Geoderma 239–240 (2015) 143–155

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Point of no return? Rehabilitating degraded soils for increased crop productivity on smallholder farms in eastern Zimbabwe

Hatirarami Nezomba [a,b], Florence Mtambanengwe [a,b], Pablo Tittonell [c], Paul Mapfumo [a,b,*]

[a] *Department of Soil Science and Agricultural Engineering, University of Zimbabwe, P.O. Box MP167, Mount Pleasant, Harare, Zimbabwe*
[b] *Soil Fertility Consortium for Southern Africa (SOFECSA), University of Zimbabwe, P.O. Box MP167, Mount Pleasant, Harare, Zimbabwe*
[c] *Farming Systems Ecology, Wageningen University, P.O. Box 430, 6700AK, Wageningen, The Netherlands*

ARTICLE INFO

Article history:
Received 20 March 2014
Received in revised form 29 September 2014
Accepted 6 October 2014
Available online xxxx

Keywords:
Ethnopedology
Indifallow
Legume-based sequences
P fertilization
Soil biological activity

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 between 2009 and 2012 on smallholder farms in eastern Zimbabwe to explore entry points for rehabilitating degraded croplands using principles of integrated soil fertility management (ISFM) supported through farmers' local knowledge of soils. Participatory research approaches were first used to investigate farmers' understanding of soil degradation and the commonly used local diagnostic indicators. Farmers' determinants of degraded soils centered on crop performance, indicator weed species and soil physical attributes, and matched laboratory parameters. Overall, physical and chemical properties of the degraded soils were significantly lower than reported values for productive sandy soils in Zimbabwe. Evaluated on ten degraded field sites of corresponding catenary positions and similar slope, the main 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. The controls were natural fallow and continuous maize. The treatments were randomly assigned to plots at each of the experimental sites and replicated across farms. Above-ground biomass carbon (C) and nitrogen (N) accumulation was 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 the 2-year natural fallow. When all the treatments 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. A regression 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 following addition of 120 kg ha^{-1} of mineral N fertilizer. 'Green-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 'Green-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 'Green-start' and 'Indifallow-start 1' was 22% higher than under natural fallow-based sequences. Continuous maize treatments gave higher metabolic quotients (qCO_2) than legume-based sequences, indicating a lower microbial efficiency under the former. We concluded that 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-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.

1. Introduction

Degradation of arable soils presents a major challenge for sustainable crop production in smallholder farming systems of sub-Saharan Africa (SSA), including Southern Africa (Muchena et al., 2005; Scherr,

---

* Corresponding author at: Department of Soil Science and Agricultural Engineering, University of Zimbabwe, P.O. Box MP167, Mount Pleasant, Harare, Zimbabwe.
E-mail addresses: pmapfumo@agric.uz.ac.zw, paulmapfumo@gmail.com (P. Mapfumo).

http://dx.doi.org/10.1016/j.geoderma.2014.10.006
0016-7061/

2000). Soil degradation, which could be due to natural or anthropogenic factors, involves negative changes in soil properties and processes, leading to loss of productivity (Lal, 2006). Between 1982 and 2002, 10% of the agricultural land in SSA lost its productivity due to human-induced degradation (Vlek et al., 2008). The major causes of the degradation include inappropriate tillage practices, overgrazing, deforestation, soil nutrient mining, pollution and inadequate soil and water conservation measures (Diagana, 2003; Tittonell and Giller, 2013). In Zimbabwe, approximately 70% of the arable land area is covered by granite-derived sandy soils known for their inherently low nutrient capital and susceptibility to degradation (Nyamapfene, 1991). Consequently, most smallholder farmers crop on these sandy soils, including those resettled on virgin lands through the government's agrarian reform programs between 1980 and 2000 (Andersson, 1999; Chimhowu and Woodhouse, 2008). The conversion of virgin sandy soils to permanent cultivation often leads to an exponential decline in organic matter and other nutrients (Zingore et al., 2005). In most smallholder farming areas, the soils are so rundown that farmers hardly yield more than 1 t ha^{-1} of maize grain (Carr, 2003; Mapfumo and Giller, 2001). Given the growing demands for food and feed production against a changing climate, interventions are critically required to rehabilitate these degraded soils and arrest production practices that are based on extensification. Extensification approaches are no longer feasible in most parts of Southern Africa due to diminishing access to arable land (Andersson, 1999; Meadows and Hoffman, 2002). However, some studies have shown that, with proper management of cropping sequences and judicious use of organic materials and mineral fertilizers, these 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 (Nezomba et al., 2014; Rusinamhodzi et al., 2013). This therefore offers prospects that declining productivity of the soils can be reversed.

Laboratory indicators based on measurements of soil physico-chemical and biological properties are commonly used to assess soil degradation (e.g. Moebius-Clune et al., 2011; Tesfahunegn et al., 2011). Some of the indicators such as microbial biomass are responsive to short-term management such that they are often used to detect early changes in soil quality (Karlen et al., 1997). The other soil parameters, that include aggregate stability and organic matter content, usually respond to long-term management practices. Apart from laboratory indicators, local people who have been using their soils over time can also have substantial knowledge on indicators of degradation (Mairura et al., 2007; Pauli et al., 2012). Tapping on such knowledge base could enable rapid appraisal of soil degradation for timely rehabilitation, particularly in African smallholder communities where the majority of farmers have poor access to laboratory-based technical services. The involvement of local communities in soil degradation assessment can also lead to better integration of local and empirical knowledge.

According to the Abuja Declaration by African Heads of States in June 2006, African farmers should increase mineral fertilizer use from current levels of <10 kg ha^{-1} to 50 kg ha^{-1} to achieve higher crop yields (Africa Fertilizer Summit, 2007). However, some of the most degraded soils often exhibit a general lack of response to mineral fertilizer addition. While degradation of these croplands is sometimes physical e.g. presence of rills and gullies (e.g., Guto et al., 2011; Kangalawe et al., 2008), 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 and severe macro- and micronutrient deficiencies (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2008). The deterioration in the soil biochemical properties is mainly a result of extractive and low external input-based soil fertility management practices (Haileslassie et al., 2005; Hilhorst and Muchena, 2000). Consequently, farmers often abandon such degraded soils due to loss of crop productivity (Chuma et al., 2000; Nyakanda et al., 2002).

Addition of cattle manure to build soil organic matter (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 cattle numbers, and are therefore unable to maintain critical levels of soil organic C required to sustain soil productivity (Bationo et al., 2007; Mtambanengwe and Mapfumo, 2005). This therefore calls for identification of complementary options to rehabilitate these degraded soils. In Zimbabwe, non-cultivated N_2-fixing herbaceous indigenous legumes were found to generate substantial biomass on nutrient-depleted soils that have <10% clay, <5 ppm available phosphorus (P), and <0.4% organic carbon C (Mapfumo et al., 2005). The non-cultivated N_2-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 N_2-fixing legumes, but also include other crops that provide soil cover to reduce erosive forces (Abayomi et al., 2001), and smoother 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). We 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 inclusion of legumes in cropping sequences as well as combined application of organic and inorganic fertilizers form the core of integrated soil fertility management (ISFM); an approach designed to increase soil productivity in resource-limited environments (Mapfumo, 2009; Vanlauwe et al., 2010).

We hypothesized that biomass generated by P-fertilized N_2-fixing herbaceous legumes with subsequent addition of cattle manure can ‘kick-start’ soil biological processes towards restoration of degraded sandy soils. We tested this approach using the non-cultivated N_2-fixing indigenous legumes mainly of the genera *Crotalaria*, *Indigofera* 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 study was to investigate potential entry points for rehabilitating degraded croplands using principles of ISFM supported through farmers' local knowledge of soils on smallholder farms in eastern Zimbabwe. Specifically, the study sought to: (i) investigate farmers' knowledge of soil degradation and the commonly used local diagnostic indicators, (ii) assess the effect of indigenous herbaceous legume fallows (indifallows) on above-ground C and N productivity on degraded soils, (iii) determine maize grain yield responses to mineral N fertilizer under indigenous legume-based ISFM sequences and (iv) determine the influence of indigenous legume-based ISFM sequences on changes in soil microbiological properties.

2. Materials and methods

2.1. Study sites

The study was carried out between 2009 and 2012 in Nyahava ward in Makoni (18° 13′S; 32° 22′E) and Goto ward in Hwedza (18° 41′S; 31° 42′ E) smallholder farming areas in eastern Zimbabwe. Goto and Nyahava wards are in Zimbabwe's natural regions (NRs) II and III, respectively. NRs II and III receive over 750 mm and 650–750 mm of rainfall $annum^{-1}$, respectively, between November and March

(Vincent and Thomas, 1961). The mean total annual rainfall has not changed much since the 1960s although both areas are now experiencing increased frequency of mid-season dry spells and reduced number of rainy days (Rurinda et al., 2013). With regard to soils, Nyahava is dominated by Lixisols and Arenosols while Goto is mostly covered by Lixisols and scattered patches of Luvisols (FAO-ISRIC, 2003; van Engelen et al., 2004; World Reference Base, 2006). In both areas, the soils are predominantly granitic sands, with low clay content in the 0–30 cm depth (Nyamapfene, 1991). Soil fertility widely varies across fields and farms largely due to preferential allocation of organic nutrient resources (Mtambanengwe and Mapfumo, 2005). Maize is the dominant crop grown in both areas, with small field sections allocated to food legumes such as groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* (L.) Walp).

