01)</td>
<td>0.2 (0.05)</td>
<td>0.8 (0.02)</td>
<td>0.6 (0.01)</td>
<td>0.1 (0.004)</td>
</tr>
</tbody>
</table>

Figures in parentheses denote standard error of mean (SEM)
Figure 6. 1 Cumulative daily rainfall received in (a) Makoni and (b) Hwedza during the study period

6.4.2 Crop yields and calorie production under different ISFM sequences

In the first year, maize grain yields in Makoni were highest under ‘Manure-start’, which gave 5.5 t ha\(^{-1}\) compared with 0.5 t ha\(^{-1}\) under continuous unfertilized maize. ‘Litter-start’ gave 3.8 t
ha\textsuperscript{-1} while ‘Fertilizer-start’ yielded 3.4 t ha\textsuperscript{-1}. These yields translated into significant ($P < 0.05$) differences in calorie production among the sequences (Figure 6.2a). ‘Manure-start’ produced 20 x 10\textsuperscript{6} kcal; about 1.6 and 11 times more calories than ‘Fertilizer-start’ and continuous unfertilized maize, respectively.

Figure 6. 2 Energy (a and b) and protein (c and d) derived from maize and soyabean grain produced under different ISFM sequences. Error bars represent standard error of the difference of means (SEDs) for comparison of sequencing options.
In the second year, maize grain yields under the sequences ranged from 5.5 t ha\(^{-1}\) under ‘Litter-start’ to 6.6 t ha\(^{-1}\) under ‘Sunnhemp-start’, resulting in an average calorie production of 20 x 10\(^6\) kcal. Due to poor rainfall distribution in the third year, all sequences gave < 8 x 10\(^6\) kcal. In the fourth year, all the sequences gave > 4 t ha\(^{-1}\) of maize grain, with the highest yield attained under ‘Fertilizer-start’ (5.5 t ha\(^{-1}\)). The high maize yield under ‘Fertilizer-start’ translated to a calorie production of 22 x 10\(^6\) kcal; significantly (\(P < 0.05\)) out-performing continuous unfertilized maize by more than 10-fold. Cumulatively over four years, ‘Manure start’ gave 60 x 10\(^6\) kcal compared with < 8 x 10\(^6\) kcal under continuous unfertilized treatments. There were no significant differences in cumulative calorie yields among ‘Litter-start’, ‘Sunnhemp-start’ and ‘Fertilizer-start’ (Figure 6.2a).

In Hwedza, all the sequences produced maize and soyabean grain yields of < 1 t ha\(^{-1}\) in the first year, resulting in calorie yields of no more than 5 x 10\(^6\) kcal per treatment (Figure 6.2b). The low yields were mainly attributed to poor rainfall distribution. In the second year, sequences produced maize grain yields of between 4.1 t ha\(^{-1}\) (‘Litter-start’) and 5.9 t ha\(^{-1}\) (‘Soya-start’). Consequently, most sequences produced > 20 x 10\(^6\) kcal, significantly (\(P < 0.05\)) out-yielding farmers’ poor fields by 400%. Similar to the second year, sequences produced maize grain yields of > 4 t ha\(^{-1}\) in the third year. This translated to most of the sequences producing more calories than under farmers’ fields. Due to poor rainfall distribution in the fourth year, sequences and farmers’ rich fields gave < 1.5 t ha\(^{-1}\) of maize grain, but produced significantly more calories than under unfertilized treatments and farmers’ designated poor fields. ‘Soya-start’ gave the highest cumulative calorie production of 46 x 10\(^6\) kcal, while continuous unfertilized treatments cumulatively yielded < 12 x 10\(^6\) kcal (Figure 6.2b).
6.4.3 Protein production under different ISFM sequences

In Makoni, 'Soya-start' gave the highest protein production of 720 kg in the first year compared with < 300 kg under 'Fertilizer-start', 'Litter-start' and unfertilized treatments (Figure 6.2c). In the second year, 'Sunnhemp-start' gave the most protein (528 kg ha\(^{-1}\)), but was not significantly different from 'Soya-start', 'Manure-start' and 'Litter-start'. Although crop yields were low in the third year due to poor rainfall distribution, 'Manure-start' gave significantly higher protein production than the other sequences. In the fourth year, protein production ranged from 48 kg under continuous unfertilized maize to 560 kg under 'Fertilizer-start'. Over the four-year period, 'Soya-start' and 'Manure-start' gave the best cumulative proteins of > 1600 kg. Unfertilized maize and soyabean gave the lowest cumulative protein yields. In Hwedza (first year), protein yields were < 120 kg across the sequences as a result of low crop yields (Figure 6.2d). In the second year, 'Sunnhemp-start', 'Soya-start' and 'Litter-start' gave an average protein production of 457 kg and was not significantly different from farmers' rich fields. In the third year, 'Manure-start' (560 kg) gave the highest protein yield, significantly out-performing farmers' rich and poor fields by 304 and 480 kg, respectively. Consistent with Makoni, 'Soya-start' and 'Manure-start' cumulatively gave the highest protein production over the four-year period (Figure 6.2d).

6.4.4 Changes in available P and influence on maize productivity

Overall, there were cumulative gains in available P in soils with sequencing of ISFM options (Figure 6.3). The highest increases were attained under ‘Sunnhemp-start’ and ‘Fertilizer-start’, with the former increasing available P from 6 mg kg\(^{-1}\) soil to approximately 10 mg kg\(^{-1}\)
soil over the four-year period. The higher available P under ‘Fertilizer-start’ and ‘Sunnhemp-start’ than the other sequences could have been due to recycling and reduced off-take of P as sunnhemp biomass was incorporated *in-situ*, although further investigations are warranted to explain why the two treatments differ.

Figure 6. Changes in available P at 0-20 cm depth under different ISFM sequences on smallholder farms in Makoni, Zimbabwe. Error bars represent standard error of the difference of means (SEDs).

Under ‘Manure-start’, and ‘Soya-start’, available P increased from 6.5 mg kg⁻¹ soil to 10 mg kg⁻¹ soil. Continuous unfertilized maize consistently gave the least available P. There was a significant positive relationship ($R^2 = 0.75\; P < 0.01$) between pre-season available P and
maize grain yields attained in sequencing in Chinyika (Figure 6.4). At least 3 t ha$^{-1}$ of maize grain was obtained on soils with pre-season available P of > 8 mg kg$^{-1}$ soil.

Figure 6. 4 Relationship between maize yields in the third year and pre-season available P in the 0-20 cm depth under different ISFM sequences in Hwedza smallholder farming area, Zimbabwe

6.4.5 Agronomic N and P efficiencies

In Makoni, ‘Fertilizer-start’ gave the highest agronomic N efficiency (N-AE) of 38 kg grain kg$^{-1}$ N; out-performing ‘Litter-start’ by 41% (Figure 6.5a). Due to poor maize grain yields in Hwedza, N-AEs did not significantly ($P > 0.05$) differ among treatments, with all treatments yielding < 10 kg grain kg$^{-1}$ N. Agronomic P efficiencies (P-AEs) showed a different trend to N-AEs (Figure 6.5b). In Makoni, ‘Soya-start’ gave the highest P-AE of 279 kg grain kg$^{-1}$ P, which was not significantly different from ‘Manure-start’ and ‘Litter-start’. Although P-AEs
in Hwedza were < 80 kg grain kg\textsuperscript{-1} P due to overall poor maize yields, most of the sequences gave better efficiencies than farmers’ designated rich and poor fields.

Figure 6. 5 Agronomic N (a) and P (b) efficiencies in the fourth year of sequencing in Makoni and Hwedza smallholder farming areas, Zimbabwe. Error bars represent standard error of the difference of means (SEDs) for a= Makoni and b= Hwedza
6.4.6 Economic profitability of ISFM sequences

In the first year in Makoni, ‘Soya-start’ and ‘Manure-start’ gave the highest gross margins of over US$ 600 ha\(^{-1}\); more than double returns under ‘Fertilizer-start’ and ‘Litter-start’ (Figure 6.6a). In the second year, ‘Sunn hemp-start’ (US$ 1093 ha\(^{-1}\)) gave the best financial returns.

![Graph showing gross margins (US$ ha\(^{-1}\)) of ISFM sequences over four seasons in (a) Makoni and (b) Hwedza smallholder farming area in Zimbabwe](image)

Figure 6.6 Gross margins (US$ ha\(^{-1}\)) of ISFM sequences over four seasons in (a) Makoni and (b) Hwedza smallholder farming area in Zimbabwe

Gross margins were negative across treatments in the third year due to poor grain yields. With better grain yields in the fourth year, gross margins were positive ranging from US$ 479 ha\(^{-1}\) under ‘Sunn hemp-start’ to US$ 648 ha\(^{-1}\) under ‘Soya-start’. Overall, ‘Soya-start’ and ‘Fertilizer-start’ gave the highest and least NPVs, respectively (Table 6.6).
Table 6.6 Net present values (US$ ha\(^{-1}\)) of ISFM sequences over four seasons in Makoni and Hwedza smallholder farming areas in Zimbabwe

<table>
<thead>
<tr>
<th>Sequencing option</th>
<th>Makoni</th>
<th>Hwedza</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Sunnhemp-start'</td>
<td>1050(a)</td>
<td>929(a)</td>
</tr>
<tr>
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<td>557(b)</td>
<td>268(b)</td>
</tr>
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</tr>
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<td>986(a)</td>
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<td>'Litter-start'</td>
<td>1181(a)</td>
<td>358(b)</td>
</tr>
<tr>
<td>Farmers' 'Rich' field</td>
<td>nd</td>
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</tr>
<tr>
<td>Farmers' 'Poor' field</td>
<td>nd</td>
<td>-72(d)</td>
</tr>
</tbody>
</table>

SED 109 86

Means in the same column followed by the same letter are not significantly different; n/d = not determined; SED – Standard error of the difference of means. Net present values were calculated at a real interest rate of 6%.

