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ORIGINAL PAPER

Effect of Natural Fallowing on Soil Fertility Status of Smallholder Farms Under Contrasting Soils and Ecologies in Zimbabwe

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Abstract

A study was conducted to examine changes in soil fertility under different fallow periods in fields of smallholder farmers under contrasting soils and agro-ecologies in North West Zimbabwe. The study was a 4*4*6 factorial design replicated three times consisting three factors namely agro-ecological region (AER) (II, III, IV, V), soil texture (sandy clay loam, sandy loam, loamy sand and sand) and fallowing period in years (0–5, 6–10, 11–15, 16–20 and two controls). Soil samples were analysed for pH, soil organic carbon (SOC), soil KCl-extractable nitrogen (N), bicarbonate-extractable phosphorus (P) and exchangeable potassium (K) using standard methods. There was no significant three-way interaction ($p > 0.05$) among AER, soil texture and the fallow period on the soil fertility properties except for soil pH. Soil KCl-extractable N was significantly influenced ($p < 0.05$) by AER and soil texture and soil texture and period of fallowing. Interaction of AER and period of fallowing had a significant effect on SOC, bicarbonate-extractable P and exchangeable K. Across all the three factors, most cultivated fields and those with low period of fallowing (≤ 15 years) had SOC, soil KCl-extractable N, bicarbonate-extractable P and exchangeable K contents below required recommendations for crop production, and soil pH was acidic. Natural fallowing has limited capacity to improve soil fertility status across different AER and soil texture in Zimbabwe on short to medium term as it takes more than 16–20 years to restore the nutrient status back to original fertility status. Therefore, with the increasing population and land shortage, other low input strategies known to improve soil fertility over a short period such as improved fallows are highly recommended.

Keywords Agro-ecologies · Natural fallowing · Smallholder farmers · Soil fertility status · Soil texture

1 Introduction

The year 2015 saw the end of the Millennium Development Goals (MDGs), ushering in Sustainable Development Goals (SDGs) the blueprint to achieve a better and more sustainable future for all (Morton et al. 2017). Seventeen SDGs were formulated and promulgated in 2016 with SDG2 and SDG13 focusing on ending hunger through appropriate agricultural practices and climate change, respectively (Friedman and Gostin 2016). Evidence-based decision-making through research-based policy formulation needs to be prioritized for the attainment of these SDGs by 2030 (Dodds 2015; United Nations 2015a, 2015b). However, population increase has led to an increased need to produce more food leading to over-exploitation of land resources through unsustainable management practices such as continuous crop cultivation with little to no nutrient replenishment especially in the smallholder farming sector of Sub-Saharan Africa (SSA) (Shah and Wu 2019; Zingore et al. 2015). This results in soil fertility degradation due to soil organic matter depletion and nutrient mining (Nezomba et al. 2015).

Soil fertility decline resulting in lower yield has become a major concern of policy makers and is an impediment to the attainment of sustainable SDG 2 and 13 in SSA. For

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example, in most communal areas of Zimbabwe, maize yields are low usually averaging below 1 t ha^{-1}, which is far below the average yields of 8 t ha^{-1} realized by commercial farmers (Chipomho et al. 2021; Gotosa et al. 2021). Continuous improvement in soil fertility and adequate supply of essential nutrients in cropping systems are a must for meeting the food security agenda as highlighted in the SDGs (Partey et al. 2017). Failure to implement sound soil fertility management strategies might cause household food insecurity resulting in hunger and poverty among the vulnerable and disadvantaged (Giller 2020; Asare-Nuamah 2021). Unfortunately, most smallholder farmers still apply sub-optimal fertilizers as they cannot afford to buy inorganic fertilizers due to high prices (Bonilla et al. 2020; Sheahan and Barrett 2017) and neither do they have adequate organic sources for improving soil fertility in their fields (Zingore et al. 2015). In a bid to rejuvenate soil fertility, most farmers are forced to use traditional methods of restoring degraded land or leave some of their fields under fallow (Saturday 2018; Pandit et al. 2020).