2.2. Identification of degraded soils and selection of experimental fields

Prior to the 2009/10 cropping season, farmer participatory research methods, that included focus group discussions, key informant interviews and a community meeting, were employed to investigate farmers' knowledge of soil degradation. The focus groups comprised of 30 farmers (15 men and 15 women) of varying age, but with sound knowledge of the areas. Most of the farmers had been practicing farming for >30 years. The farmers were categorized into three resource groups (RGs) based on a typology developed by Mtambanengwe and Mapfumo (2005), which used resource endowment as the main criteria. The typology recognizes resource-endowed (RG1), resource-intermediate (RG2) and resource-constrained (RG3) households. The key informants included village heads, community leaders and extension workers. The discussions and interviews were guided by the following questions: (i) what are the indicators of a productive and degraded (least-productive) cropland? and (ii) what are the perceived causes of soil degradation? After the key informant interviews and focus group discussions, a community meeting was then conducted to build consensus on the indicators of degraded soils and ranking them in order of importance. Ranking was done by assigning each indicator a score based on head counts of farmers who had selected that indicator. Using the indicators, transect walks to locate the degraded fields were then led by village heads, community leaders and local extension leading to identification of fields for experimentation. Four experimental sites were selected in Nyahava (NRIII) and six in Goto (NRII). The experimental fields had corresponding catenary positions, and similar slope and history of management.

At field each site, soils were sampled at 0–20 cm depth and subsequently analyzed for total C, N, plant available soil P (Olsen), pH, exchangeable bases, exchangeable acidity, effective CEC and texture using methods described by Anderson and Ingram (1993). The sampling depth represented the plow layer, based on the animal-drawn moldboard plow commonly used for tillage by smallholder farmers in Zimbabwe (Baudron et al., 2012a; Shumba, 1989). Most organic materials and mineral fertilizers used for crop production are incorporated within this depth. Given the high sand content in these soils, highly mobile nutrients such as mineral N and exchangeable bases can be leached to lower depths, and often beyond the rooting depth of most crops (Chikowo et al., 2004a). Bulk density (BD) of undisturbed soils was measured using the core method (Blake and Hartge, 1986). Part of the soil samples were incubated for 2 weeks under anaerobic conditions and mineral N extracted using 1 M KCl, and analyzed as described by Keeney and Nelson (1982).

2.3. Establishment of indigenous legume-based ISFM sequences

In the first cropping season, fields were tilled once to the 20 cm depth soon after the first effective rains during November 2009 using an animal-drawn moldboard plow. At plowing, there were negligible amounts of crop residues on the soil surfaces from the 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 10 m × 10 m, were demarcated. Two of the plots were put under indigenous legumes, with one intended for a 2-year fallow, resulting in the following treatments: (i) 1-year indifallow and (ii) 2-year indifallow to initiate 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 plowed 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 'Green-start' sequence. The treatments were randomly assigned to plots at each of the experimental sites and replicated across farms. With the exception of continuous unfertilized maize, basal P fertilizer was added in each plot at 26 kg ha^{-1} in a PKS blend formulation (32% P_2O_5: 16% K_2O: 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 0.9 m (inter-row) and 0.3 m (within rows) to attain a population density of approximately 37,000 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 manual weeding. In the succeeding seasons, the treatments were allocated to the respective sequences as shown in Table 1. Cattle manure was applied at 10 t ha^{-1} and incorporated into soil. The chemical properties of the manure applied across sites were: total N = 0.7%, total P = 0.16%, extractable Mg = 0.1%, extractable Ca = 0.3% and extractable K = 0.5%. Tillage was done as previously described. Total seasonal rainfall received during the experimental period averaged 686 mm and 745 mm in Goto and Nyahava, respectively (Fig. 1), and within-season distribution varied strongly, particularly in Goto.

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 main species were *Chamaecrista mimosoides* Greene., *Crotalaria laburnifolia* (L.), *Crotalaria ochroleuca* G. Don, *Crotalaria cylindrostachys* Welw. ex Baker, *Crotalaria pallida* (L.), *Crotalaria glauca* Willd., *Eriosema ellipticum* Welw. ex Baker, *Indigofera arrecta* Hochst. ex A. Rich., *Indigofera astragalina* DC., *Macrotyloma daltonii* (Webb) Verdc., *Neonotonia wightii* (Wight & Arn.) J.A. Lackey, *Tephrosia radicans* Welw. ex Baker, *Tephrosia purpurea* Pers. and *Tephrosia longipes* Meisn. The seed mixes were planted at 120 seeds m^{-2} $species^{-1}$ on the plowed fields. The legume seeds had been collected by farmers from fallowed fields as previously detailed in Mapfumo et al. (2005). The sunnhemp mixed fallow was established by broadcasting sunnhemp seed at 20 kg ha^{-1}. Sunnhemp is a green manure crop being promoted by the Soil Fertility Consortium for Southern Africa (SOFECSA) research initiatives in the study areas (Mtambanengwe and Mapfumo, 2009).

2.4. Fallow C and N productivity and species abundance

Above-ground biomass productivity of indifallows, sunnhemp fallow and natural fallows was quantified using random grid sampling (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 (e.g. Chikowo et al., 2004b; Khan et al., 2003). A 1 m^2 quadrat was randomly thrown on three positions in each plot and the contained biomass cut at soil level. The harvested plants were separated into individual species biomass under shade and oven-dried at 60 °C to

Table 1
Sequencing framework of integrated soil fertility management (ISFM) options on degraded sandy soils on smallholder farms in Zimbabwe.

Sequencing option	Year 1	Year 2	Year 3
'Indifallow-start 1'	Indifallow + P	Maize + cattle manure + mineral fertilizer N and P	Maize + mineral fertilizer N and P
'Green-start'	Sunnhemp fallow + P	Maize + cattle manure + mineral fertilizer N and P	Maize + mineral fertilizer N and P
'Natural fallow-start 1'	Natural fallow + P	Maize + cattle manure + mineral fertilizer N and P	Maize + mineral fertilizer N and P
'Indifallow-start 2'	2-Year indifallow + P		Maize + mineral fertilizer N and P
'Natural fallow-start 2'	2-Year natural fallow + P		Maize + mineral fertilizer N and P
Fertilized maize	Fertilized maize	Fertilized maize	Fertilized maize
Unfertilized maize	Unfertilized maize	Unfertilized maize	Unfertilized maize

determine dry matter. Relative species abundance was calculated by expressing the mass of each species as a percentage of the total biomass productivity. A sub-sample of the total biomass from each quadrat was ground on a Wiley Mill and analyzed for total N using the micro-Kjeldahl method (Anderson and Ingram, 1993). 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 (assuming that the harvested biomass contained 45% C) (Nezomba et al., 2009).

2.5. Maize N response under the different treatments

During the third cropping season (2011–12), all the treatments were planted to a maize test crop (Table 1). Two weeks before planting the maize crop, all above-ground biomass in the fallows was incorporated to a depth of 20 cm using a moldboard plow. A blanket basal P application of 26 kg ha^{-1} was made across all the treatments. Maize (SC 513) was planted at a population density of 37,000 plants ha^{-1} as previously described. 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 4 m × 5 m under each of the main treatments. At physiological maturity, maize ears (grain + cob) were harvested from net plots of 1.8 m × 3 m (middle rows) and grain yield quantified at 12.5% moisture content.

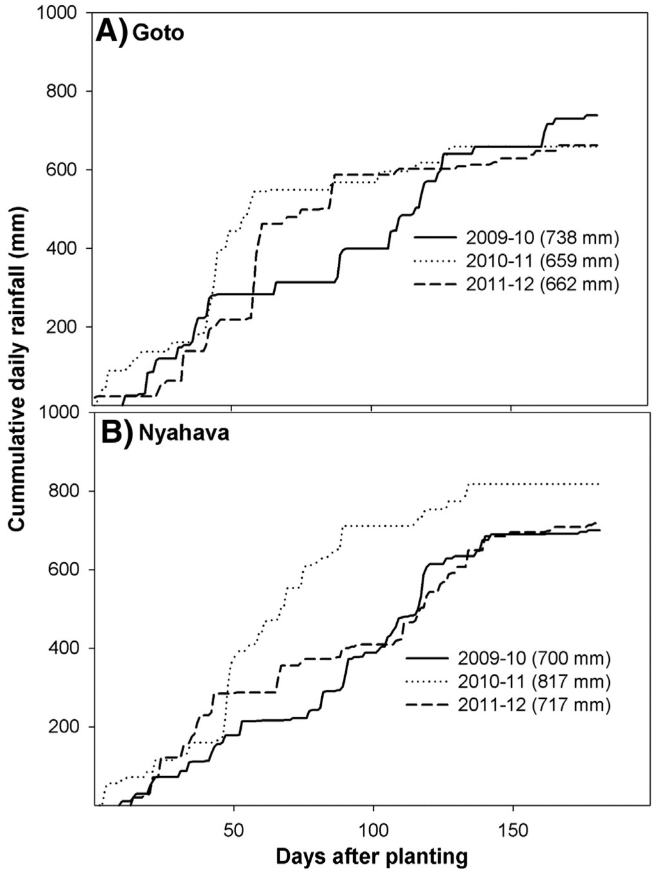

Fig. 1. Rainfall distribution during the experimental period.

2.6. 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 analyzed for microbial biomass, basal respiration and total organic C. Samples for microbial biomass determination were kept at 4 °C in cool boxes before analysis, while part of the samples was air-dried for determination of total organic C. Soil microbial biomass C and N were determined using the chloroform-fumigation extraction method (Amato and Ladd, 1988).

Soil basal respiration was determined only on soils sampled 6 weeks after maize planting using the sealed incubation-alkali absorption method (Stotzky, 1965). 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. The CO_2–C released was quantified on days 1, 4, 8, 16 and 21, and the amounts added to obtain the total CO_2–C evolved. Metabolic quotient (qCO_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).