In Hwedza, financial returns were negative in the first year as grain yields were low due to drought (Figure 6.6b). In the second year, ‘Soya-start’ (US$ 1015 ha\(^{-1}\)) gave the highest gross margin; 3 and 44 times financial returns under farmers’ rich and poor fields, respectively. In the third year, gross margins under sequences ranged from US$ 308 ha\(^{-1}\) (‘Litter-start’) to US$ 753 ha\(^{-1}\) (‘Fertilizer-start’). The farmers’ poor fields gave US$ 11 ha\(^{-1}\). All the treatments recorded negative gross margins in the fourth year as a result of low grain yields. As was the case in Chinyika, ‘Soya-start’ (US$ 1147 ha\(^{-1}\)) gave the highest NPV while farmers’ rich fields accrued < US$ 300 ha\(^{-1}\). Farmers’ designated poor fields gave a negative NPV (Table 6.6).

6.5 Discussion

Most of the sequences gave higher calorie and protein production than the designated farmers’ rich and poor fields. These results suggest that such ISFM-based sequences can enhance crop
productivity on sandy soils to significantly contribute to energy and protein needs of smallholder farmers. The high crop productivity under the sequences could be explained by repeated P fertilization. Cumulatively over the four-year period, the sequences received between 78 and 93 kg P ha\(^{-1}\), with more than 90% of the P being added through inorganic fertilizer. However, addition of inorganic P fertilizers under smallholder cropping is often minimal, particularly in maize production (Zingore, 2006). Most smallholder farmers apply organic materials solely as basal and use mineral N fertilizer as top-dressing. Yet, most organic materials are known to be poor sources of P (Buresh et al., 1997b). On granitic sandy soils predominating the smallholder farming systems in Southern Africa, N and P are the most limiting nutrients (Nyamapfene, 1991; Hartemink and Huting, 2008).

The inclusion of soyabean under the sequences also contributed to better calorie and protein production than the farmers' designated rich and poor fields, which were predominantly under maize monocropping. Soyabean grain contains more calories and protein than maize grain per unit mass (USDA, 1984; Blackman et al., 1992). While smallholder farmers often grow grain legumes on degraded and small field sections with limited nutrient inputs (Giller and Cadisch, 1995; Mapfumo et al., 2001), their inclusion in fertilized cropping sequences, as shown in this study, could increase yields and significantly contribute to protein needs. This could be particularly important for improving diets of the majority of resource-constrained smallholder farmers who normally face constraints in accessing other sources of protein such as meat. The high calories and proteins produced under ‘Soya-start’ and ‘Manure-start’ were partly because these sequences did not include sunnhemp, a non-food legume, over the four-year period. While ‘Litter start’ had a similar cropping pattern, it gave less calories and proteins than manure-based sequences. This result further confirm the importance of cattle manure in
enhancing productivity of sandy soils through mechanisms such as alleviation of deficiencies in soil bases and moisture conservation (Mugwira et al., 2002; Rusinamhodzi et al., 2013).

Seasonal inorganic P fertilization remains the major options for building P on sandy soils. In this study, available P under the sequences increased by 4 mg kg\(^{-1}\) over the four-year period. While the increase translates to approximately 14 kg P ha\(^{-1}\) in sandy soils with an average dry bulk density of 1700 kg m\(^{3}\), it is a better P-building strategy that repeated application of organic materials only as commonly practised by smallholder farmers. In a study on similar soils in Zimbabwe, 25 t ha\(^{-1}\) of cattle manure repeatedly applied for 9 years was required to increase available P by 7 mg kg\(^{-1}\) (Rusinamhodzi et al., 2013). The high loading of cattle manure presents a major challenge as most smallholder farmers cannot generate sufficient quantities due to low livestock numbers (Mapfumo and Giller, 2001). Given that most smallholder farmers often face challenges in accessing inorganic fertilizers to meet the recommended rates, applying the P fertilizer at alternating rates in systematic cropping sequences, as shown in this study, will not only increase crop yields but also build soil P. While the inherent acidity of sandy soils could lead to fixation of the P on sesquioxides, the P sorption capacity has been found to be low due to the dominance of inactive clays (Buresh et al., 1997b).

The positive relationship between pre-season available P and maize yields suggests that high maize productivity under sequences was largely supported by increased P supply. For example, ‘Fertilizer-start’, which had the highest amounts of pre-season available P, yielded more maize grain than the other sequences in the fourth year. Positive relationships between available P and maize yields have also been reported in other studies (Tittonell et al., 2005; Janssen, 2011). Soyabean grain yields were also higher under sequences compared with
unfertilized controls. Phosphorus is known to limit legume productivity under natural and managed systems (Giller and Cadisch, 1995; Mapfumo, 2011). The high agronomic N and P efficiencies under sequences can as well be attributed to residual effects of P due to repeated seasonal additions (Janssen and Wolf, 1988). Split application of inorganic N fertilizer could also have increased agronomic efficiencies through improved N uptake by maize (Piha, 1993; Vanlauwe et al., 2011).

Smallholder farmers often repeatedly apply high quantities of organic nutrient resources to rich fields (Mtambanengwe and Mapfumo, 2005; Zingore, 2006). Manure application rates of up to 40 t ha\(^{-1}\) have been reported (Mtambanengwe, 2006). Crop yields on the rich fields were, however, lower than under sequences where organic nutrient resources were applied once over the four-year period. These results suggest that there is little crop yield benefit in repeated application of high quantities of organic materials only on the same fields. Co-addition of adequate inorganic fertilizers is required to complement the usually low and organically-bound nutrients supplied through organic materials. Working on coarse sandy soils, Mapfumo et al. (2007) showed that there are no added nutrient benefits in applying organic materials above 10 t ha\(^{-1}\). Besides yielding better calories and proteins than the farmers' fields, overall NPVs over the four years showed that ISFM sequences are more profitable than maize monocropping as commonly practiced by farmers on their rich and poor fields. Working on smallholder farms in Mozambique, Rusinamhodzi et al. (2012) also recorded better financial returns under cereal-legume intercrops compared with maize monocropping. Given the high calorie and protein yields, and financial returns under most of the sequences, farmers could realize better returns to seed, fertilizer and labour through systematic allocation of nutrients to fields.
‘Sunnhemp-start’ and ‘Fertilizer-start’ are potential sequencing options for RG1 farmers. With their good resource base, the RG1 farmers have high capacity to secure inputs on time (Mtambanengwe and Mapfumo, 2005). They are therefore better able to absorb any yield penalty from the inclusion of sunnhemp in the cropping sequences. By employing sunnhemp sequences, farmers do not only increase calorie production in the medium-long term, but also save on mineral N fertilizer. For example, over the four-year period, cumulative mineral N fertilizer added in the ‘Sunnhemp-start’ sequence was 50% lower than under ‘Manure-start’.

‘Soya-start’ and Manure-start’ could best-fit RG1 and RG2 farmers since they require relatively high quantities of manure. Through ‘Soya-start’ and ‘Manure-start’, farmers realize both high calorie and protein production and good financial returns. The high NPVs attained under ‘Soya-start’, despite differences in season quality between study sites, indicate that such sequences can potentially generate income for smallholder farmers even under variable rainfall conditions. In a related study in Zimbabwe, combined application of cattle manure and mineral fertilizers increased profitability of soyabean-maize rotations (Zingore, 2006).

Due to challenges of accessing manure as the majority are non-cattle owners, RG3 farmers can practice the ‘Litter-start’ sequence. ‘Litter-start’ gave comparable cumulative calories and proteins to ‘Sunnhemp-start’ and ‘Fertilizer-start’ in Chinyika, indicating that such sequences can significantly contribute to household food needs of RG3 farmers. Considering that RG3 farmers often fallow some of their fields due to lack of resources to hire labour, they could also practice the ‘Sunnhemp-start’ sequence because of its low mineral N input. However, supporting policies will be required to enhance accessibility of such technologies by the farmer groups. Affordable inorganic fertilizers, ready access to legume seed and farmer training will be key to enable farmers to practice these sequences.
6.6 Conclusions

The different ISFM sequences and crops evaluated in the study can substantially contribute to protein and energy requirements of smallholder farmers while maintaining use efficiency of the often limited nutrient and labour resources. Systematic fertilization of both the legumes and maize was not only key to achieving better crop yields under sequences compared with farmers’ currently designated rich and poor fields, but also resulted in cumulative gains in soil P stocks. Cattle manure-based sequences, (‘Manure-start’ and ‘Soya-start’) produced the highest cumulative calorie and protein yields while sunnhemp-based (‘Sunnhemp-start’ and ‘Fertilizer-start’) sequences attained the highest increase in plant available soil P levels. Based on costs of seed, fertilizers and labour, the ISFM sequences used in this study gave better financial returns than the farmers’ designated rich and poor fields that are predominantly monocropped to maize. Sequencing of ISFM options is therefore a potential entry point for intensification of crop production on smallholder farms in Southern Africa.
CHAPTER 7

Putting ISFM to test under farmer management practices and rainfall variability on smallholder farms