Fallowing is a practice done as a way of restoring soil fertility in response to a decline in crop productivity and often decrease in organic matter content due to continuous cultivation (Burdukovskii et al. 2020; Voltr et al. 2021). Natural fallowing relies on germplasm already on the land with nothing being brought in, while in improved fallows, leguminous plants are grown to improve the soil fertility through biological nitrogen fixation (Mamuye et al. 2020; Musokwa and Mafongoya 2021). In SSA, large-scale, landscape-level adoption of improved fallows is yet to be achieved, although it has great potentials for simultaneous achievement of the three pillars of climate smart agriculture of sustainably increasing agricultural productivity and incomes, adapting and building resilience of people and food systems to climate change and reducing and/or removing greenhouse gas emissions, where possible (Mamuye et al. 2020; Musokwa and Mafongoya 2021; Partey et al. 2017). Hence, most farmers rely on natural fallows for soil fertility improvement. Natural fallowing results in regrowth of vegetation on abandoned fields, and this helps in rebuilding nutrients and protecting soils from erosion, thus helping to maintain better soil physical and biological conditions (Iwara et al. 2018). According to Nyamadzawo et al. (2012) and Chemura et al. (2020), fallowing helps optimize water storage within the soil profile through increased infiltration of water and reduced evaporation as well as increased availability of plant nutrients through reduced soil erosion. Soil regeneration under the low input agriculture systems is enhanced by fallowing cycles which allow natural vegetation to grow for some years and then cleared for cropping (Onijigin et al. 2016). Soil regeneration refers to the improvement of soil health and restoration of highly degraded soil, which symbiotically enhances the quality of water, vegetation and land productivity (Rhodes 2017). The amount of soil organic matter is normally low on arable land compared to natural environments because crop harvesting reduces organic matter inputs (Purwanto and Alam 2019). Soil organic matter (SOM) is an important soil quality indicator since it influences nutrient availability, biological activity and soil aggregation (Vortr et al. 2021).

In SSA, smallholder farmers often fallow their land when they realize a decrease in productivity. The period of fallowing depends on land availability with shorter fallow lengths becoming more common where there is a land shortage and higher competition for other land uses (Kozak and Pudelko 2021). This may reduce the benefits of fallowing since the degree of soil fertility restoration depends on the length of the fallow period. For instance, Musokwa and Mafongoya (2021) found short-term improved fallows to not positively influence NPK and soil organic carbon (SOC). On the other hand, a study by Onijigin et al. (2016) reported a gradual increase in most soil properties including soil pH with an increase in fallow time in Nigeria. In addition to fallow length, the amount of rainfall received in an area also indirectly influences soil chemical properties differently for different soil textures (Kwiatkowski and Hasim 2020). In low rainfall areas, the rate of vegetation growth is relatively low compared to higher rainfall areas resulting in less SOM input and accelerated leaching in the soil. Moreover, the ability of a fallow to buffer the effects of variable rainfall on crop yield depends on soil texture since it has an influence on water holding capacity (WHC) and SOC protection in the soil (Nielson and Calderon 2011; Six et al. 2002). Higher clay content soils under any rainfall pattern are more likely to have high SOC and buffering capacity resulting in better fallowing benefits compared to low clay soils (Daly et al. 2016).

Several studies have shown how fallowing (both natural and improved fallows) improve soil properties (Mamuye et al. 2020; Musokwa and Mafongoya 2021; Onijigin et al. 2016). Many others have explored the impact of soil texture on physicochemical properties (Daly et al. 2016; Nielson and Calderon 2011; Six et al. 2002), while the impact of rainfall on both chemical and soil physical properties is also well documented (Kwiatkowski and Hasim 2020). However, there is a dearth of information on how these three factors interact to influence soil physicochemical properties. In Zimbabwe, farmers in different agro-ecological regions and on different soil textures practice fallowing that differs in lengths, but there is a paucity of knowledge on the degree of soil restoration. We hypothesized that fallow period, soil texture and agro-ecological zoning have a significant interactive influence on soil pH, SOC and primary macronutrients, i.e. nitrogen, phosphorus and potassium (NPK). Thus, the objective of this study was to examine changes in SOC and primary macronutrients (NPK) in smallholder farmers' fields under different fallow periods, contrasting soils and distinct agro-ecological zones in Zimbabwe.