2.7. Data analyses

Statistical differences in fallow C and N productivity and maize yields were assessed through analysis of variance (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 Tukey'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:

$$Y_x = Y_0 + \Delta Y_{\max} (1 - \exp(-kx))$$

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}), ΔY_{max} is the maximum yield increase from the initial (kg ha^{-1}) and k is the rate constant (kg^{-1}) or a specific responsiveness factor.

3. Results

3.1. Farmer criteria and interpretation of degraded soils

Farmers' diagnostic indicators of soil degradation were centered on crop performance, indicator weed species, and soil physical attributes

Table 2
Indicators of soil degradation (ranked in order of importance) identified through farmer participatory research approaches in Nyahava and Goto smallholder farming areas in Zimbabwe.

Indicators		
Dominant weed species	Soil attributes	Crop performance
1. *Richardia scabra* L. (Mexican clover)	1. Top soil becomes loose (can be easily eroded by wind and water)	1. Soils give <2 scothcarts[a] of maize grain per hectare
2. *Eragrostis minor* Host (Little love grass)	2. Shallow plow depth (hard pan close to the soil surface)	2. Crops have yellowish leaves, stunted and poorly established (uneven stand)
3. *Bulbostylis hispidula* (Vahl) R.W. Haines	3. Low macro-fauna activity	3. Low crop response to addition of mineral fertilizers
4. *Melinis repens* (Willd.) Zizka (Natal red top)	4. Low moisture retention	4. Crops quickly show signs of moisture stress after a rainfall event
5. Low weed diversity and vigor	5. Light-colored, with high sand content	

[a] A scothcart carries approximately 400–500 kg of maize grain (Mapfumo and Giller, 2001).

such as moisture and texture (Table 2). *Richardia scabra* L. (Mexican clover) and *Eragrostis minor* Host (Little love grass) were identified as the main indicator weed species of degraded croplands. The other attributes included presence of a plow pan, and loss of macro-fauna namely millipedes, earthworms and ants. The weed species perceived to dominate productive soils included *Bidens pilosa* L. (Black jack), *Leucas martinicensis* (Jacq.) Ait. f. (Bobbin weed) and *Commelina benghalensis* L. (Wandering dew) (data not shown). 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 3). 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. Plant available soil P on the degraded soils was 4 ppm compared with 9 ppm reported on productive sandy soils in Zimbabwe. Effective CEC, 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.

3.2. Species abundance, biomass productivity and, C and N yields under fallows

One-year indifallow was dominated by annual legume species, with *C. laburnifolia* and *C. ochroleuca* contributing >50% of the total system biomass (Table 4). In the 2-year indifallow, most of the system biomass was contributed by non-leguminous species such as *Setaria pumila* (25%) and *Cynodon dactylon* (33%). The 1-year indifallow produced >10 t ha^{-1} above-ground biomass compared with <3 t ha^{-1} under natural fallow, translating to significantly ($P < 0.05$) higher above-ground biomass C and N accumulation than in natural fallow (Fig. 2a–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 three times the biomass C and N attained under 2-year natural fallow (Fig. 2e–f).

Table 3
Physical and chemical characteristics of soils on degraded fields in Goto and Nyahava smallholder farming areas in Zimbabwe.

Parameter	Site		Productive sandy soils[a]
	Goto (n = 6)	Nyahava (n = 4)	
Clay (%)	8 (0.2)	9 (0.1)	8
Sand (%)	81 (2)	77 (3)	87
Organic C (%)	0.3 (0.05)	0.4 (0.03)	0.7
Total N (%)	0.02 (0.007)	0.03 (0.005)	0.07
Available P (ppm)	4 (2)	4 (1)	9
pH (0.01 M $CaCl_2$)	4.1 (0.11)	4.5 (0.13)	5.4
Mineral N (mg kg^{-1})	17 (1)	21 (4)	22
Exc. Ca (cmol$_{(c)}$ kg^{-1})	0.4 (0.02)	0.4 (0.02)	3.2
Exc. Mg (cmol$_{(c)}$ kg^{-1})	0.3 (0.01)	0.2 (0.01)	0.9
Exc. K (cmol$_{(c)}$ kg^{-1})	0.2 (0.001)	0.2 (0.001)	1.0
Exc. Al and H (cmol$_{(c)}$ kg^{-1})	0.4 (0.002)	0.2 (0.001)	0.2
ECEC (cmol$_{(c)}$ kg^{-1})	2.8 (0.03)	3.1 (0.08)	4.6
Bulk density (kg m^{-3})	1700 (56.6)	1750 (65.8)	1640

[a] Average values for productive sandy soils obtained from studies conducted in smallholder farming areas in Zimbabwe (Chikuvire et al., 2007; Masvaya et al., 2010; Mugwira and Nyamangara, 1998; Mtambanengwe and Mapfumo, 2005; Nezomba et al., 2014; Rusinamhodzi et al., 2013; Zingore et al., 2006). Figures in parentheses denote standard error of mean.

3.3. Maize response to mineral N fertilizer under ISFM sequences

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 ($R^2 = 0.4$; $P = 0.005$) (Fig. 3a). The model predicted an average maximum grain yield ($Y_{\max}$) of 4 t ha^{-1} under ‘Indifallow-start 1’ and ‘Green-start’; three times the predicted yields under natural fallow-based sequences and continuous fertilized maize (Table 5). In Goto,

Table 4
Relative species abundance under 1- and 2-year indifallows in Goto smallholder farming area in Zimbabwe.

Treatment/plant species	Relative species abundance (%)	Legume	Non-legume
1-Year indifallow			
Acanthospermum hispidum	3		+
Crotalaria cylindrostachys	8	+	
Crotalaria laburnifolia	25	+	
Crotalaria ochroleuca	34	+	
Crotalaria pallida	3	+	
Cynodon dactylon	3		+
Eleusine indica	4		+
Eriosema ellipticum	2	+	
Hibiscus meeusei	3		+
Indigofera arrecta	2	+	
Melinis repens	3		+
Richardia scabra	6		+
Other non-legume species	4		
2-Year indifallow			
Ageratum conyzoides	8		+
Commelina benghalensis	2		+
Crotalaria laburnifolia	5	+	
Cynodon dactylon	33		+
Eriosema ellipticum	9	+	
Hibiscus meeusei	6		+
Indigofera arrecta	3	+	
Leucas martinicensis	3		+
Setaria pumila	25		+
Vernonia poskeana	4		+
Other non-legume species	2		

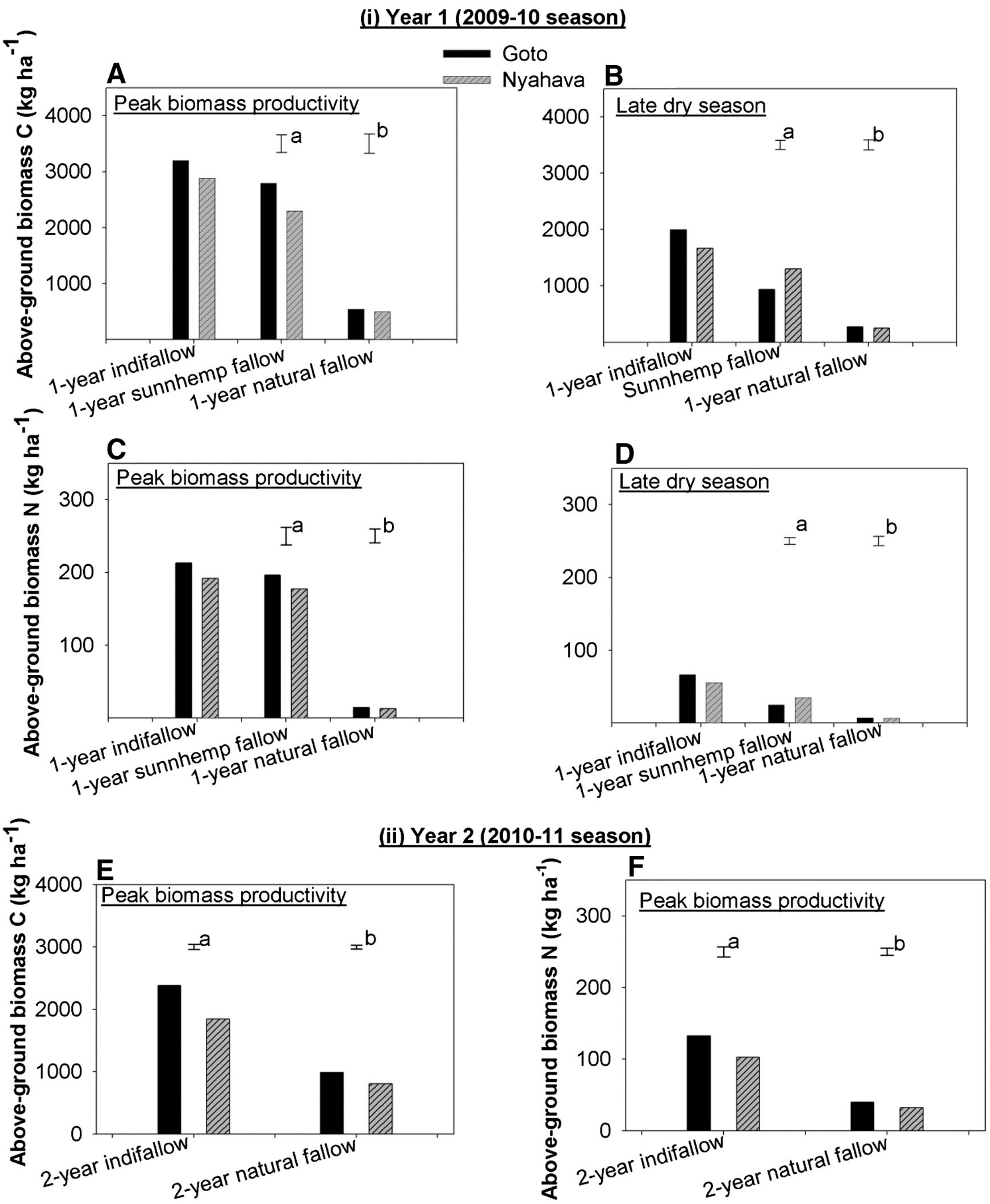

Fig. 2. Above-ground biomass C and N produced under 1-year fallows (a, b, c, d), and 2-year fallows (e, f) on degraded soils in Goto and Nyahava smallholder farming areas in Zimbabwe. Bars indicate standard error of differences of means (SEDs) for a = Goto and b = Nyahava.