7.1 Abstract

Achieving household food self-sufficiency is a major challenge in smallholder cropping systems of Southern Africa. While ISFM is considered an option for raising crop productivity, overcoming initial constraints to its adoption entails responding to resource endowments of individual households and varying biophysical conditions, including climate variability. The main objective of this study was to evaluate ISFM sequencing options that could enable resource-endowed (RG1), resource-intermediate (RG2) and resource-constrained (RG3) farmers to meet their food needs. The study was conducted in Hwedza smallholder farming area, in Eastern Zimbabwe. First, APSIM, a crop growth model, was used to simulate measured maize and soyabean grain yields from an ISFM-sequences experiment conducted over 4 years on degraded sandy soils. The evaluated ISFM sequences were ‘Fertilizer-start’ and ‘Sunnhemp-start’ [Crotalaria juncea (L.)-based sequences], ‘Litter-start’ (a woodland litter-based sequence), ‘Soya-start’ (a soyabean-based sequence) and ‘Manure-start’ (a cattle manure-based sequence). Secondly, the validated model was used to analyze agronomic and economic risks associated with different sequencing options as influenced by rainfall variability. Thirdly, APSIM and farm characterization data were used to evaluate best-fit ISFM sequences for RG1, RG2 and RG3 farmers. APSIM closely simulated observed maize and soyabean grain yields, expressed in calories equivalents, in three of the four seasons (years) (RMSE = 0.13-0.44; R² = 0.74-0.92). Using 49-year rainfall data (1962-2011), ‘Fertilizer-start’ was the least risk ISFM option with 41 of the 49 years (16% risk) having maize yields greater than the minimum acceptable limit of 1.5 t for household food self-sufficiency for a family of six people. Conversely, ‘Litter-start’ was the most risk option as 35 out of the 49 years (29% risk) had maize grain yields above the minimum acceptable limit. Of the 49 years, the ‘Litter-start’ sequence had 16 years with negative gross margins compared with 9 under ‘Soya-start’. Under RG1 management scenarios, simulated maize yields averaged 3.8 t ha⁻¹ for the early and normal planting windows, with no significant differences (P < 0.05) among ‘Fertilizer-start’, ‘Soya-start’, and ‘Manure-start’. Under management scenarios of RG2 farmers, the sequences gave more than 1.5 t of maize grain, with the highest aggregate yield of 2.4 t ha⁻¹ attained under ‘Soya-start’. Under RG3 management scenarios, simulated maize grain yields reached a maximum of 1.8 t ha⁻¹ at a planting density of 3.0 plants m⁻². At current agronomic management practices, including nutrient use, ISFM sequences can support maize productivity on 1 ha of the available arable croplands to meet households food self-sufficiency requirements for different farmer resource categories, and surplus grain in the case of RG1 and RG2 households. This implies that ISFM provides an opportunity for smallholder farmers to intensity and diversify their cropping systems, which, in turn, can cushion them against climate variability.
7.2 Introduction

Reported benefits of ISFM in SSA have largely been drawn from data generated from short-term field-level experiments on well-managed plots, where agronomic operations are conducted following recommended practices (Bationo et al., 2007b). However, extrapolating the benefits to farm-scale is confronted with various biophysical and socio-economic realities, which influence the performance of the ISFM technologies and therefore farmers' adoption decisions. Studies on farmer typologies revealed differences in access to seed, nutrient inputs, labour and draught power among farmers (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007; Kamanga et al., 2010). In as much as ISFM can increase crop yields (e.g. Nezomba et al., 2015a, b), farmers of different resource endowment would thus require different sets of ISFM options to intensify production. Given the differences in complements of resources at the farmers' disposal, it is also important to determine land areas/muforo that can be cropped per season to produce sufficient grain to meet household food self-sufficiency and possibly generate surplus. This is not only important to ensure efficient utilization of the often limited resources, but also to maximize crop production on small farm sizes given the declining arable land due to population pressure. A muforo is a portion of the field approximately 0.2 ha, which can be ploughed and completed within a session of 3 to 4 hours (Mtambanengwe et al., 2007).

Given the difficulty in drawing recommendations based on short-term data derived from field experiments, options for best-fitting technologies such as ISFM to smallholder farms are best explored through characterization of farming systems and simulation models (Tittonell et al., 2009; Zingore et al., 2009). Farm characterization enables an appraisal of farmer's resource base and
therefore their ability to manage certain technologies, while simulation models provide an opportunity to explore different scenarios and analyze tradeoffs (Waithaka et al., 2006; Rufino et al., 2011). Due to their low capital base and limited livelihood opportunities, smallholder farmers are risk averse (Legesse and Drake, 2005; Tittonell et al., 2009). ISFM involves use of mineral fertilizers and hybrid seed, among other external inputs, and these constitute a significant cost to farmers. Under changing rainfall patterns, the use of these inputs become increasingly risky. However, there is no empirical evidence on the technical feasibility of managing ISFM options in ways that stabilize yields and reduce risk under changing rainfall patterns. Rainfall variability is predicted to negatively affect crop production in Southern Africa (Lobell et al., 2008; IPCC, 2013; Zinyengere et al., 2013). Under such conditions, it is therefore important to assess the risk associated with different ISFM sequences to achieving crop yields that meet both household food requirements and enable positive economic returns to investments in seed, nutrients and labour.

Simulation models that capture interactions among soil processes, nutrient dynamics and climatic conditions in cropping systems are commonly used to assess risk (Whitbread et al., 2010). One of the most widely used simulation models in assessing climate-related risks in cropping systems in SSA is the Agricultural Production Systems Simulator (APSIM) (e.g. Shamudzarira and Robertson, 2002; Chikowo, 2011; Dixit et al., 2011). In most of these studies, APSIM has largely been employed to simulate maize productivity under monocropped systems. The model has not been extensively used to analyze climate-related risk in fertilized maize-legume cropping sequences on sandy soils. The objectives of this Chapter were therefore to (i) assess the capability of APSIM to predict maize and soyabean grain yields under cattle manure/woodland litter-, NPK fertilizer- and legume-based ISFM sequences on degraded sandy soils over a 4-year period, (ii) analyze agronomic
and economic risks associated with different sequencing options as influenced by rainfall variability and (iii) evaluate best-fit ISFM sequences for farmers differing in resource endowment.

7.3 Materials and methods

7.3.1 Summary of the ISFM sequencing experiment

This Chapter builds on earlier work conducted in Hwedza to assess the effects of sequencing different ISFM options, based on organic and mineral fertilizer resources available to smallholder farmers, on maize and soyabean productivity, and build-up of soil P on degraded sandy soils over a 4-year period (Chapter 6; Nezomba et al., 2015a). Degraded croplands in Hwedza (Goto) occupy 40% of the arable lands (Chapter 4). Five sequences were designed drawing on participatory enquiries with farmers regarding ranges of quantities of organic and inorganic fertilizers commonly applied, and cropping sequences. The sequences were based on N and P as the most limiting nutrients on sandy soils (Chapter 6; Nezomba et al., 2015a), and were envisaged to support 4 t ha⁻¹ of maize grain and 2 t ha⁻¹ of soyabean grain by the 4th year. Maize and soyabean grain yields were quantified every season over the four years. To compare maize and soyabean productivity under the different sequences, grain yields were converted to energy (kilocalories) equivalents. In addition, soil samples were collected after every cropping season to assess changes in available P. Drawing on farmer resource endowment and therefore their ability to manage the ISFM sequences, the following sequences were recommended for the different farmer resource groups: ‘Fertilizer-start’, ‘Manure-start’ and ‘Soya-start’ for RG1 farmers, ‘Soya-start’ and ‘Manure-start’ for RG2 farmers, and ‘Litter-start’ and ‘Fertilizer-start’ for RG3 farmers.
7.3.2 APSIM parameterization and validation

Agricultural Production Systems Simulator (APSIM) (version 7.6) was used to simulate maize and soyabean grain yield responses under ISFM sequences involving cattle manure/woodland litter, NPK mineral fertilizers and N\textsubscript{2}-fixing grain and green manure legumes on degraded sandy soils. The APSIM modules used in this study were soil N (SOILN2), soil P (SOILP), soil water (SOILWAT2) and management (Keating et al., 2003). The modules were selected on the basis that the ISFM sequences led to build-up of soil P and enhanced use efficiencies of applied N and P (Chapter 6; Nezomba et al., 2015a). It was envisaged that P build-up under the sequences would lead to increased water use efficiency (Rockström et al., 2009).

The SOILN2 module simulates soil C and N transformations, including organic matter decomposition, and immobilization, mineralization, nitrification and denitrification of N. In the SOILN2 module, organic matter is divided into 3 pools: freshly added organic matter (FOM), the labile fraction, including microbial biomass (BIOM) and the more stable organic matter (HUM). The C:N of the pools are considered constant, and decomposition rates in the BIOM and HUM pools are assumed to decrease with soil depth. SOILP simulates soil P dynamics, including mineralization-immobilization patterns as determined by C:P ratios. Availability of soil P for crop uptake is determined by the size of the labile pool and sorption characteristics of the soil. To parameterize the SOILN2 and SOILP modules, pits of 120 cm depth were dug adjacent to each of the 5 experimental field sites in Hwedza in the fourth cropping season (Chapter 6) and soil samples collected at 0-10, 10-20, 20-41, 41-68, 68-94 and 94-120 cm depth. The soils were analyzed for NH\textsubscript{4}\textsuperscript{+}-N, NO\textsubscript{3}\textsuperscript{-}-N, labile P,
pH and organic C (Table 3.1). Phosphorus sorption values were obtained from a previous study on similar soils (Shamudzarira and Robertson, 2002).

The SOILWAT2 module simulates soil water balance based on the cascading layer concept. Inputs to the SOILWAT2 module are soil water lower limit ($LL_{15}$), drained upper limit ($DUL$), saturated volumetric water content (SAT), bulk density, and first ($U$) and second ($CONA$) stage soil evaporation for each soil layer. In this study, $U$ and $CONA$ were set at 6.0 mm day$^{-1}$ and 3 mm day$^{-1}$, respectively (Chikowo, 2011). Bulk density was measured from pits dug adjacent to the experimental field sites (Table 3.1). $LL_{15}$ and $DUL$ were estimated on the basis of soil bulk density using pedo-transfer functions as described by Chikowo (2011). $SWCON$, a coefficient that specifies the proportion of the water in excess of field capacity that drains to the next soil layer in one day, was set at 0.7 (Chikowo, 2011). Due to high infiltration rates on sandy soils, bare soil runoff curve number ($CN$) was set at 50 (Hussein, 1987). The soil properties are presented in Table 7.1.