2 Materials and Methods

2.1 Study Sites

The study was conducted in four contrasting agro-ecological regions (AER) (II, III, IV and V), in smallholder areas situated in Zvimba and Hurungwe districts in North West Zimbabwe (Fig. 1). Zimbabwe is demarcated into five AERs based on rainfall amount and potential for crop production (Mugandani et al. 2012). Potential for crop production decreases from AER I to AER V. The AER II receives annual average rainfall of 750–1000 mm and has a mean annual temperature of 16–19 °C and is suitable for intensive cropping and livestock production. The AER III is characterized by annual rainfall of 500–750 mm, mid-season dry spells and high temperatures with farmers growing drought-tolerant crops and practising semi-intensive livestock farming. Agro-ecological region IV receives an annual rainfall of 450–650 mm with severe dry spells during the rainy season and is characterized by extensive livestock production with some drought-tolerant crops such as sorghum and millet rapoko, but farmers in this region also grow some short-season maize varieties. Agro-ecological region V is of lowest agricultural potential and is located in the semi-arid climate with average annual rainfall of < 500 mm and mean annual temperature of 18–24 °C. Two wards with different soil textures and in contrasting AERs were selected from both Zvimba and Hurungwe districts as study sites. Zvimba area is approximately 120 km north west of Harare and lies between 17°S and 18°S and 30°E and 31°E, while Hurungwe is 235 km of Harare and lies between 16°S and 17°S and 29°E and 30°E. In each AER, one ward with contrasting soils was chosen for this research. In Zvimba district, ward 3 in AER II and ward 7 situated in AER III were chosen, while ward 23 situated in AER IV and ward 24 located in AER V were selected from Hurungwe district.

2.2 Experimental Design, Data Collection and Analysis

2.2.1 Experimental Design and Layout

The primary level of sampling was based on the AER. For each AER, four types of soils with different textures were