'Indifallow-start 2' gave the highest response to mineral N fertilizer ($R^2 = 0.64$), with all the other sequences recording R^2 of <0.5 (Fig. 3b). 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. Because of the low yields, the model estimated a maximum grain yield of <2 t ha^{-1} across all treatments. In both sites, the regression model predictions were significant ($P < 0.05$) for most of the treatments.

3.4. Soil microbial biomass under the different treatments

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 6a). '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 at 6 WAP. Overall, 'Green-start' gave the highest MBC across treatments. Microbial biomass carbon to organic C ratios were highest under 'Indifallow-start 1' and 'Green-start' at both 3 and 6 WAP. For example, at 3 WAP, 'Green-start' gave a microbial biomass carbon to organic C ratio of 5.6 compared with <4.4 under natural fallow-based sequences and 'Indifallow-start 2'. At 6 WAP, microbial biomass N (MBN) was >30 mg kg^{-1} under 'Indifallow-start 1' and 'Green-start' against <20 mg kg^{-1} under 'Natural-fallow start 2' and continuous maize treatments.

In Nyahava (3 WAP), MBC did not differ significantly among treatments (Table 6b). MBC had, however, increased at 6 WAP, with 'Indifallow-start 1' and 'Indifallow-start 2' giving 24 and 14% more MBC than 'Natural-fallow start 2'. 'Indifallow-start 1' gave the highest microbial biomass carbon to organic C ratios at both 3 and 6 WAP. MBN was not significantly different among treatments 3 WAP, with 'Indifallow-start 1' and continuous unfertilized maize giving the highest and least values, respectively. MBN had increased in all the treatments 6 WAP, with the exception of continuous unfertilized maize. 'Indifallow-start 1' gave approximately three times the MBN recorded under 'Natural fallow-start 2' and continuous fertilized maize.

3.5. Soil CO_2–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 (Fig. 4). In Goto, 'Indifallow-start 1' (157 mg CO_2–C kg^{-1} soil) and 'Green-start' (163 mg CO_2–C kg^{-1} soil) gave the greatest CO_2–C emissions (Fig. 4a). Continuous maize treatments and 'Natural fallow-start 2' released <115 mg CO_2–C kg^{-1} soil. In Nyahava (0–10 cm), 'Indifallow-start 1' and 'Green-start' consistently released the most CO_2–C compared with the continuous maize treatments (Fig. 4b). Natural fallow-based sequences and continuous maize gave higher metabolic quotients (qCO_2) than legume-based sequences (Fig. 5). In Goto (0–10 cm), qCO_2 was approximately 0.1 mg CO_2–C g^{-1} microbial C day^{-1} under 'Indifallow-start 1', 'Green-start' and 'Indifallow-start 2', but doubled under continuous maize and natural fallow-based sequences (Fig. 5a). A similar trend was recorded for the 10–20 cm depth. The qCO_2 patterns of soils from Nyahava were consistent with those from Goto (Fig. 5b).

4. Discussion

4.1. Farmers' local knowledge of soil degradation and implications for management

Fields that were identified by farmers as being degraded, based on local diagnostic indicators, had lower chemical properties than reported values for productive soils of similar textural class. This match indicates farmers' knowledge on soil properties as they relate to productivity. Farmers' selection of *R. scabra* as the dominant indicator weed species on degraded soils confirms earlier findings in Zimbabwe that the species is often prevalent on disturbed acidic sandy soils (Agronomy Research Institute, 1998; Mabasa et al., 1995). Consistent with the farmers' criteria, *B. pilosa* and *L. martinicensis* have also been reported as indicator weeds of productive soils (Mairura et al., 2007). These findings, and other studies that have also reported congruency between local

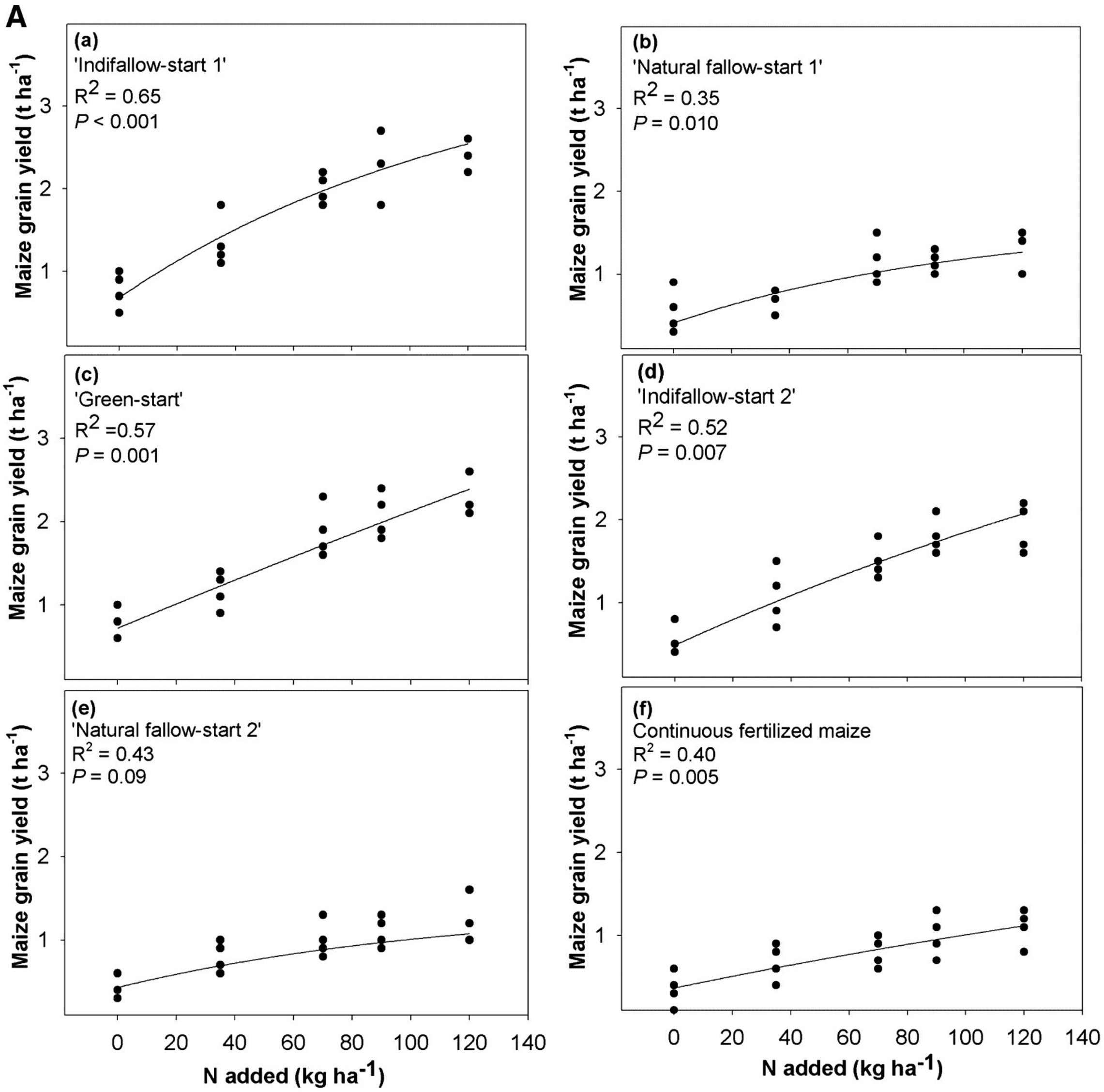

Fig. 3. a. Maize grain yield responses to mineral N fertilizer under different ISFM sequences on degraded soils in Nyahava smallholder farming area in Zimbabwe. The lines represent the fitted exponential functions. b. Maize grain yield responses to mineral N fertilizer under different ISFM sequences on degraded soils in Goto smallholder farming area in Zimbabwe. The lines represent the fitted exponential functions.