Other data required in APSIM are daily rainfall, maximum and minimum daily temperatures, and solar radiation. Daily rainfall was obtained from rain gauge measurements on farmers' fields (Chapter 6; Nezomba et al., 2015a), while temperature and solar radiation data were obtained from Hwedza's Meteorological Services station (approximately 30 km from the study site). A medium maturing maize cultivar (SC 501) and a short-medium soyabean cultivar (Magoye), both already parameterized in APSIM, were used to run the simulations. The maize cultivar (SC 501) was used on the basis that it has similar phenological characteristics with SC 513 (Rurinda, 2014) that was used in the experiment, while the same soyabean cultivar was used during experimentation.
Table 7.1 Soil physical and chemical properties used in APSIM simulations

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<tr>
<th>Soil depth (m)</th>
<th>Db (kg m⁻³)</th>
<th>OC (%)</th>
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<th>DUL (m³ m⁻³)</th>
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<td>1.0</td>
<td>200</td>
<td>5.5</td>
</tr>
<tr>
<td>0.94-1.20</td>
<td>1780</td>
<td>0.05</td>
<td>0.08</td>
<td>0.22</td>
<td>0.35</td>
<td>1.5</td>
<td>1.4</td>
<td>1.0</td>
<td>250</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Db = bulk density; OC = organic carbon; LL = Lower limit (volumetric water content at -15 bar pressure potential); DUL = drained upper limit; SAT = Saturation volumetric water content.
In the simulations, maize and soyabean were planted at population densities of 3.7 plants m$^{-2}$ and 14.4 plants m$^{-2}$, respectively, following 25 mm of rainfall in 3 successive rain days. Planting dates and fertilizer inputs (organic and inorganic) were as described by Nezomba et al., 2015a. During simulations, maize surface residue was set at 0 kg ha$^{-1}$ to mimic removal through dry season livestock grazing (Mtambanengwe and Mapfumo, 2005). Cattle manure, woodland litter and sunnhemp biomass were termed ‘manure’ in the simulations, but with different C:N and C:P ratios based on measured values in the experiment (Chapter 6; Nezomba et al., 2015a). The soil and water variables were not reset during simulations to allow the model to capture residual effects (Shamudzarira and Robertson, 2002).

The simulated maize and soyabean grain yields were converted to kilocalories (Chapter 6: Section 6.3.4) and compared with observed data. Root mean square error (RMSE) was used to assess model predictive performance (Willmott et al., 1985):

$$\text{RMSE} = \left[ \frac{1}{n} \sum (x_i - y_i)^2 \right]^{0.5}$$

Equation 7.1

Where: $x_i$ is the predicted yield; $y_i$ is the observed yield,

and $n$ is the number of observations.

If a model is simulating the observed data accurately, the RMSE should be as close to zero as possible (Willmott et al., 1985).

7.3.3 Assessing agronomic and economic risk of different ISFM sequences under a changing climate

To assess climate risk under the ISFM sequences, the validated model was configured to simulate maize grain yields using 49-year daily rainfall and temperature data (between 1962 and 2011) for
Hwedza. The risk was assessed for maize yields in the fourth year only. The underlying rationale was to evaluate the robustness of each sequencing option to support high maize yields under variable rainfall and temperature once the soil has been rehabilitated. Risk was assessed based on a minimum acceptable maize grain yield limit of 1.5 t year\(^{-1}\) to meet household food self-sufficiency for a family of 6 people (FAO, 2009b). An additional 1 t was considered for distress sales and strategic grain storage (Fonte, 2002; Kamanga \textit{et al.}, 2010; Rurinda \textit{et al.}, 2013). A sequencing option was therefore considered to be most risk if it had the highest number of years (seasons) with maize grain yields below the minimum acceptable production limit. Economic risk was determined by calculating a net present value (NPV) of the yearly gross margins under each sequencing option over the 49-year period (Gittinger, 1984). A sequencing option was considered to be most risk if it had the highest number of years (seasons) with negative gross margins, and the lowest NPV. The gross margins were calculated as the difference between the economic value of the maize grain and the cost of inputs (fertilizers, seed and labour) as described in Nezomba \textit{et al.}, 2015a. Input and output prices used in the determination of gross margins were adapted from Nezomba \textit{et al.}, 2015a, and assumed to be fixed over the over the 49-year period.

7.3.4 Characterization of farms

In order to explore how the recommended ISFM sequences could be best-fitted into current soil fertility and agronomic management practices employed by different categories of farmers, 9 farmers were selected for detailed characterization of their farms between 2009 and 2012. The farmers were selected based on a typology developed in similar smallholder farming areas in Zimbabwe (Mtambanengwe and Mapfumo, 2005). The 9 farmers comprised 3 farmers from each of the three identified resource groups: RG1, RG2 and RG3. Selection of 3 households per resource group was
meant to acquire detailed information as also supported by Zingore et al. (2009). Data on livestock ownership, household demographics, draught power ownership and physical assets were gathered before each cropping season using a semi-structured questionnaire. Following the resource flow mapping procedure of Defoer et al. (2000), each farmer also drew a map of their farm indicating location of homestead, location of fields (cultivated and fallowed), and crops and nutrients allocated to each field during the 2009/2010, 2010/2011 and 2011/2012 cropping seasons. In addition, each farmer was provided with a diary to record quantities of seed, organic nutrient resources (manure, woodland litter), NPK mineral fertilizers (basal and top dressing) and grain (maize and legumes) harvested per field. Where quantities were given in local units, they were converted to standards units using commonly known estimates for the areas (e.g. Zingore et al., 2007). Field sizes were determined by taking coordinates at the centre and boundaries of each field using a Global Positioning System (GPS) device (Garmin eTrex 10 model), and the area calculated in ArcView GIS (version 10.3). Labour (man days) used for land preparation, incorporation of organics, planting, weeding, fertilizer application and harvesting was also collected using the diaries. Each household was visited at the end of each month within a cropping season to monitor the diaries.

7.3.5 Farmer management scenarios tested using APSIM

Soil fertility and general agronomic management practices that could be employed under the recommended ISFM sequences were discussed with the farmers and extension at the start of the 2010/2011 cropping season. The scenarios were built on the basis of maize productivity at farm scale against labour, seed, nutrients and draught power availability (Table 7.2).
Table 7. 2 Nutrient inputs and agronomic management options evaluated using APSIM under ISFM sequences for different farmer resource groups

<table>
<thead>
<tr>
<th>Nutrient input/agronomic management options</th>
<th>Resource-endowed</th>
<th>Resource-intermediate</th>
<th>Resource-constrained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral P fertilizer farm$^{-1}$</td>
<td>17 kg farm$^{-1}$</td>
<td>9 kg farm$^{-1}$</td>
<td>4 kg farm$^{-1}$</td>
</tr>
<tr>
<td>Mineral N fertilizer (topdressing) farm$^{-1}$</td>
<td>97 kg farm$^{-1}$</td>
<td>41 kg farm$^{-1}$</td>
<td>26 kg farm$^{-1}$</td>
</tr>
<tr>
<td>Cattle manure farm$^{-1}$</td>
<td>9.5 t farm$^{-1}$</td>
<td>4.5 t farm$^{-1}$</td>
<td>1.7 t farm$^{-1}$</td>
</tr>
<tr>
<td>Time of planting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Normal (26 Nov-15 Dec)</td>
<td>2. Normal</td>
<td>2. Late</td>
<td></td>
</tr>
<tr>
<td>3. Late (after 15 Dec)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize planting density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. 3.7 plants m$^{-2}$</td>
<td>1. 3.0 plants m$^{-2}$</td>
<td>1. 3.0 plants m$^{-2}$</td>
<td></td>
</tr>
<tr>
<td>2. 4.4 plants m$^{-2}$</td>
<td>2. 3.7 plants m$^{-2}$</td>
<td>2. 2.0 plants m$^{-2}$</td>
<td></td>
</tr>
<tr>
<td>Weed density</td>
<td>Weed-free</td>
<td>20 plants m$^{-2}$</td>
<td>24 plants m$^{-2}$</td>
</tr>
</tbody>
</table>
The target farm-level maize grain production was set at 1.5 t year\(^{-1}\) as previously described. Farmers in RG1 were considered to plant during the early (25 Oct-25 Nov) and normal (26 Nov-15 Dec) planting windows because of ready access to draught power, high capacity to timely secure seed and fertilizers, and the ability to hire labour (Mtambanengwe and Mapfumo, 2005; Rurinda et al., 2013). Farmers in RG2 were considered to plant during the normal and late (after 15 Dec) windows because of fewer draught animals than RG1. Farmers in RG3 were considered to plant late due to lack of own draught power, limited cash to buy seed and fertilizers on time, and labour bottlenecks as they often work for the wealthier farmers (Shumba et al., 1992; Mtambanengwe and Mapfumo, 2005; Rurinda et al., 2013). The planting windows were defined based on previous studies in similar areas in Zimbabwe (Mtambanengwe et al., 2012; Rurinda et al., 2013). Farmers in RG1 were considered to attain the recommended maize population density of between 3.7 and 4.4 plants m\(^{-2}\) (Agronomy Institute, 2002), while farmers in RG3 were assumed to plant their maize at lower population densities due to challenges in accessing adequate seed (Waddington et al., 1991; Ellis-Jones and Mudhara, 1995).

Because of their high capacity to purchase pre-emergence herbicides and or hire labour for timely weeding (Mtambanengwe and Mapfumo, 2005), farmers in RG1 were considered 'weed-free' throughout the season. Conversely, farmers in RG3 were assumed to have high weed infestation in their maize fields because they usually do not have time to carry-out their own weeding, but instead sell their labour to the wealthier farmers (Tittonell et al., 2007). As such, in APSIM, the maize crop under RG3 was intercropped with an annual grass weed sown 5 weeks after planting of the maize at a weed density of 24 plants m\(^{-2}\) (Chikowo et al., 2008; Dixit et al., 2011). Due to their intermediate, but limited resource base (Mtambanengwe and Mapfumo, 2005; Rurinda et al., 2014), RG2 farmers were
assumed to encounter less weed pressure than the RG3, and thus the maize was intercropped with the annual grass weed at 20 plants m$^{-2}$ (Chikowo, 2011). The weed densities were verified with the respective farmer RGs during the 2011/2012 cropping season (Chapter 4-Section 4.3.4), and fall within reported values in smallholder farming areas of Zimbabwe (Mashingaidze, 2004). The 'C4 summer weed' option in APSIM was used in the simulation. Using the validated model, maize yields under the different management scenarios were then simulated using long-term rainfall and temperature data as described earlier. The seasonal (yearly) maize yields were averaged to obtain an aggregate value for each sequence.