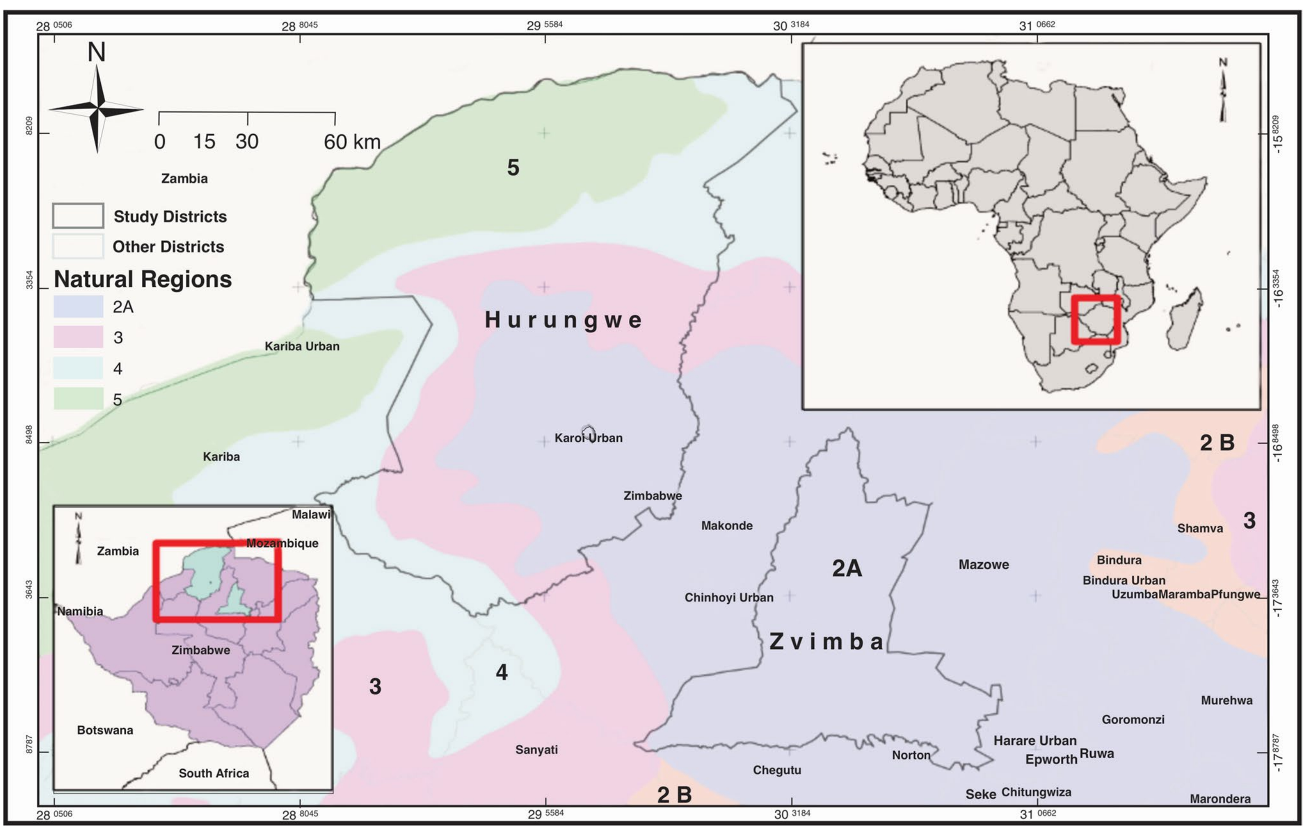

Fig. 1 Map showing Hurungwe and Zvimba district study sites in Zimbabwe

selected, and for each soil type, six different fallow ages were considered to give a total of 96 situations. Therefore, the study was a 4*4*6 factorial design replicated three times to give a total of 288 sampling units, consisting three factors namely AER, soil texture and period of abandonment. The AER comprised four levels (AER II, AER III, AER IV and AER V) that differed on mean annual rainfall and temperature. Soil texture consisted of four classes (sandy clay loam, sandy loam, loamy sand and sand) which varied on the basis of clay content. The three classes of sandy loam, loamy sand and sand are Lixisols with inherently poor nutrient supply potential, while the sandy clay loam class is Luvisols (IUSS Working Group WRB 2015). Sandy clay loam contained 35% clay content, while sandy loam, loamy sand and sand have clay content of 20, 15 and 10%, respectively. Period of natural fallowing comprised six levels (cultivated land, 0–5 years, 6–10 years, 11–15 years, 16–20 years, forested area). In each study site, the cultivated land and forested areas were used as the negative and positive controls, respectively; naturally fallowed fields and period of abandonment were identified through collective effort as advised by farmers, local leadership and the Department of Agricultural Technical and Extension Services (AGRITEX) officials in the Ministry of Lands, Agriculture, Water, Climate and Rural Resettlement from both Zvimba and Hurungwe districts of Zimbabwe. Fields close to the homesteads with known cropping history were chosen as cultivated land. The idea was to choose old growth forest; however, these were difficult to find in the study sites; hence, secondary forests with old trees, thick shrubs, dense understory and where signs of disturbance are no longer evident and with no history of cultivation were selected to represent the forest.