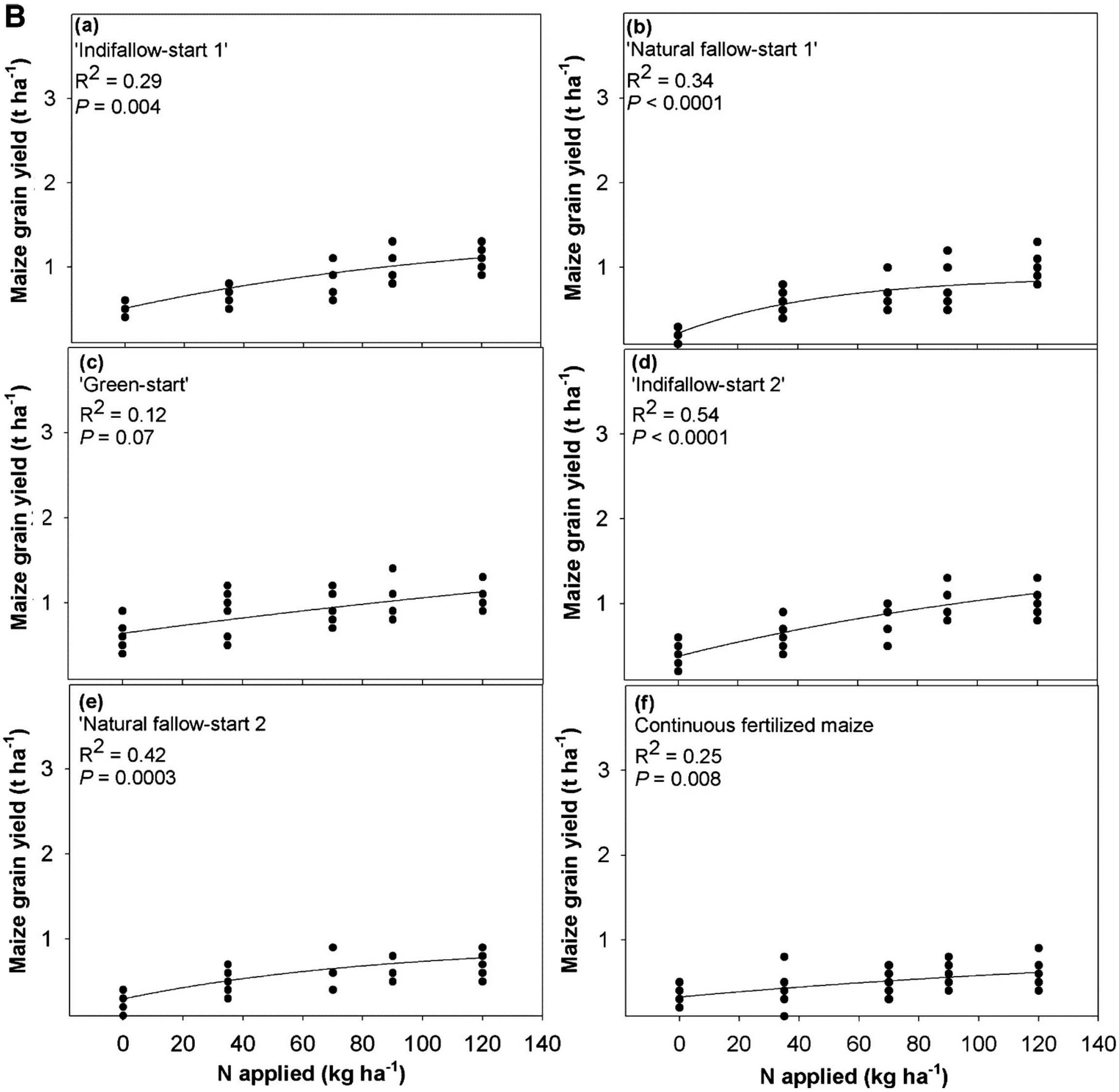

Fig. 3 (*continued*).

indicators of soil productivity and laboratory indices (e.g. Tesfahunegn et al., 2011; Tittonell et al., 2013), validate farmers' local knowledge as it is inclusive of soil physico-chemical and biological properties and the associated vegetation. The local indicators such as weed species could then be used to aid farmers to target soil fertility management options to different fields. For example, the dominance of *R. scabra* on a farmer's field indicates soil acidity, and therefore a need to apply liming materials such as dolomitic and calcitic lime, cattle manure or termitaria to raise soil pH (Watson, 1976; Zingore et al., 2008). On the other hand, on soils with high prevalence of *B. pilosa* and *L. martinicensis*, crop productivity could be sustained through maintenance addition of mineral fertilizers and organic materials. Such management decisions are particularly important for most smallholder farmers in Africa because of challenges in accessing seed, fertilizer and labor resources (Giller et al., 2011). However, more studies are apparently required to further explore the relationship between weed species dynamics and the underlying soil properties in space and time to strengthen the local diagnostic indicators.

4.2. Generating high initial biomass on degraded sandy soils

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, 2006). 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. An earlier study conducted on relatively productive soils also reported that indigenous legumes and sunnhemp contributed up to 88% of the total biomass generated under 1-year fallows (Nezomba et al., 2010). 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*. While the predominantly grass weeds and biennial legume species under 2-year indifallow could not produce sufficient above-ground biomass to match productivity under the 1-year indifallow, the biomass productivity was better than leaving the soils under a 2-year natural fallow. Although not measured in this study, basing on above-ground biomass productivity, and commonly known shoot to root ratios of grasses and herbaceous legumes (Bolinder et al.,

Table 5
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.

Site/treatment	Y_0 (t ha^{-1})	Y_{max} (t ha^{-1})	$-k$
Nyahava			
'Indifallow-start 1'	0.7	3.9	0.0080
'Natural fallow-start 1'	0.4	1.2	0.0098
'Green-start'	0.7	4.1	0.0009
'Indifallow-start 2'	0.5	3.1	0.0030
'Natural fallow-start 2'	0.4	0.9	0.0087
Continuous fertilized maize	0.4	1.7	0.0027
Goto			
'Indifallow-start 1'	0.5	0.9	0.0082
'Natural fallow-start 1'	0.2	0.7	0.0204
'Green-start'	0.6	1.8	0.0027
'Indifallow-start 2'	0.4	1.4	0.0065
'Natural fallow-start 2'	0.3	0.6	0.0115
Continuous fertilized maize	0.3	0.6	0.0049

2002; Pang et al., 2011), the legume-based fallows 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. Given the <3 t ha^{-1} shoot biomass produced under natural fallows, it is likely that the root biomass produced under these systems was also low. Herbaceous legumes therefore offer better prospects for generating high initial biomass on degraded soils than natural fallowing.

4.3. Soil biological activity and maize yield response under herbaceous legume-based ISFM sequences

The high microbial biomass attained under 'Green-start' and 'Indifallow-start 1' suggests that the legume 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 (Silva et al., 2010; Yusuf 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 carbon to total soil organic C was highest under 'Green-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 'Green-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 qCO_2 as microbes spend more energy on maintaining metabolic activity than in accumulating biomass (Hu et al., 2010). The lower metabolic quotient (qCO_2) obtained under legume-based sequences therefore indicated more available carbon and thus less microbial stress compared with natural fallow-based sequences and continuous maize treatments. However, we had anticipated a low qCO_2 under 'Natural fallow-start 2' due to better succession than under continuous maize treatments. This could be attributable to limitations associated with the qCO_2 method. Wardle and Ghani (1995) have shown the qCO_2 to be rather an unpredictable index at distinguishing disturbed and stressful soils in certain environments.

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,

Table 6a
Soil organic C (t ha^{-1}), and microbial biomass C and N (mg kg^{-1}) under different ISFM options on degraded soils at 3 and 6 weeks after planting (WAP) of maize in Goto smallholder farming area during the 2011–12 season cropping season.

Sampling depth/treatment	3 WAP				6 WAP			
	MBC (mg kg^{-1})	MBN (mg kg^{-1})	Soil organic C (t ha^{-1})	MBC/organic C (%)	MBC (mg kg^{-1})	MBN (mg kg^{-1})	Soil organic C (t ha^{-1})	MBC/organic C (%)
0–10 cm								
'Indifallow-start 1'	185	9.2	3.1	4.7	235	31.4	3.2	6.5
'Natural fallow-start 1'	179	11.6	3.3	4.4	211	20.2	3.5	5.1
'Green-start'	196	11.3	3.4	5.6	265	37.7	3.4	7.6
'Indifallow-start 2'	186	11.5	3.4	4.3	247	25.1	3.2	5.7
'Natural fallow-start 2'	172	10.8	3.5	3.9	198	15.1	3.3	4.5
Continuous fertilized maize	188	9.9	3.4	4.4	196	14.6	3.1	4.8
Continuous unfertilized maize	174	10.1	3.4	4.0	182	11.9	3.2	4.2
10–20 cm								
'Indifallow-start 1'	172	8.8	3.2	4.6	244	28.6	3.1	5.2
'Natural fallow-start 1'	172	9.6	3.3	3.8	195	19.4	3.2	4.5
'Green-start'	183	9.9	3.3	4.3	255	31.7	3.4	6.1
'Indifallow-start 2'	177	10.6	3.1	4.4	231	21.7	3.2	4.7
'Natural fallow-start 2'	168	8.9	3.0	3.2	185	13.3	3.3	3.3
Continuous fertilized maize	185	8.6	3.1	3.9	176	11.5	3.1	4.2
Continuous unfertilized maize	182	8.4	3.1	3.8	183	10.7	3.2	3.6

	Statistical significance[a]			
	MBC	MBN	Soil organic C	MBC/organic C
Treatment	*		ns	*
Depth	*	*	ns	*
Time	*	*	ns	*
Time × depth	ns	ns	ns	*
Time × treatment	*	*	ns	*
Depth × treatment	*	ns	ns	ns
Time × depth × treatment	*	ns	ns	ns

ns = not significant; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; OC = organic carbon.

[a] Significantly different at $^*P < 0.05$.

Table 6b
Soil organic C (t ha^{-1}), and microbial biomass C and N (mg kg^{-1}) under different ISFM options on degraded soils at 3 and 6 weeks after planting (WAP) of maize in Nyahava smallholder farming area during the 2011–12 season cropping season.