Differences in simulated maize yields among the management scenarios were assessed through ANOVA, and the resultant means separated using least significant difference (LSD) at $P < 0.05$. The ISFM sequences were evaluated for maize yields after the fourth year to assess how farmer management practices would influence the performance of the sequencing options once the soil has been rehabilitated.

7.4 Results

7.4.1 Comparison of observed versus predicted calorie production

In the first year (2007/2008 season), APSIM closely simulated observed maize and soyabean grain yields, and thus subsequent calories ($\text{RMSE} = 0.13$; $R^2 = 0.92$), particularly under 'Litter-start', continuous unfertilized maize and continuous unfertilized soyabean (Figure 7.1a).
Figure 7. Observed and predicted energy derived from maize and soyabean grain produced under different ISFM sequences in Hwedza smallholder farming area over a 4-year period. Error bars represent standard error of mean (SEM). RMSE = root mean square error.

In the second year (2008/2009 season), the model, however, under-predicted calorie production, by almost half, for most of the treatments (RMSE = 2.66; \( R^2 = 0.52 \)) (Figure 7.1b). The measured crop yields in the 2008/2009 cropping season were uncharacteristically high, a reflection of a season that was typified by evenly distributed rainfall, which minimized moisture stress on the crops and enabled timely application of top-dressing N fertilizer. In the third year (2009/2010 season), the simulated
calories were within reasonable range of the measured values (RMSE = 0.44; $R^2 = 0.88$) (Figure 7.1c). Similarly, in the fourth year (2010/2011 season), APSIM predicted well calories produced under most of the ISFM sequences (RMSE = 0.21; $R^2 = 0.74$), with the exception of an over-prediction under 'Fertilizer-start' (Figure 7.1d).

7.4.2 Simulated agronomic and economic risk of different ISFM sequences as influenced by seasonal rainfall and temperature variability

‘Fertilizer-start’ was the least risk ISFM option as 41 of the 49 years (16% risk) had maize yields above the minimum acceptable limit of 1.5 t (Figure 7.2). On the other hand, ‘Litter-start’ was the most risk ISFM option as 35 out of the 49 years (29% risk) had maize grain yields above the minimum acceptable limit. ‘Manure-start’ and ‘Soya-start’ were 1.5 and 1.6 times, respectively, less risky than ‘Litter-start’.

Of the 49 years, the number of years with at least 2.5 t of maize grain were 5, 13, 13 and 23 for ‘Litter-start’, ‘Manure-start’, ‘Fertilizer-start’ and ‘Soya-start’, respectively. ‘Litter-start’ had the highest number of years with negative gross margins (16) while ‘Soya-start’ had the least (9) (Figure 7.3). Consistently, over the 49-year period, the highest net income (NPV) was attained by practicing the ‘Soya-start’ sequence (US$ 2852 ha$^{-1}$) compared with ‘Manure-start’ (US$ 1861 ha$^{-1}$), ‘Fertilizer-start’ (US$ 1279 ha$^{-1}$) and ‘Litter-start’ (US$ 911 ha$^{-1}$).
Figure 7. 2 Simulated agronomic risk under different ISFM sequencing options as influenced by rainfall and temperature over a 49-year period. The dotted line indicates the minimum acceptable maize grain yield limit of 1.5 t to meet household food self-sufficiency
Figure 7.3 Predicted gross margins and net present values (NPVs) under different ISFM sequencing options as influenced by rainfall and temperature over a 49-year period (1962-2011).

7.4.3 Crop management practices by households differing in resource endowment

Across the resource groups (RGs), household size averaged six, with approximately 50% of the household members providing agricultural labour (Table 7.3). Farmers in RG1 had a mean farm size of 3.2 ha; approximately 1.1 times larger than for farmers in RG3. Farmers in RG1 had up to 66% of the cultivated area under maize production compared with 46% for farmers in RG3. Area allocated to grain legumes was less than 0.3 ha across the RGs. Farmers in RG3 had the largest arable land under fallow (1.2 ha), with their RG1 and RG2 counterparts fallowing less than 0.6 ha.
Table 7. Attributes of farms (n= 3 for each resource group) surveyed in Hwedza smallholder farming area. Values are averages for 2009/2010, 2010/2011 and 2011/2012 cropping seasons.

<table>
<thead>
<tr>
<th>Farm characteristics</th>
<th>Resource-endowed</th>
<th>Resource-intermediate</th>
<th>Resource-constrained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household size</td>
<td>6 (4-8)</td>
<td>6 (3-9)</td>
<td>5 (4-7)</td>
</tr>
<tr>
<td>Members providing agricultural labour</td>
<td>3 (1-5)</td>
<td>2 (1-4)</td>
<td>2 (1-3)</td>
</tr>
<tr>
<td>Farm size (ha)</td>
<td>3.2</td>
<td>3.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Cultivated area under maize (ha)</td>
<td>2.1 (1.8-3.0)</td>
<td>2.0 (1.6-2.8)</td>
<td>1.3 (0.7-1.6)</td>
</tr>
<tr>
<td>Cultivated area under grain legumes (ha)</td>
<td>0.3 (0.2-0.5)</td>
<td>0.2 (0.1-0.4)</td>
<td>0.1 (0.05-0.11)</td>
</tr>
<tr>
<td>Fallowed land (ha)</td>
<td>0.4 (0.3-0.7)</td>
<td>0.6 (0.4-1.0)</td>
<td>1.2 (0.6-1.4)</td>
</tr>
<tr>
<td>Number cattle owned</td>
<td>11 (7-16)</td>
<td>6 (5-9)</td>
<td>2 (0-3)</td>
</tr>
<tr>
<td>Number goats owned</td>
<td>7 (5-9)</td>
<td>4 (2-6)</td>
<td>2 (0-4)</td>
</tr>
<tr>
<td>Draught power (pair of oxen)</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

**Nutrient and seed inputs**

- Mineral P basal fertilizer (kg/farm) 17 (11-24) 9 (7-13) 4 (1-6)
- Mineral N top-dressing fertilizer (kg/farm) 97 (86-132) 41 (38-59) 26 (0-52)
- Manure applied (t/farm) 9.5 (8.0-14.5) 4.5 (2.0-5.6) 1.7 (0.4-2.6)
- Woodland litter applied (kg/farm) 2.5 (1.4-2.9) 0.6 (0.4-1.1) 0.4 (0.1-0.5)
- Hybrid maize seed (kg/farm) 65 (35-75) 45 (25-55) 15 (8-20)
- Hybrid grain legume seed (kg/farm) 10 (5-15) 5 (2-10) 0
- Retained grain legume seed (kg/farm) 25 (10-30) 15 (5-20) 5 (1-10)

**Crop yields**

- Maize grain (t/farm) 2.2 (1.5-3.1) 1.4 (0.9-2.8) 0.6 (0.2-0.8)
- Cowpea grain (t/farm) 0.1 (0.04-0.3) 0.04 (0.01-0.06) 0.04 (0.01-0.06)
- Groundnut grain (t/farm) 0.2 (0.04-0.3) 0.1 (0.03-0.2) 0.1 (0.02-0.3)
- Soyabean grain (t/farm) 0.1 (0.04-0.2) 0.05 (0.01-0.06) 0.05 (0.01-0.05)

---

1Basal mineral was applied as Compound D (7% N, 16% P₂O₅; 7% K₂O); †Mineral N top-dressing was applied as Ammonium nitrate (34.5% N). Compound D and ammonium nitrate are the commonly used mineral fertilizers in maize production in Zimbabwe. Figures in brackets are ranges.
Mineral basal P applied by the farmers ranged from 4 (RG3) to 17 kg farm\(^{-1}\) (RG1), while amounts of cattle manure used were 9.5, 4.5 and 1.7 t farm\(^{-1}\) for farmers in RG1, RG2 and RG3, respectively. Farmers in RG1 used 65 kg farm\(^{-1}\) of hybrid maize seed compared with 15 kg farm\(^{-1}\) by RG3 farmers. However, all the RGs planted mostly retained grain legume seed. Aggregate farm-level maize production ranged from 0.6 t farm\(^{-1}\) for farmers in RG3 to 2.2 t farm\(^{-1}\) for farmers in RG1. Grain legumes harvested per farm did not exceed 0.2 t across the RGs, and for all the legume types.

7.4.4 Predicted maize productivity under farmer management of ISFM sequencing options

Under RG1 management scenarios, all the sequencing options (‘Fertilizer-start’, ‘Manure-start’ and ‘Soya-start’) gave more than 1.5 t ha\(^{-1}\) of maize grain irrespective of planting window and maize planting density (Figure 7.4a). Simulated maize yields averaged 3.8 and 3.7 t ha\(^{-1}\) for the early and normal planting windows, respectively, with no significant differences (\(P < 0.05\)) among sequences, and between planting times. Increasing maize population density from 3.7 to 4.4 plants m\(^{-2}\) did not translate to significant increases in maize grain yields for both the early and normal planting windows. As was the case for RG1 farms, sequencing options under RG2 farms yielded more than 1.5 t ha\(^{-1}\) of maize grain across all the management scenarios, with aggregate yields of 2.3 t ha\(^{-1}\) for ‘Manure-start’ and 2.4 t ha\(^{-1}\) for ‘Soya-start’ (Figure 7.4b). However, maize planted during the late window gave significantly lower grain yields than the normal-planted crop at both 3.0 and 3.7 plants m\(^{-2}\). There were no significant differences in maize yields between ‘Manure-start’ and ‘Soya-start’ at both 3.0 and 3.7 plants m\(^{-2}\). Under RG3 management at 3.0 plants m\(^{-2}\), simulated maize grain yields were above 1.5 t ha\(^{-1}\) for both ‘Fertilizer-start’ (1.8 t ha\(^{-1}\)) and ‘Litter-start’ (1.7 t ha\(^{-1}\)). However, the
two sequencing options yielded below 1.5 t ha$^{-1}$ when maize planting density was reduced to 2.0 plants m$^{-2}$.