2.2.2 Soil Sampling and Analysis

For each plot, soil samples were collected to a soil depth of 0–15 cm which is the layer normally sampled for soil testing and fertilizer recommendation purposes in the smallholder sector (Nyamangara et al. 2000). A total of 10 sub-samples were collected randomly using a zig-zag sampling approach in each geo-referenced plot and were mixed to make a composite sample. Within each plot, sampling was undertaken in a circular plot of radius 10 m centred at the middle of the plot to avoid any edge effects. The size and shape of the volume of material from which a sample is drawn is called the sample's support. All statistics are conditional on the sample support. It is also important that the sample support is consistent over all the observations. This is the reason for not forming a composite sample across the whole of each plot, as these were varied markedly in shape and size. The collected samples were air-dried and crushed using a wooden pestle and mortar to pass through 2-mm sieve and were stored in paper bags at room temperature. The samples were then analysed for soil pH using the 0.01 M calcium chloride ($CaCl_2$) method (FAO 2008) that is widely used in Zimbabwe for soil testing and fertilizer recommendations (DRSS 1974). This method is less affected by soil electrolyte concentration and overcomes the problems of seasonal variation in soil pH when measured in water, especially in soils with low total salts that are common in Zimbabwe (Kissel et al. 2009). The $CaCl_2$ method gives much more accurate laboratory results, and more importantly, it is a truer measure of what the soil acidity will be under field conditions during the growing season in Zimbabwe (Rowell 1994). Other analysed parameters were particle size distribution (hydrometer method), SOC (Walkely-Black method, employing a spectrophotometric procedure for titration end point determination instead of using the indicator) (Bahadori and Tofighi 2016) and KCl-extractable N (incubation technique) then determined calorimetrically (Keeney and Nelson 1982). Bicarbonate-extractable P (simplified resin membrane technique whereby strips of anion (HCO^{-}_3 form) and cation (Na^+ form) exchange membrane were shaken with suspensions of soil in deionised water for 16–17 h thereafter the phosphate retained on the anion exchange resin strip was determined by shaking the strip directly with phosphate reagent) then determined by the spectrophotometer (Saggar et al. 1990) and exchangeable K (acidified ammonium acetate method) that was determined by atomic emission spectrophotometry were also determined (FAO 2008).

2.2.3 Soil Fertility Classification of the Fields

Soil fertility classification for SOC was done based on criteria outlined by Singh et al. (2018), while pH, KCl-extractable N, bicarbonate-extractable P and exchangeable K fertility parameters were assessed using criteria expressed by Mashiringwani (1983) and Nyamangara et al. (2000) as shown in Table 1. Current lime and fertilizer recommendations given to farmers by the Department of Research and Specialist Services (DRSS) in Zimbabwe are based on these criteria.

2.2.4 Percentage Changes

In order to get a better understanding of how long-term fallowing improves soil properties, percentage changes were calculated between the two controls (cultivated and forest) against the longest fallowing period of 16 to 20 years. The percentage change was calculated as:

$$Percentagechange = \frac{X - Y}{Y} \times 100 \quad (1)$$

where X is the value of the soil parameter under either cultivated or forest plot and Y is the value of the soil parameter under 16- to 20-year fallow period.

Table 1 Classification of soil pH and selected fertility properties used in Zimbabwe

*Soil pH (0.01 M $CaCl_2$)	Very strongly acidic (4.0–4.4)	Strongly acidic (4.5–4.9)	Medium acidic (5.0–5.4)	Slightly acidic (5.5–5.9)
	Neutral (6.0–6.4)	Mildy alkaline (6.5–7.0)		
Soil fertility parameters	Organic C (%)*	KCl-extractable N (mg kg^{-1})	Bicarbonate-extractable P (mg kg^{-1})	Exch. K ($cmol_{(+)}kg^{-1}$)
Very low/acutely deficient	< 0.5	< 20	< 20	< 0.45
Low/marginal/deficient	0.5–0.75	20–30	20–40	0.45–0.7
Adequate (medium) to high	> 0.75	> 30	> 40	> 0.7

Classification adapted from *Singh et al. (2018), Mashiringwani (1983) and Nyamangara et al (2000). This is the classification that is used for lime and fertilizer recommendations in Zimbabwe

2.2.5 Data Analysis

The soil data was subjected to analysis of variance to test the significance of differences at 5% using the general linear model in the R statistical software version 3.6.0 (R Core Team 2019). Data were tested for the assumption of normal distribution and satisfied the normality requirement at the 5% significance level. Mean separation of the soil properties was done using standard error of means (s.e.m). The general linear model used was:

$$Y = \mu + P_i + R_j + T_k + (PR)_{ij} + (PT)_{ik} + (RT)_{jk} + (PRT)_{ijk} + e_{ijke}$$

where Y is the total sum of the following components:

μ is the overall mean.

P_i is the effect of the i^{th} period of natural fallowing ($i = 1, 2, 3, 4, 5, 6$).