Sampling depth/treatment	3 WAP				6 WAP			
	MBC (mg kg^{-1})	MBN (mg kg^{-1})	Soil organic C (t ha^{-1})	MBC/organic C (%)	MBC (mg kg^{-1})	MBN (mg kg^{-1})	Soil organic C (t ha^{-1})	MBC/organic C (%)
0–10 cm								
'Indifallow-start 1'	183	10.7	3.3	5.2	251	31.1	3.3	7.2
'Natural fallow-start 1'	168	10.2	3.4	4.1	203	17.4	3.4	4.9
'Green-start'	174	8.6	3.1	4.5	222	25.2	3.1	5.7
'Indifallow-start 2'	168	9.6	3.2	3.9	231	19.3	3.1	5.4
'Natural fallow-start 2'	156	8.3	3.1	3.5	183	12.1	3.2	4.2
Continuous fertilized maize	167	8.3	3.1	3.9	197	12.2	3.2	4.6
Continuous unfertilized maize	162	9.4	3.0	3.7	173	9.3	3.3	4.0
10–20 cm								
'Indifallow-start 1'	142	7.4	3.1	4.1	202	9.8	3.2	6.8
'Natural fallow-start 1'	121	8.6	3.3	2.9	171	9.2	3.3	4.2
'Green-start'	133	8.3	3.1	3.4	193	11.3	3.3	5.9
'Indifallow-start 2'	138	8.4	3.3	3.2	191	9.4	3.1	4.4
'Natural fallow-start 2'	124	5.2	3.2	2.8	132	8.2	3.4	4.0
Continuous fertilized maize	113	6.2	3.2	2.6	165	8.1	3.2	4.3
Continuous unfertilized maize	110	7.9	3.3	2.5	142	7.9	3.1	4.3

	Statistical significance[a]			
	MBC	MBN	Soil organic C	MBC/organic C
Treatment	*	*	ns	*
Depth	*	*	ns	*
Time	*	*	ns	*
Time × depth	ns	*	ns	*
Depth × treatment	ns	*	ns	ns
Time × treatment	*	*	ns	ns
Time × depth × treatment	*	*	ns	ns

ns = not significant; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; OC = organic carbon.

[a] Significantly different at $^*P < 0.05$.

nodules and other N compounds deposited in the rhizosphere. Belowground 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). Apart from increasing the residence time of mineral N fertilizer in the soil, the organic materials could moreover 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 was 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 'Green-start' include provision of multiple nutrients and acidity regulation effects through the addition of cattle manure (Zingore et al., 2008). The overall low responses to fertilizer N under continuous maize imply that, even if N-based mineral fertilizers are provided to farmers through various schemes by governments and non-governmental organizations (NGOs) as is normally the case in smallholder farming areas in Zimbabwe (Chuma et al., 2000; Zingore et al., 2006), farmers are bound to get low crop yield responses on degraded soils. This therefore suggests the need for organic matter management strategies and balanced fertilization to address multiple nutrient deficiencies often associated with such soils (Rusinamhodzi et al., 2013; Tittonell et al., 2008).

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 staple cereals, particularly maize (Mapfumo et al., 1999; Ncube et al., 2007). Our study therefore suggests that these experiments on ISFM-based sequences could open new opportunities for analyzing 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 these external inputs has been a major constraining factor.

4.4. The niche for herbaceous legume-based ISFM sequences in rehabilitating degraded soils on smallholder farms

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). Overall,

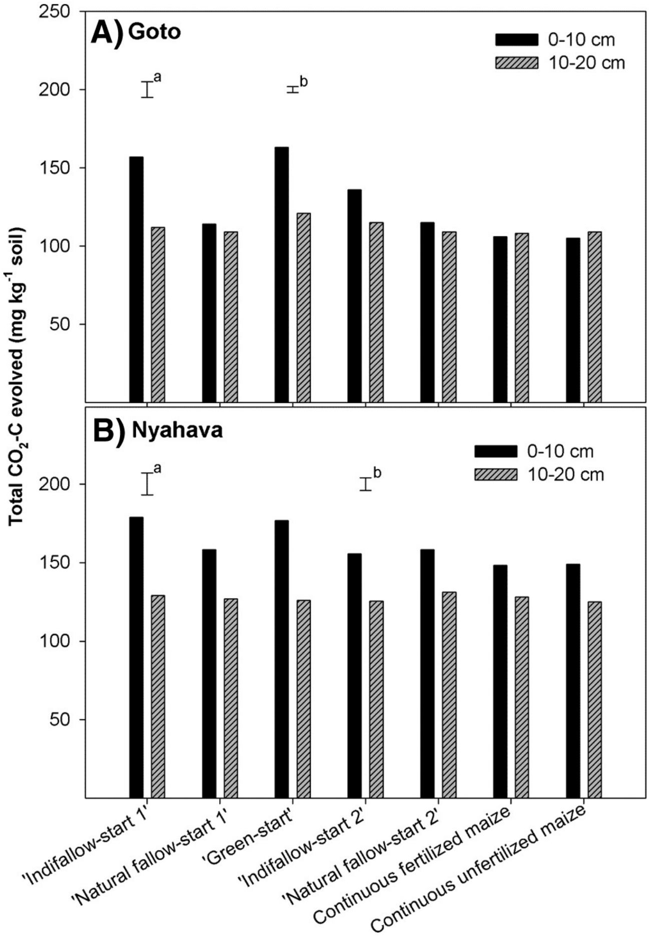

Fig. 4. Total CO_2–C released from degraded soils under different ISFM options in (a) Goto and (b) Nyahava smallholder farming areas, Zimbabwe. Bars indicate standard error of differences of means (SEDs) for a = ISFM option and b = depth.

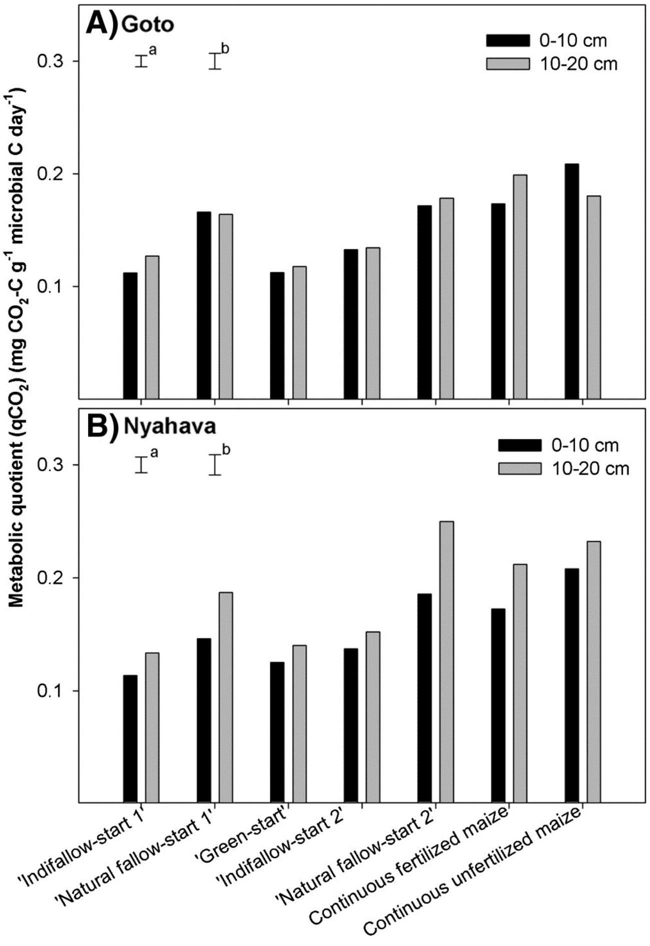

Fig. 5. Soil metabolic quotient (qCO_2) under different ISFM options in (a) Goto and (b) Nyahava smallholder farming areas, Zimbabwe. Bars indicate standard error of differences of means (SEDs) for a = ISFM option and b = depth.

mineral fertilizer use by African smallholder farmers has been low due to a myriad of challenges including unavailability, inaccessibility and low profitability (Africa Fertilizer Summit, 2007; Camara and Heinemann, 2006). 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), our results add 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 implies that there is minimal loss of the nutrient, and the rotational crops could in turn benefit from the residual P. 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 (Amede, 2003; Drechesel et al., 1996; 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 remains 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 is therefore important.

5. Conclusions

Farmers' criteria for identifying degraded soils closely support laboratory indices, suggesting that such ethnopedological approaches could be used to assess soil degradation to enable farmers to make timely and site-specific decisions on soil fertility management. Further research is required to develop consistent criteria for categorizing the degraded croplands and quantifying their geographical spread in smallholder farming communities. Seeding of indigenous legumes and sunnhemp on degraded sandy soils, with P fertilization, led to more 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.

Acknowledgments

Funding for this work was provided by the European Union through the African Conservation Tillage Network (ACT) (Europe Aid/128500/C/ACT/Multi) under the *Agroecology-based Aggradation–Conservation Agriculture: Tailoring innovations to combat food insecurity in semiarid Africa (ABACO)* project to the Soil Fertility Consortium for Southern Africa (SOFECSA). Additional financial support from the International Foundation for Science—Sweden (IFS) through Grant No. C/5031-1 is greatly appreciated.

References

Abayomi, Y., Fadayomi, O., Babatola, J., Tian, G., 2001. Evaluation of selected legume cover crops for biomass production, dry season survival and soil fertility improvement in a moist Savanna location in Nigeria. Afr. Crop Sci. J. 9, 615–627.

Africa Fertilizer Summit, 2007. Proceedings of the African Union Special Summit and Heads of State and Governments, June 9–13, 2006 Abuja, Nigeria, Special Publication IFDC, Muscle Shoals, Alabama (178 pp.).

Agronomy Research Institute, 1998. Integrated Weed Management and Control in Selected Field Crops. A Field Guide Manual. Department of Research & Specialist Services, Weed Research Unit, (64 pp.).

Amato, M., Ladd, J.N., 1988. Assay for microbial biomass based on ninhydrin reactive nitrogen in extracts of fumigated soil. Soil Biol. Biochem. 20, 107–114.

Amede, T., 2003. Pathways for fitting legumes into East African Highlands farming systems: A dual approach. In: Waddington, S.R. (Ed.), Grain Legumes and Green Manures for Soil Fertility in Southern Africa: Taking Stock of Progress. SoilFertNet/CIMMYT, Harare, Zimbabwe, pp. 21–29.