Figure 7. 4 Predicted mean maize yields in ISFM sequences under perceived farmer management scenarios. Error bars represent SEDs for a = ISFM sequencing option, b = time of planting and c = maize planting density.
7.5 Discussion

Over a 49-year period (1962-2011) in Hwedza, all the ISFM sequencing options had seasons with maize grain yields below 1.5 t ha\(^{-1}\) due to poor seasonal rainfall distribution. Conversely, more than 4 t ha\(^{-1}\) was measured under the same sequences during a good rainfall season in Makoni district in Zimbabwe (Nezomba et al., 2015a). This implies that, even with improved soil fertility management practices, seasonal rainfall variability remains a major risk to crop production under rain-fed farming systems (Lobell et al., 2008; Rurinda, 2014). Nevertheless, the low maize yields attained under the ISFM sequences during poor rainfall seasons are likely to be better than on most farmers’ fields where maize is often monocropped, with addition of mineral fertilizer only. Combined application of organic nutrient resources and mineral fertilizers, as was the case under the ISFM sequences over a 4-year period (Nezomba et al., 2015a), improves soil moisture retention leading to better crop yield benefits in drought years than where mineral fertilizer only is applied (Vanlauwe et al., 2001a).

The ability by the ‘Fertilizer-start’ sequence to support maize yields above 1.5 t ha\(^{-1}\) for the highest number of seasons could be linked to high levels of soil P, which, in turn, increased use efficiency of water and other nutrients such as N (Cooper et al., 1987; Rockström et al., 2009; Chikowo et al., 2010). Earlier work on ISFM sequences showed that soils under ‘Fertilizer-start’ had the highest available P by the fourth season, and maize yields positively correlated well with the soil P (Nezomba et al., 2015a). Among the sequencing options, RG3 farmers are most likely to employ ‘Litter-start’-related soil fertility management practices as the majority are non-cattle owners (Mtambanengwe and Mapfumo, 2005). However, the high agronomic risk under ‘Litter-start’ indicates that RG3 farmers are most vulnerable to crop failure and thus household food insecurity under changing seasonal
rainfall patterns. The vulnerability is further compounded by the low probability of producing surplus maize grain under ‘Litter-start’, which could otherwise be used to cater for household food needs during poor rainfall seasons. ‘Soya-start’ had the highest number of seasons with at least 2.5 t of maize grain indicating that, with this option, farmers have high chances of producing surplus maize grain for distress sales and strategic storage. Cattle manure-based sequences, ‘Soya-start’ and ‘Manure-start’, had the highest simulated NPVs over the 49-year period confirming findings from the field study (Nezomba et al., 2015a). In related studies, use of combinations of cattle manure and mineral fertilizers in grain legume-cereal rotations also resulted in high financial returns (Zingore et al., 2008b; Rusinamhodzi et al., 2012; Franke et al., 2014). In this study, input and output prices used in the simulations were, however, fixed over the 49 years. The profitability of the soil fertility management options is therefore likely to change in response to fluctuations in input and output prices, and other factors such as discount rate and inflation (Waddington et al., 2007).

Under the RG1 management scenarios, simulated maize yields were no less than 3.5 t ha\(^{-1}\) implying that, at the current level of nutrient use coupled with recommended maize spacing, and effective weed control, the RG1 farmers can potentially produce surplus maize grain on productive croplands. The lack of differences in simulated maize yields among ‘Soya-start’, ‘Manure-start’ and ‘Fertilizer-start’ suggests that the farmers can employ either of the sequencing options and still get similar residual maize grain yield benefits after the fourth year. Simulated yields during the early and normal planting windows were not significantly different confirming earlier findings from a field study in the same area (Rurinda et al., 2013). The wide planting period (15 October to 15 December) is particularly important for smallholder farmers given the increased lateness in on-set of rainfall seasons (Rurinda et al., 2013), and poor health condition of draught animals during the early part of
the season (Francis and Ndhlovu, 1995; Chatikobo et al., 2013). Simulated maize yields were not significantly different at 3.7 and 4.4 plants m\(^{-2}\) across planting times. Conversely, measured maize yields on smallholder farms in Zimbabwe decreased at populations above 3.7 plants m\(^{-2}\) (Fanadzo et al., 2007) suggesting the need to further calibrate the model to increase its sensitivity to high maize planting densities. Mapping of spatial extent of soil degradation on smallholder farms in Hwedza revealed that 42% of the arable land under RG1 farms is degraded (Chapter 4). This implies that of the total average farm size of 3.2 ha measured in this study, approximately 1.9 ha is productive and the remaining 1.3 ha degraded. This scenario suggests that RG1 farmers could systematically apply N and P fertilizers as well as cattle manure in cereal-grain legume rotations (Nezomba et al., 2015a) on the productive croplands alone and obtain farm-level maize yields of more than 3.5 t ha\(^{-1}\) compared with the current yield of 2.2 t farm\(^{-1}\) obtained from the 2.1 ha allocated to maize.

Predicted maize grain yields of up to 2.8 t ha\(^{-1}\) attained under RG2 management suggest such farmers can produce sufficient maize grain to cater for household consumption as well as for storage and distress sales on productive fields. Overall, maize yields were, however, lower for the late than normal planting windows, consistent with field studies (Waddington and Hlatshwayo, 1991; Shumba et al., 1992; Rurinda et al., 2013). The higher simulated maize yields at 3.7 than 3.0 plants m\(^{-2}\) concur with findings by Dixit et al. (2011) using the same model in Kenya. Given that degraded soils on RG2 farms have been estimated to constitute 33% of the arable land (Chapter 4) implies that of the total farm size of 3.1 ha recorded in this study, 1 ha is degraded and 2.1 ha is productive. Thus, with current amounts of nutrients, RG2 farmers could potentially produce 3 t of maize grain on 1 ha of the productive croplands compared with 1.4 t farm\(^{-1}\) currently attained on 2 ha. Considering their limited resource ownership (Mtambanengwe and Mapfumo, 2005), the RG2 farmers could employ such
sequencing options as ‘Soya-start’ and ‘Manure-start’ to produce maize and grain legumes on 1 ha of the productive croplands per season as opposed to spreading the few nutrients and seed resources over larger land areas.

Under RG3 management, simulated maize grain yields reached a maximum of 1.8 t ha\(^{-1}\) indicating that, with 1.7 t cattle manure, 26 kg N and 4 kg P, the farmers can produce adequate maize grain to meet household food requirements on productive soils. Maize grain yields of less than 1.5 t ha\(^{-1}\) attained at 2.0 plants m\(^{-2}\) suggests that, even on productive soils, RG3 farmers could still get low yields as they often use below recommended maize population densities due to lack of sufficient seed, including for re-planting and gap filling (Waddington et al., 1991; Waddington and Hlatshwayo, 1991; Makuvaro et al., 2014). ‘Fertilizer-start’ and ‘Litter-start’ gave similar yields suggesting that farmers can select either option depending on their obtaining biophysical and socio-economic circumstances. Spatially, degraded croplands have been estimated to cover 44% of the arable land on RG3 farms (Chapter 4), implying that of the total farm size of 2.8 ha measured in this study, about 1.6 ha is productive land. The majority of RG3 farmers are non-cattle owners who rely on hired draught power, thus it is highly unlikely that they are able to have the productive fields ploughed in time for planting. Given that a span of two oxen takes approximately 4 days to plough a hectare of land (Francis and Ndlovu, 1995), there is high probability that RG3 farmers can only hire draught power late in the season. Other land preparation methods such as planting basins have not been widely adopted by smallholder farmers due to high labour demands (Giller et al., 2009; Andersson et al., 2011).
Ideally, the RG3 farmers could grow maize on two *miforo* (0.4 ha) and grain legumes on one *muforo* (0.2 ha) of the productive croplands per season. Allocating the few seed, nutrient and labour resources on the two *miforo* could also lead to higher farm-level maize production than the 0.6 t farm⁻¹ currently attained on 1.3 ha. Across the RGs, non-food legumes, such as sunnhemp and N₂-fixing indigenous legumes, could then be used to rehabilitate the degraded croplands (Nezomba *et al.*, 2010; 2015).

### 7.6 Conclusions

Overall, APSIM predicted maize and soyabean grain yields under ISFM sequences suggesting that the model can be employed to simulate crop productivity in the predominantly maize-legume based cropping systems of Southern Africa. However, there is need for further calibration of the model to increase its sensitivity to residual soil fertility-rainfall interactions as well as high maize planting densities. Under long-term rainfall (49 years), all the sequencing options had seasons with maize yields below the recommended 1.5 t for an average household of 6 people, with ‘Fertilizer-start’ and ‘Litter-start’ recording the lowest and highest agronomic risk, respectively. ‘Soya-start’ had the highest number of seasons with at least 2.5 t ha⁻¹ of maize grain yield suggesting the high probability of producing surplus maize grain for distress sales and strategic storage under this option. Financially, ‘Soya-start’ and ‘Manure-start’, were the least risk options under the long-term rainfall. At current agronomic management practices, including nutrient use, ISFM sequences can support maize productivity on existing croplands to meet households food self-sufficiency requirements for different resource categories of smallholder farmers, and surplus grain in the case of RG1 and RG2 households.
CHAPTER 8

Overall discussion, conclusions and recommendations

8.1 Introduction

Soil degradation is a major constraint to crop production in smallholder farming systems of Southern Africa, threatening food and nutritional security as well as income opportunities of households. The situation is aggravated by negative impacts of climate change and variability. Despite concerted research and development efforts to improve crop productivity, the yield gap between actual and attainable yields has remained wide (Tittonell and Giller, 2013). Mineral fertilizer use in the region is low due to accessibility challenges, with most farmers applying less than 10 kg ha\(^{-1}\) (Africa Fertilizer Summit, 2007). This implies that on most smallholder farms crops are largely grown on nutrients supplied from the soil. The rising human population has aggravated matters as natural fallowing, which hitherto was used to restore soil fertility, is no longer feasible due to the high demand for land (Andersson, 1999). As a result, degradation of croplands has continued unabated in most parts of Southern Africa as well as the generality of SSA (Eswaran et al., 2005; Vlek et al., 2008).