R_j is the effect of the j^{th} AER ($j = 1, 2, 3, 4$).

T_k is the effect of the k^{th} soil texture ($k = 1, 2, 3, 4$).

$(PR)_{ij}$ is the interaction effect of the period of natural fallowing and AER.

$(PT)_{ik}$ is the interaction effect of the period of natural fallowing and soil texture.

$(RT)_{jk}$ is the interaction effect of the AER and soil texture.

$(PRT)_{ijk}$ is the interaction effect of the period of natural fallowing, AER and soil texture.

e_{ijke} are the random residuals where $e_{ijke} \sim N(0, \sigma^2)$.

3 Results

3.1 Soil pH

The results of this study showed a strong three-way interaction among AER, soil texture and the fallow period on soil pH (Table 2). There was a general increase in soil pH with a decrease in rainfall (i.e. AER II to V), increase in clay content (sand to sandy clay loam) as well as with increase in the fallow period (Fig. 1A of supplementary file). The soil pH was significantly low in sand soils of fields under cultivation and those with low period of fallowing (0–5, 6–10 and 11–15 years) in AER II and high in sandy clay loam soils under forest and fields with a long period of fallowing (11–15 and 16–20 years) in AER V. Soil pH tended to increase significantly with fallow period from 4.2 to 4.5 under 0–5 and 16–20 years, respectively, in sand soils under AER II. The same trend of significant increase in pH was observed in sand and loamy sandy under AER V. According to pH classes from the DRSS, all soil textures under various periods of fallowing in the high rainfall region (AER II) were strongly acidic (Table 3). All soil textures in AER III under various periods of fallowing were of the medium acid class, while those in AER IV were in the slightly acid class. Soil pH in AER IV ranged from slightly acidic for sand soils under cultivated and the fields with low period of fallowing to mildly alkaline for forest areas and fields with a long fallow period. Having noted a general increase in soil pH with fallow period, percentage differences in soil pH were calculated between soil pH for 16–20 years and soil pH of forest land (i.e. undisturbed) and between soil pH of cultivated land and soil pH for 16–20 years (Fig. 2A). It was observed that fallowing fields with sandy soils for up to 20 years in high rainfall areas such as AER II resulted in higher pH increase of more than 8% compared to other textures in AER III and IV. Relatively higher increases in soil pH of up to 6% were also observed in AER V for most soil types compared to other AER. Despite the increase in pH with fallow period, it was noted that even after up to 20 years of fallowing, sand soils under different AER remained very strongly acidic and never reached the mildly alkaline levels of undisturbed forest soils (Fig. 2A).

3.2 Soil Organic Carbon

There was no significant interaction of AER, soil texture and period of fallow on SOC neither was there an interaction between soil texture and fallow period nor between AER and

Table 2 ANOVA for selected soil properties (pH, SOC, N, P and K) across AER, soil textures and period of fallowing

	Parameters														
	pH			SOC (%)			KCl-extractable N (mg kg^{-1})			Bicarbonate-extractable P (mg kg^{-1})			Exchangeable K (cmol$_{(+)}$kg^{-1})		
	F statistics	*P* values	% variance	*F* statistics	*P* values	% variance	*F* statistics	*P* values	% variance	*F* statistics	*P* values	% variance	*F* statistics	*P* values	% variance
Factor															
AER	50,119.11	<0.01	90.32	23.65	<0.01	15.89	21.65	<0.01	15.39	37.26	<0.01	18.59	22.55	<0.01	22.18
ST	4210.41	<0.01	7.43	8.40	<0.01	6.89	8.04	<0.016	5.38	3.92	<0.035	1.94	2.10	0.074	1.78
FP	235.16	<0.01	6.57	0.12	<0.01	0.71	0.83	<0.01	1.23	0.35	<0.01	1.16	0.59	<0.01	1.05
AER*ST	162.50	<0.01	1.08	1.80	0.119	8.20	1.78	<0.01	4.45	3.36	<0.182	4.16	1.30	0.374	3.16
AER×FP	8.98	<0.01	0.11	0.43	0.035	2.60	0.99	<0.01	3.72	1.17	<0.022	6.35	0.73	0.016	3.17
ST×FP	4.13	<0.01	0.04	1.32	0.549	5.80	0.78	0.323	3.28	0.86	0.643	5.39	1.09	0.840	4.83
AER×ST×FP	8.48	<0.01	0.22	0.98	0.151	12.94	1.46	0.356	16.02	0.94	0.987	13.42	1.19	0.979	14.27