Anderson, T.H., Domsch, K.H., 1990. Application of eco-physiological quotients (qCO_2 and qD) on microbial biomass from soils of different cropping histories. Soil Biol. Biochem. 22, 251–255.

Anderson, J.M., Ingram, J.S.I., 1993. Tropical Soil Biology and Fertility: A Handbook of Methods, Second edition. C.A.B. International, Wallingford, UK.

Andersson, J.A., 1999. The politics of land scarcity: land disputes in Save Communal Land, Zimbabwe. J. S. Afr. Stud. 25, 553–578.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric. Syst. 94, 13–25.

Baudron, F., Andersson, M., Corbeels, M., Giller, K.E., 2012a. Failing to Yield? Ploughs, conservation agriculture and the problem of agricultural intensification. An example from the Zambezi Valley, Zimbabwe. J. Dev. Stud. 48, 393–412.

Baudron, F., Tittonell, P., Corbeels, M., Letourmy, P., Giller, K.E., 2012b. Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe. Field Crops Res. 132, 117–128.

Blake, G.R., Hartge, K.H., 1986. Bulk density, In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1, 2nd edition Agronomy Monogram 9. American Society of Agronomy, Madison, WI, pp. 363–375.

Bolinder, M.A., Angers, D.A., Bélanger, G., Michaud, R., Laverdière, M.R., 2002. Root biomass and shoot to root ratios of perennial forage crops in eastern Canada. Can. J. Plant Sci. 82, 731–737.

Camara, O., Heinemann, E., 2006. Overview of the fertilizer situation in Africa. African Fertilizer Summit Background Paper, Abuja Nigeria.

Carr, S.J., 2003. More people more soil degradation: the Malawi Experience. Afr. Crop Sci. J. 6, 401–405.

Chikowo, R., Mapfumo, P., Nyamugafata, P., Giller, K.E., 2004a. Maize productivity and mineral N dynamics following different soil fertility management practices on a depleted sandy soil in Zimbabwe. Agric. Ecosyst. Environ. 102, 119–131.

Chikowo, R., Mapfumo, P., Nyamugafata, P., Giller, K.E., 2004b. Woody legume fallow productivity, biological N_2-fixation and residual benefits to two successive maize crops in Zimbabwe. Plant Soil 262, 303–315.

Chikuvire, T.J., Mpepereki, S., Foti, R., 2007. Soil fertility variability in sandy soils and implications for nutrient management by smallholder farmers in Zimbabwe. J. Sustain. Agric. 30, 69–87.

Chimhowu, A., Woodhouse, P., 2008. Communal tenure and rural poverty: land transactions in Svosve Communal Area, Zimbabwe. Dev. Change 39, 285–308.

Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P., Six, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. Soil Tillage Res. 94, 328–337.

Chuma, E., Mombeshora, B.G., Murwira, H.K., Chikuvire, J., 2000. The dynamics of soil fertility management in communal areas of Zimbabwe. In: Hilhorst, T., Muchena, F.M. (Eds.), Nutrients on the Move—Soil Fertility Dynamics in African Farming Systems. International Institute for Environment and Development, London, pp. 45–64.

Diagana, B., 2003. Land degradation in sub-Saharan Africa: what explains the widespread adoption of unsustainable farming practices? Working Paper. Department of Agricultural Economics and Economics, Montana State University, U.S.A. (19 pp.).

Drechesel, P., Steiner, K.G., Hagedorn, F., 1996. A review on the potential of improved fallows and green manure in Rwanda. Agrofor. Syst. 33, 109–136.

Dunjana, N., Nyamugafata, P., Shumba, A., Nyamangara, J., Zingore, S., 2012. Effects of cattle manure on selected soil physical properties of smallholder farms on two soils of Murewa, Zimbabwe. Soil Use Manag. 28, 221–228.

Eswaran, H., Almaraz, R., van den Berg, E., Reich, P., 2005. An Assessment of the Soil Resources of Africa in Relation to Productivity. World Soil Resources, Soil Survey Division, USDA, Natural Resources Conservation Service, Washington, D.C.

FAO-ISRIC, 2003. Soil and terrain database for Southern Africa (1:2 million scale). FAO Land and Water Digital Series 25 (CD ROM). FAO, Rome.

Franchini, J.C., Crispino, C.C., Souza, R.A., Torres, E., Hungria, M., 2007. Microbiological parameters as indicators of soil quality under various soil management and crop rotation systems in southern Brazil. Soil Tillage Res. 92, 18–29.

Frere, M., 1984. Ecological zones and production of sorghum and millet. In: Virmani, S.M., Sivakumar, M.V.K. (Eds.), Agrometeorology of Sorghum and Millet in the Semi-arid Tropics. ICRISAT, Patancheru, India, pp. 33–39.

Gentile, R., Vanlauwe, B., van Kessel, C., Six, J., 2009. Managing N availability and losses by combining fertilizer-N with different quality residues in Kenya. Agric. Ecosyst. Environ. 131, 308–314.

Giller, K.E., Cadisch, G., 1995. Future benefits from biological nitrogen fixation: an ecological approach to agriculture. Plant Soil 174, 255–277.

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agric. Syst. 104, 191–203.

Glasener, K.M., Wagger, M.G., Mackown, C.T., Volk, R.J., 2002. Contributions of shoot and root nitrogen-15 labelled legume nitrogen sources to a sequence of three cereal crops. Soil Sci. Soc. Am. J. 66, 523–530.

Guto, S.N., Pypers, P., Vanlauwe, B., de Ridder, N., Giller, K.E., 2011. Tillage and vegetative barrier effects on soil conservation and short-term economic benefits in the Central Kenya highlands. Field Crops Res. 122, 85–94.

Haileslassie, A., Priess, J., Veldkamp, E., Teketay, D., Lesschen, J.P., 2005. Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. Agric. Ecosyst. Environ. 108, 1–16.

Hartemink, A.E., Huting, J., 2008. Land cover, extent, and properties of Arenosols in Southern Africa. Arid Land Res. Manag. 22, 134–147.

Hilhorst, T., Muchena, F.M., 2000. Nutrients on the Move—Soil Fertility Dynamics in African Farming Systems. International Institute for Environment and Development, London.

Hu, J., Lin, X., Wang, J., Dai, J., Chen, R., Zhang, J., Ming, H.W., 2010. Microbial functional diversity, metabolic quotient, and invertase activity of a sandy loam soil as affected by long-term application of organic amendment and mineral fertilizer. J. Soils Sediments http://dx.doi.org/10.1007/s11368-010-0308-1.

Kamanga, B.C.G., Kanyama-Phiri, G.Y., Waddington, S.R., Almekinders, C.J.M., Giller, K.E., 2014. The evaluation and adoption of annual legumes by smallholder maize farmers for soil fertility maintenance and food diversity in central Malawi. Food Secur. 6, 45–59.

Kangalawe, R.Y.M., Christiansson, C., Wilhelm O¨stberg, W., 2008. Changing land-use patterns and farming strategies in the degraded environment of the Irangi Hills, central Tanzania. Agric. Ecosyst. Environ. 125, 33–47.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61, 4–10.

Keeney, D.R., Nelson, D.W., 1982. Nitrogen–inorganic forms. In: Page, A.L., Miller, P.H., Keeney, D.R. (Eds.), Methods of Soil Analysis Volume 2. American Society of Agronomy, Monograph No. 9, Madison. Wisconsin, pp. 643–698.

Khan, D.F., Peoples, M.B., Schwenke, G.D., Felton, W.L., Chen, D., Herridge, D.F., 2003. Effects of below-ground nitrogen on N balances of field-grown fababean, chickpea and barley. Aust. J. Agric. Res. 54, 333–340.

Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degrad. Rehabil. 17, 197–209.

Mabasa, S., Rambakudzibga, A.M., Mandiringana, O.T., Ndebele, C., Bwakaya, F., 1995. Tillage practices, fertilizer use and weed management in a maize crop in three communal areas of Zimbabwe. Soil Fertility Network for Maize-based Farming Systems. Proceedings of the Second Meeting of the Networking Group, Kadoma, Zimbabwe.

Mairura, F.S., Mugendi, D.N., Mwanje, J.I., Rarmisch, J.J., Mbugua, P.K., Chianu, J.N., 2007. Integrating scientific and farmers' evaluation of soil quality indicators in central Kenya. Geoderma 139, 134–143.

Mapfumo, P., 2009. Developing a Soil Fertility Consortium for Southern Africa (SOFECSA). Enhancing Integrated Soil Fertility Management (ISFM) Impacts on Food Security and Household Incomes in Smallholder Farming Systems of Southern Africa. SOFECSA, CIMMYT-Southern Africa, Harare, Zimbabwe (64 pp.).

Mapfumo, P., 2011. Comparative analysis of the current and potential role of legumes in Integrated Soil Fertility Management in southern Africa. In: Bationo, A., Waswa, B., Okeyo, J.M., Maina, J.K., Mokwunye, U. (Eds.), Fighting Poverty in Sub-Saharan Africa: The Multiple Roles of Legumes in Integrated Soil Fertility Management, pp. 175–200.

Mapfumo, P., Giller, K.E., 2001. Soil Fertility Management Strategies and Practices by Smallholder Farmers in Semi-arid Areas of Zimbabwe. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) with permission from the Food and Agriculture Organization of the United Nations (FAO), Bulawayo, Zimbabwe (60 pp.).

Mapfumo, P., Giller, K.E., Mpepereki, S., Mafongoya, P.L., 1999. Dinitrogen fixation by pigeonpea of different maturity types on granitic sandy soils in Zimbabwe. Symbiosis 27, 305–318.