In light of the challenge of degradation of croplands in Southern Africa, this study explored how ISFM, underpinned by combined use of available organic resources and mineral fertilizers, and systematic rotations of cereals with N\(_2\)-fixing legumes, could be employed to rehabilitate degraded soils and intensify crop production in smallholder farming areas in
Zimbabwe. The ensuing discussion synthesizes the major findings from the study and their implications in the context of smallholder farming in Zimbabwe and similar agro-ecologies in Southern Africa.

8.2 Can integration of local and empirical knowledge offer opportunities for assessing soil degradation on smallholder farms?

Farming communities have an in-depth understanding of their soil environment in relation to productivity potential and state of degradation (Chapters 4 and 5). Common weeds, soil physical attributes, crop performance and macro-faunal activity are key local indicators of soil productivity on smallholder farms (Chapter 4). In this study, these indicators were used to categorize croplands as productive, moderately productive, degraded and severely degraded (Chapter 4). With the exception of pH, exchangeable K and exchangeable acidity, measured soil bio-chemical properties decreased in the order: productive > moderately productive > degraded > severely degraded — a trend consistent with the farmers' categorization. Furthermore, most of the weed species highlighted by the farmers to be indicative of either productive or degraded soils were consistent with field measurements. Local knowledge of soil productivity, iteratively passed through generations, can thus be packaged to assist farmers to assess land degradation, the majority whom have limited access to laboratory services. However, given differences in agro-ecological regions, the knowledge requires harmonization for wider application to reduce limitations associated with site-specificity.

While this study showed that farmers' local indicators of soil productivity can largely match empirical measurements, there can be inconsistencies among some of the indices (Chapters 4
and 5). For example, results in Chapter 4 revealed that some of the dominant weed species measured on croplands in different productive classes were not highlighted by the farmers to be indicative of soil productivity. Another point of departure was that GIS and remote sensing techniques could not discern soil productivity at field-level. Yet, the fields were in different productivity classes based on both farmers' criteria and laboratory characterization of soils (Chapter 4). The inconsistencies between some of the local and empirical indicators suggest that employing either of the methodologies in isolation could be challenging when assessing soil degradation at local scale. Joint local-empirical methodologies that embrace synergies and complementarities between the two frames are therefore key in developing robust criteria for assessing degradation of croplands on smallholder farms.

8.3 Degraded agricultural lands on smallholder farms in Zimbabwe are not beyond remedy but require investment

Integrated soil fertility management (ISFM) is one option for rehabilitating degraded croplands on smallholder farms (Chapters 5, 6 and 7). Given that the soil rehabilitation options evaluated in this study were largely drawn from commonly practiced soil fertility management regimes by farmers of different resource endowment (Chapters 6 and 7), presents ISFM as a viable pathway for bringing back into production large tracks of degraded croplands on smallholder farms. Central to the rehabilitation is seasonal addition of mineral P fertilizer coupled with external organic resource inputs as well as inclusion of N₂ fixing herbaceous legumes in the cropping sequences. These components enhance functioning of soil biological processes and build-up of soil P leading to better responses of crops to mineral fertilizer addition and increased crop productivity (Chapters 5 and 6). Drawing on the results
from this study, when degraded soils are put under ISFM sequences, a time frame of 3 to 4 cropping seasons is required to raise maize grain yields, from initial levels of less than 0.5 t ha\(^{-1}\), to between 2.5 and 4 t ha\(^{-1}\) by the third and fourth season, respectively (Chapters 5 and 6). Considering that most croplands on smallholder farms are degraded to support any meaningful crop production, it is worthwhile for farmers to invest in the ISFM sequences to raise crop yields to meet household food security needs. With the limited crop production resources on smallholder farms, the strategy would be to start with small land areas and then systematically spread the nutrient resources in space and time until all fields are in a productive state (Chapter 6). It is noteworthy that the rehabilitation trajectory will obviously depend on such factors as the initial extent of degradation of the cropland, rainfall variability and farmer agronomic management techniques, among other factors.

8.3.1 Phosphorus fertilization- a must on degraded croplands

Most smallholder farms in Zimbabwe as well as Southern Africa are located on granite-derived sandy soils inherently deficient in P. Unlike N and exchangeable bases, which can be replenished in these soils, in part, through commonly used organic nutrient resources such as cattle manure, woodland litter and/\ N\(_2\)-fixing legumes, tissue P is low in most of these organic materials. Thus, mineral fertilizers remain the major pathway for significantly adding P to cropping systems. Seasonal additions of mineral P fertilizer under manure/woodland litter- and legume-based ISFM sequences on degraded sandy soils leads to incremental build-up of available P over time (Figure 6.3). Building soil P stocks is integral for sustaining crop productivity on degraded sandy soils as maize grain yields positively correlate well with available P (Figure 6.4).
Phosphorus fertilization should therefore be an important component of soil fertility management strategies designed to rehabilitate degraded sandy soils in Zimbabwe and similar areas in Southern Africa. Currently, most smallholder farmers in Zimbabwe fertilize their crops using organic nutrient resources as basal with mineral fertilizer, mostly N, only being applied when crops require top dressing. Lack of information and knowledge, and high costs of mineral fertilizers in general are some of the major reasons for the low use of P fertilizer on smallholder farms. Thus, training of farmers and building awareness among policy makers on the importance of investing in P fertilizer management in cropping systems as well as subsidising prices of basal fertilizers are paramount to promoting the use of P-based mineral fertilizers on smallholder farms. On the other hand, fertilizer companies could also produce formulations with higher P content than are currently on the market. An example of such a fertilizer is PKS blend (32% P$_2$O$_5$: 16% K$_2$O: 5% S), which was used in this study. PKS was jointly developed by SOFECSA and a local fertilizer company, Windmill Private Limited. Most commonly used compound fertilizers in Zimbabwe such as Compound D (7% N: 14% P$_2$O$_5$: 7% K$_2$O: 5% S) have less than half the P in PKS.

This study focused on P and N mineral fertilizers only as the major inorganic nutrient inputs for rehabilitating degraded sandy soils. Further studies could assess the extent of soil rehabilitation under liming, and balanced fertilization to include base nutrients (Mg, K, Ca), and micronutrients such as zinc and iron. The role of mineral fertilizers in rehabilitating degraded croplands is often not emphasized in other soil fertility technologies for smallholders such as CA (Haggblade and Tembo, 2003; Vanlauwe et al., 2014). However, it has been argued that the crop yield increases under CA are largely due to high fertilizer application rates achieved by concentrating nutrients e.g. in basins and ripper lines similar to
the micro-dosing concept (Twomlow et al., 2010) rather than mulching and minimum soil disturbance effects (Baudron, 2011).

8.3.2 Critical role of medium-high quality organic nutrient resources in the rehabilitation of degraded soils

Rehabilitation of degraded croplands hinges on consistent use of organic nutrient resources with at least 1% N (Chapters 5 and 6) — classified as medium-high quality organic materials according to organic resources databases. Such materials include cattle manure and legume biomass. Alongside mineral N fertilizers, legumes are the second major pathway for net N input in cropping systems through BNF and organic matter addition. Particularly important to this end are non-food herbaceous legumes as the fixed N is not exported in harvested grain. Cattle manure is a commonly used organic nutrient resource on smallholder farms in Southern Africa as it can supply appreciable quantities of N and exchangeable bases to enhance crop growth. A combination of legume biomass and cattle manure leads to stimulation of microbial activity on degraded sandy soils (Tables 5.4 and 5.5; Figure 5.8), and high maize grain yield response to mineral N fertilizer addition (Figure 5.6a-f). The inclusion of non-food herbaceous legumes in ISFM sequences for rehabilitating degraded soils can also enhance recycling of P leading to its build-up in the soil (Chapter 6).

The use of cattle manure in the rehabilitation of degraded croplands in smallholder farming areas in Zimbabwe is likely to be constrained by low livestock numbers, particularly with regards to RG2 and RG3 farmers (Chapter 7). There are limited opportunities for increasing
cattle herds due to the high costs associated with purchasing the cattle, shortage of land, poor quality pastures, and pressures of climate variability and change, among other factors.

Non-food herbaceous legumes have not been widely adopted by farmers because of shortage of seed and lack of direct food benefits. Yet, they remain the only realistic option for generating sufficiently high quality biomass required to 'kick-start' rehabilitation of degraded croplands in Zimbabwe. In the case of introduced herbaceous legumes such as sunnhemp, the problem of shortage of seed could be partly addressed through establishment of community seed banks followed by seed 'pass-on' schemes among farmers with the facilitation of extension and local leadership. As for indigenous legumes, the farmers could be trained by extension and researchers on identification methods to gather the germplasm — similar to initiatives by Mapfumo et al. (2005). Instead of abandoning the degraded croplands to natural fallowing, farmers can plough their fields and broadcast seed of the herbaceous legumes, with no subsequent weeding. The rotational crop yield benefits are better than after natural fallowing or continuously growing maize on the degraded croplands, even with addition of mineral fertilizers (Chapter 5).

8.4 ISFM sequences for intensification of crop production on smallholder farms?

8.4.1 Opportunities

In Southern Africa, crop production on smallholder farms can only increase through intensification as most areas have insufficient land for extensification practices. ISFM sequences of commonly used organic resources, N$_2$-fixing green manure and grain legumes,
and mineral fertilizers are a potential option for intensifying crop production on smallholder farms as they conform to the three pillars of intensification: (i) increasing crop productivity, (ii) improving soil quality and (iii) enhancing use efficiency of external resources (Cassman, 1999; Tittonell and Giller, 2013).