**SOC* soil organic carbon, *AER* agro-ecological region, *ST* soil texture, *FP* period of fallowing

soil texture on SOC (Table 2). Only AER and period of fallow interacted to influence SOC (Table 2). It was observed that in most instances, soils under forest and those fallowed for a long period (16–20 years) had higher SOC compared to cultivated soils and those fallowed for a short period of time (Fig. 1B of supplementary file). SOC significantly varied ($p<0.05$) across AER, soil texture and period of fallowing. SOC of the fields ranged from very low to medium (Table 4). Most of the sand soil across AER and period of fallowing had very low (<0.5%) to low SOC (0.5–0.75%) except in AER V with more than 5 years of fallowing. Most forest areas across AER and soil texture and soils with more than 5 years of fallowing in AER V had adequate SOC (>0.75%) (Table 4). A comparison between SOC under cultivated and fallowed for 16–20 years and also forested land showed a similar trend observed with pH where the percentage difference was higher under AER II and V (Fig. 2B). SOC content in soils fallowed for 16–20 years had lower SOC compared to forest soils (Fig. 2B). The results also showed that in high rainfall areas (AER II) and under sand soils, the SOC under forest was still more than double SOC in soils fallowed to up to 20 years. Only loamy sandy soils under AER 5 had significantly higher SOC in 16–20 fallow soils compared to forest. These results show that natural fallowing up to 20 years has limited capacity to restore SOC to the levels as in undisturbed soil.

3.3 Primary Macronutrients NPK

There was no significant interaction of AER, soil texture and period of fallow on primary macronutrients (KCl-extractable N, bicarbonate-extractable P and exchangeable K) (Table 2). There was also no significant interaction observed between soil texture and period of fallow on NPK. However, the study indicated a significant and weak positive correlation between SOC and KCl-extractable N ($r=0.14$), SOC and bicarbonate-extractable P ($r=0.38$) and SOC and exchangeable K ($r=0.38$) (Table 5). Soil pH had a significant ($p<0.01$) and weak positive correlation with SOC ($r=0.45$), KCl-extractable N ($r=0.44$), bicarbonate-extractable P ($r=0.52$) and exchangeable K ($r=0.40$) (Table 5).

3.4 Nitrogen

KCl-extractable N was significantly influenced ($p<0.05$) by the interaction effect of AER and period of fallow as well as the interaction between AER and soil texture (Table 2). Longer period of fallowing (i.e. 16–20 years) in low potential areas had high KCl-extractable N accumulation (i.e. AER V) (Fig. 1C of supplementary file). KCl-extractable N was also significantly influenced ($p<0.05$) by the main factors AER, soil texture and period of fallow. Most soils with 10 years and below of fallowing across all soil textures and

Table 3 Soil pH variations across AER, soil texture and period of fallowing in Zimbabwe

AER	Soil texture	Period of fallowing (years)					
		Control (cultivated)	0–5	6–10	11–15	16–20	Control (forest)
II	Sand	Very strongly acidic	Very strongly acidic	Very strongly acidic	Very strongly acidic	Very strongly acidic	Strongly acidic
	Loamy sand	Strongly acidic	Strongly acidic	Strongly acidic	Strongly acidic	Strongly acidic	Strongly acidic
	Sandy loam	Strongly acidic	Strongly acidic	Strongly acidic	Strongly acidic	Strongly acidic	Strongly acidic
	Sandy clay loam	Strongly acidic	Strongly acidic	Strongly acidic	Strongly acidic	Strongly acidic	Strongly acidic
III	Sand	Medium acidic	Medium acidic	Medium acidic	Medium acidic	Medium acidic	Medium acidic
	Loamy sand	Medium acidic	Medium acidic	Medium acidic	Medium acidic	Medium acidic	Medium acidic
	Sandy loam	Medium acidic	Medium acidic	Medium acidic	Medium acidic	Medium acidic	Medium acidic
	Sandy clay loam	Medium acidic	Medium acidic	Medium acidic	Medium acidic	Medium acidic	Medium acidic
IV	Sand	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic
	Loamy sand	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic
	Sandy loam	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic
	Sandy clay loam	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic	Slightly acidic
V	Sand	Slightly acidic	Slightly acidic	Slightly acidic	Neutral	Neutral	Neutral
	Loamy sand	Neutral	Neutral	Mildy alkaline	Mildy alkaline	Mildy alkaline	Neutral
	Sandy loam	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
	Sandy clay loam	Neutral	Neutral	Mildy alkaline	Mildy alkaline	Mildy alkaline	Mildy alkaline