Mapfumo, P., Mtambanengwe, F., Giller, K.E., Mpepereki, S., 2005. Tapping indigenous herbaceous legumes for soil fertility management by resource poor farmers in Zimbabwe. Agric. Ecosyst. Environ. 109, 221–233.

Masvaya, E.N., Nyamangara, J., Nyawasha, R.W., Zingore, S., Delve, R.J., Giller, K.E., 2010. Effect of farmer management strategies on spatial variability of soil fertility and crop nutrient uptake in contrasting agro-ecological zones in Zimbabwe. Nutr. Cycl. Agroecosyst. 88, 111–120.

Meadows, M.E., Hoffman, M.T., 2002. The nature, extent and causes of land degradation in South Africa: legacy of the past, lessons for the future? Area 34, 428–437.

Moebius-Clune, B.N., van Es, H.N., Idowu, O.J., Schindelbeck, R.R., Kimetu, J.M., Ngoze, S., Lehmann, J., Kinyangi, M., 2011. Long-term soil quality degradation along a cultivation chronosequence in western Kenya. Agric. Ecosyst. Environ. 141, 86–99.

Mtambanengwe, F., Mapfumo, P., 2005. Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe. Nutr. Cycl. Agroecosyst. 73, 227–243.

Mtambanengwe, F., Mapfumo, P., 2008. Smallholder farmer management impacts on particulate and labile carbon fractions of granitic sandy soils in Zimbabwe. Nutr. Cycl. Agroecosyst. 81, 1–15.

Mtambanengwe, F., Mapfumo, P., 2009. Combating food insecurity on sandy soils in Zimbabwe: the legume challenge. Symbiosis 48, 25–36.

Mtambanengwe, F., Mapfumo, P., Vanlauwe, B., 2006. Comparative short-term effects of different quality organic resources on maize productivity under two different environments in Zimbabwe. Nutr. Cycl. Agroecosyst. 76, 271–284.

Muchena, F.N., Onduru, D.D., Gachini, G.N., de Jager, A., 2005. Turning the tides of soil degradation in Africa: capturing the reality and exploring opportunities. Land Use Policy 22, 23–31.

Mugwira, L.M., Nyamangara, J., 1998. Organic carbon and plant nutrients in soils under maize in Chinamora communal area, Zimbabwe. In: Bergström, L., Kirchmann, H. (Eds.), Carbon and Nutrient Dynamics in Natural and Agricultural Tropical Systems. CAB International, Wallingford, pp. 15–21.

Ncube, B., Twomlow, S.J., van Wijk, M.T., Dimes, J.P., Giller, K.E., 2007. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in southwestern Zimbabwe. Plant Soil 299, 1–15.

Nezomba, H., Tauro, T.P., Mtambanengwe, F., Mapfumo, P., 2009. Indigenous legumes biomass quality and influence on C and N mineralization under indigenous legume fallow systems. Symbiosis 48, 78–91.

Nezomba, H., Tauro, T.P., Mtambanengwe, F., Mapfumo, P., 2010. Indigenous legume fallows (indifallows) as an alternative soil fertility resource in smallholder maize cropping systems. Field Crops Res. 115, 149–157.

Nezomba, H., Mtambanengwe, F., Chikowo, R., Mapfumo, P., 2014. Sequencing integrated soil fertility management options for sustainable crop intensification by different categories of smallholder farmers in Zimbabwe. Exp. Agric. http://dx.doi.org/10.1017/S0014479714000131.

Nyakanda, C., Mariga, I.K., Murwira, H.K., Nyamugafata, P., Salimfu, D., 2002. The status of existing set aside fallows in smallholder farming: a case of two contrasting agricultural land-use systems in Zimbabwe. In: Rao, M.R., Kwesiga, F.R. (Eds.), Agroforestry Impacts on Livelihoods in Southern Africa: Putting Research Into Practice, pp. 1–10.

Nyamapfene, K., 1991. Soils of Zimbabwe. Nehanda Publishers, Harare, Zimbabwe (173 pp.).

Pang, J., Yang, J., Ward, P., Siddique, K.H.M., Lambers, H., Tibbett, M., Ryan, M., 2011. Contrasting responses to drought stress in herbaceous perennial legumes. Plant Soil 348, 299–314.

Pauli, N., Barrios, E., Conacher, A.J., Oberthür, T., 2012. Farmer knowledge of the relationships among soil macrofauna, soil quality and tree species in a smallholder agroforestry system of western Honduras. Geoderma 189–190, 186–198.

Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggaard-Nielsen, H., Jensen, E.S., 2009. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis 48, 1–17.

Piha, M.I., 1993. Optimizing fertilizer use and practical rainfall capture in a semi-arid environment with variable rainfall. Exp. Agric. 29, 405–415.

Rurinda, J., Mapfumo, P., van Wijk, M.T., Mtambanengwe, F., Rufino, M.C., Chikowo, R., Giller, K.E., 2013. Managing soil fertility to adapt to rainfall variability in smallholder cropping systems in Zimbabwe. Field Crops Res. 154, 211–225.

Rusinamhodzi, L., Corbeels, M., Zingore, S., Nyamangara, J., Giller, K.E., 2013. Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. Field Crops Res. 147, 40–53.

Scherr, S.J., 2000. A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. Food Policy 25, 479–498.

Shumba, E.M., 1989. An agronomic Study of Appropriate Maize (*Zea mays*) Tillage and Weed Control Technologies in a Communal Area of ZimbabweDPhil Thesis University of Zimbabwe, Harare.

Silva, A.P., Babujia, L.C., Franchini, J.C., Souza, R.A., Hungria, M., 2010. Microbial biomass under various soil- and crop-management systems in short and long-term experiments in Brazil. Field Crops Res. 119, 20–26.

Snapp, S.S., Rohrbach, D.D., Simtowe, F., Freeman, H.A., 2002. Sustainable soil management options for Malawi: can smallholder farmers grow more legumes? Agric. Ecosyst. Environ. 91, 159–174.

Sparling, G.P., 1992. Ratio of microbial biomass carbon to soil organic carbon as a sensitive indicator of changes in soil organic matter. Aust. J. Soil Res. 30, 195–207.

Stotzky, G., 1965. Microbial respiration. In: Black, C.A. (Ed.), Methods of Soil Analysis. American Society of Agronomy, Monograph No. 9, Madison, USA vol. 2, pp. 1550–1572.

Tesfahunegn, G.B., Tamene, L., Vlek, P.L.G., 2011. A participatory soil quality assessment in Northern Ethiopia's Mai-Negus catchment. Catena 86, 1–13.

Tittonell, P., Giller, K.E., 2013. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res. 143, 76–90.

Tittonell, P., Vanlauwe, B., Corbeels, M., Giller, K.E., 2008. Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313, 19–37.

Tittonell, P., Scopel, E., Andrieu, N., Posthumus, H., Mapfumo, P., Corbeels, M., van Halsema, G.E., Lahmar, R., Lugandu, S., Rakotoarisoa, J., Mtambanengwe, F., Pound, B., Chikowo, R., Naudin, K., Triomphe, B., Mkomwa, S., 2012. Agroecology-based aggradation–conservation agriculture (ABACO): targeting innovations to combat soil degradation and food insecurity in semi-arid Africa. Field Crops Res. 132, 168–174.

Tittonell, P.A., Muriuki, A., Klapwijk, C.J., Shepherd, K.D., Coe, R., Vanlauwe, B., 2013. Soil heterogeneity and soil fertility gradients in smallholder agricultural systems of the East African Highlands. Soil Sci. Soc. Am. J. 77 (2), 525–538.

van Engelen, V.W.P., Mantel, S., Dijkshoorn, J.A., Huting, J.R.M., 2004. Impact of desertification of food security in southern Zimbabwe: a case study in Zimbabwe. Report 2004/02. ISRIC-World Information Centre, Wageningen, The Netherlands (88 pp.).

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., Sanginga, N., 2010. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. Outlook Agric. 39, 17–24.

Versteeg, M.N., Amadji, F., Eteka, A., Gogan, A., Koudokpon, V., 1998. Farmers' adoptability of *Mucuna* fallowing and agroforestry technologies in coastal savanna of Benin. Agric. Syst. 56, 269–287.

Vincent, V., Thomas, R.G., 1961. An Agroecological Survey of Southern Rhodesia: Part 1—Agro-ecological Survey. Government Printer, Salisbury, Rhodesia.

Vlek, P., Le, Q.B., Tamene, L., 2008. Land Decline in Land-rich Africa—A Creeping Disaster in the Making. CGIAR Science Council Secretariat, Rome, Italy (55 pp.).

Wardle, D.A., Ghani, A., 1995. A critique of the microbial metabolic quotient as a bioindicator of disturbance and ecosystem development. Soil Biol. Biochem. 27, 1601–1610.

Watson, J.P., 1976. The composition of mounds of the termite *Macrotermes falciger* (Gerstaker) on soil derived from granite in three rainfall zones of Rhodesia. J. Soil Sci. 27, 295–503.

World Reference Base for Soils, FAO/ISRIC/ISSS, 2006. World Soil Resources Report No. 103. Food and Agriculture Organization, Rome.

Yusuf, A.A., Abaidoo, R.C., Iwuafor, E.N.O., Olufajo, O.O., Sanginga, N., 2010. Rotation effects of grain legumes and fallow on maize yield, microbial biomass and chemical properties of an Alfisol in the Nigerian savanna. Agric. Ecosyst. Environ. 129, 325–331.

Zingore, S., Manyame, C., Nyamugafata, P., Giller, K.E., 2005. Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. Eur. J. Soil Sci. 57, 727–736.

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2006. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agric. Ecosyst. Environ. 119, 112–126.

Zingore, S., Delve, R.J., Nyamangara, J., Giller, K.E., 2008. Multiple benefits of manure: the key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. Nutr. Cycl. Agroecosyst. 80, 267–282.