1. Increasing crop productivity: While most smallholder farmers in Southern Africa repeatedly apply large quantities of organic nutrient resources and mineral fertilizers on most-productive fields, crop yields attained on these fields are lower than under ISFM sequences where nutrients are systematically spread across fields in space and time (Chapters 5 and 6).

2. Improving soil quality: Establishment of ISFM sequences on degraded croplands leads to improvement in soil biological activity and build-up of soil P under appropriate fertilization (Chapters 5 and 6).

3. Enhancing use efficiency of external resources: The high crop yields attained under ISFM sequences translate to superior cumulative calorie and protein as well as better economic returns to investment in seed, labour and fertilizers than on farmers’ most-and least-productive fields (Chapter 6).

Poor seasonal rainfall distribution, linked to climate change, is a major factor constraining crop production in the predominantly rain-fed smallholder farming systems of Southern Africa. Nevertheless, crops grown under ISFM sequences can somewhat withstand seasonal fluctuations in rainfall and temperature as they still gave high grain yields when assessed under long-term climate (Chapter 7). Differential access to crop production resources such as seed, labour and draught power can also limit crop productivity on smallholder farmers, negatively impacting on household food self-sufficiency. However, once degraded croplands are rehabilitated through ISFM sequences, farmers can, in the long-term, achieve maize grain
production in the excess of 1.5 t, meeting requirements for household food self-sufficiency (Figure 7.3). ISFM sequences can thus reduce the gap between actual and attainable crop yields on smallholder farms in Zimbabwe by raising crop production per unit area and enhancing other ecosystems services.

Although this study showed that ISFM can intensify crop production on smallholder farms in Zimbabwe, there is need for supporting policies to link farmers to input and output markets. Policies that can promote collective action at farm level and establishment of innovation platforms to enable farmers to interact with agro-service providers could enhance timely access to crop production inputs. Through the same channels, farmers can also access outputs markets to sell their surplus grain. Value addition of maize and legume grain is also key to increase economic returns from crop production, which could enable farmers to diversify their livelihood options. In the wake of increased frequency of droughts in Zimbabwe, which in some cases results in total crop failure, the farmers also require post-harvest management techniques to be able to store surplus grain for longer periods.

8.4.2 Constraints

The high maize grain yields attained under ISFM sequences were undoubtedly due to inclusion of N₂-fixing in the cropping sequences (Chapters 5 and 6). However, adoption of ISFM sequences as a crop intensification option is likely to be constrained by the disproportionate areas currently put under maize and legumes (Chapters 7). Maize is the staple crop in Zimbabwe, and is therefore planted to most of the arable land. The crop is particularly important on smallholder farms where sources of calories are limited. On the other hand, legumes are grown on small land areas, and on residual fertility because they are
less prioritized. Despite calls by the Government for farmers to diversify their cropping systems by allocating at least a third of their land to grain legumes, most farmers continue to consider legumes as minor crops. For example, in this study, cultivated area under maize was up to 2.2 ha compared with less than 0.3 ha under legumes (Table 7.3). The need to fertilize legumes, particularly non-food legumes, lack of farmer access to legume germplasm and lack of output markets present major obstacles for up-scaling legume production on smallholder farms in Zimbabwe.

Under the predominantly rain-fed smallholder cropping systems of Zimbabwe, intensifying crop production on small land areas presents a big risk due to increased rainfall variability (Chapters 5, 6 and 7). In this study, in two of the four seasons in Hwedza, crop yields were low due to poor rainfall distribution despite adequate N and P fertilization, and weeding (Chapter 6). Fear of total crop failure due to drought can partly explain farmers' current practices of growing maize on several fields, and at different times (staggered planting), even if nutrients are sub-optimally applied across the fields.

8.5 Relevance of study to national research and development programmes

Results from this study could be used to inform research and development programmes in Zimbabwe in a number of ways. The ZimAsset policy crafted to direct sustainable development in Zimbabwe between 2013 and 2018, specifies the need to increase crop productivity under the food security and nutrition cluster (Government of Zimbabwe, 2013). The need to raise crop yields in smallholder farming areas to ensure household food security is also emphasized in the Zimbabwe Agricultural Policy Framework. This study showed that
ISFM sequences based on commonly used low-quality organic resources, N₂-fixing green manure and grain legumes, and mineral fertilizers can increase crop yields and rehabilitate degraded croplands dominant in smallholder farming areas of Zimbabwe (Chapters 5 and 6).

Basing on the Crop and Livestock Assessment Report of 2014, communal areas, old resettlement areas and the newly formed A1 farms contributed the majority of maize grain produced in Zimbabwe. Yet, yields in those smallholder farming areas averaged less than 1 t ha⁻¹ (Ministry of Agriculture, Mechanization and Irrigation Development, 2014). As shown in this study, ISFM practices could increase maize productivity on smallholder farms to between 2.5 and 4 t ha⁻¹ depending on the initial state of soil degradation (Chapters 5 and 6). Soyabean grain yields under the ISFM sequences were up to 1.3 t ha⁻¹ (Chapter 6) against less the 0.5 t ha⁻¹ often reported under farmer management. The higher maize and grain legume yields attained under the ISFM sequences could address persistent problems of household food and nutritional insecurity in smallholder farming areas.

Zimbabwe has not been spared by climate change. The most affected are smallholder farmers as they rely on rain-fed agriculture. As a result, the country has formulated a National Climate Response Strategy (Ministry of Environment and Natural Resources Management, 2013). Soil fertility management could be one adaptation strategy for smallholder farmers. By building soil fertility through ISFM, as shown in this study (Chapters 5 and 6), smallholder farmers can maximize crop yields during good rainfall seasons and store the surplus grain for future needs.
8.6 Areas for further research

This study provided empirical evidence that ISFM could be employed to rehabilitate degraded sandy soils as well as intensify crop production on smallholder farms in Zimbabwe, and similar agro-ecologies in Southern Africa. The following knowledge gaps exist:

- Quantifying the extent to which soil degradation is undermining food and nutritional security in smallholder farming systems to inform crop production and health policies in Southern Africa.

- Integration and harmonization of approaches to use of farmers' local indicators of soil degradation from different agro-ecological regions in SSA for wider application to reduce limitations associated with site-specificity.

- Quantifying loss of agro-biodiversity and ecosystem services on degraded croplands at field and farm scales.

- An understanding of the nexus between soil degradation and climate change, and the implications on household food security in smallholder farming systems of SSA.

- Field-and farm-level comparison of ISFM, with other soil rehabilitation and crop intensification technologies such as CA to present farmers with options depending on their biophysical and socioeconomic settings.

- Exploring how non-food herbaceous N$_2$-fixing legumes could be utilized by farmers besides soil fertility purposes (e.g. fodder provision for livestock) to enhance their adoption.


Kanonge, G., Nezomba, H., Chikowo, R., Mtambanengwe, F. and Mapfumo, P. 2009. Assessing the potential benefits of organic and mineral fertilizer combinations on maize and legume


APPENDICES

Appendix 1. Description of soils based on colour and texture and perceived productivity status by farmers in Goto smallholder farming area in Zimbabwe

<table>
<thead>
<tr>
<th>Local soil name</th>
<th>Texture</th>
<th>Colour</th>
<th>Location</th>
<th>Moisture retention</th>
<th>Perceived productivity status at first cultivation</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Shapa</em></td>
<td>Sandy</td>
<td>White coloured deep sandy soils associated with <em>Pilostigma thonningii</em> trees</td>
<td>Variable</td>
<td>Soils easily dry up after a rainfall event</td>
<td>Relatively productive but require frequent addition of nutrients</td>
</tr>
<tr>
<td><em>Rukangarahwe</em></td>
<td>Sandy with high stoniness</td>
<td>White coloured shallow sandy soils associated with <em>Uapaca kirkiana</em> trees</td>
<td>Upper and mid slope positions</td>
<td>Soils easily dry up after a rainfall event</td>
<td>Non-productive</td>
</tr>
<tr>
<td><em>Mhukutu</em></td>
<td>Clayey</td>
<td>Red clays associated with <em>Julbernardia globiflora</em> tress</td>
<td>Variable</td>
<td>Good moisture retention</td>
<td>Highly productive</td>
</tr>
<tr>
<td><em>Chiombwe</em></td>
<td>Clayey</td>
<td>Yellowish clays associated with <em>Syzygium</em> sp. tress</td>
<td>Mid and lower slope positions</td>
<td>Good moisture retention</td>
<td>Non-productive. Suitable for pottery and ceramics</td>
</tr>
</tbody>
</table>
Appendix 2. Causes of soil degradation, reasons for abandoning/fallowing of degraded fields and perceived rehabilitation options (ranked in order of importance) identified by farmers during participatory meetings in Goto smallholder farming area, Zimbabwe

<table>
<thead>
<tr>
<th>Causes of soil degradation</th>
<th>Reasons for abandoning/fallowing of degraded fields</th>
<th>Perceived rehabilitation options</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sub-optimal application of inorganic fertilizers</td>
<td>1. Field give low crop yields year after year</td>
<td>Degraded 1. Apply cattle manure/woodland litter regularly (after every two seasons)</td>
</tr>
<tr>
<td>2. Soil erosion</td>
<td>2. Shortage of inorganic fertilizers</td>
<td>2. Apply top dressing N fertilizer yearly</td>
</tr>
<tr>
<td>4. Poor inherent soil fertility status</td>
<td>4. Field no longer respond to external nutrient inputs</td>
<td>4. Fallowing</td>
</tr>
<tr>
<td>5. Monocropping</td>
<td>5. Shortage of seed</td>
<td>5. Liming</td>
</tr>
</tbody>
</table>

Severely degraded

1. Fallowing
2. Construct soil and water conservation structures
3. Change land use e.g. plant fruit trees instead of cropping
Appendix 3. Normalized difference vegetation index (NDVI) values for Goto ward in (a) January and (b) February 2014. Blue = water bodies; Green = less vigorous vegetation; Orange and red = highly vigorous vegetation.
Appendix 4. Publications from this thesis