Classification adapted from Mashiringwani (1983) and Nyamangara et al (2000); very strongly acidic (4.0–4.4), strongly acidic (4.5–4.9), medium acidic (5.0–5.4), slightly acidic (5.5–5.9), neutral (6.0–6.4) and mildy alkaline (6.5–7.0)

AER had very low (20 mg kg^{-1}) to low (20–30 mg kg^{-1}) soil KCl-extractable N status to adequately support crop growth (Table 6). However, most soil with more than 15 years of fallowing across all AER and soil textures had medium to high (> 30 mg kg^{-1}) KCl-extractable N status, while all forest areas on all soil textures in AER III, IV and V had medium to high (> 30 mg kg^{-1}) soil N status (Table 6). Differences between cultivated fields and fields fallowed for 16–20 years showed that fallowing increased KCl-extractable N in soil as most of the percentage differences were positive (Fig. 2C). Comparison between the longest fallowed fields and forest soils showed that forest soils still had higher KCl-extractable N levels compared to fallowed soils (Fig. 2C).

3.5 Soil Bicarbonate-Extractable P

Soil bicarbonate-extractable P was influenced by the interaction effect ($p < 0.05$) of AER and period of fallow (Table 2). Bicarbonate-extractable P was found to be higher in soils with more than 10 years of fallowing in AER III and IV compared to soils in AER II and III with 10 years and below of fallowing (Fig. 1D of supplementary file). Soil bicarbonate-extractable P significantly varied ($p < 0.05$) across AER, soil texture and period of fallowing (Table 2). Soil bicarbonate-extractable P significantly increased from AER II to V. Forests and fields with more than 15 years of fallowing had significant higher ($p < 0.05$) soil bicarbonate-extractable P compared to the cultivated land and fields with a short period of fallowing (Fig. 1D of supplementary file). Sand clay loams had a significant higher ($p < 0.05$) bicarbonate-extractable P followed by loamy sands compared to sandy loam and sandy soils. Soil bicarbonate-extractable P ranged from deficient (< 20 mg kg^{-1}) to adequate (> 40 mg kg^{-1}) across AER, soil texture and period of fallowing (Table 7). All soil textures under different periods of fallowing in AER II and III had deficient (< 20 mg kg^{-1}) and marginal (20–40 mg kg^{-1}) soil bicarbonate-extractable P to sustain crop growth. Moreover, all cultivated land and fields of 0–5 years of fallowing across all soil textures and AER had deficient (< 20 mg kg^{-1}) to marginal (20–40 mg kg^{-1}) soil bicarbonate-extractable P. Sand clay loams and all soil textures in fields with more than 5 years of fallowing in AER IV and V respectively had adequate (> 40 mg kg^{-1}) soil bicarbonate-extractable P. Soil bicarbonate-extractable P responded similarly to N except for sandy clay loam in AER II and sandy loam in AER III and sandy loam in AER IV where fallowing soils for up to 20 years resulted in higher soil bicarbonate-extractable P than in forest soils (Fig. 2D).

3.6 Exchangeable K

Like soil bicarbonate-extractable P, exchangeable K was significantly influenced ($p < 0.05$) by the interaction effect of AER and period of fallow (Table 2). Similarly, K was

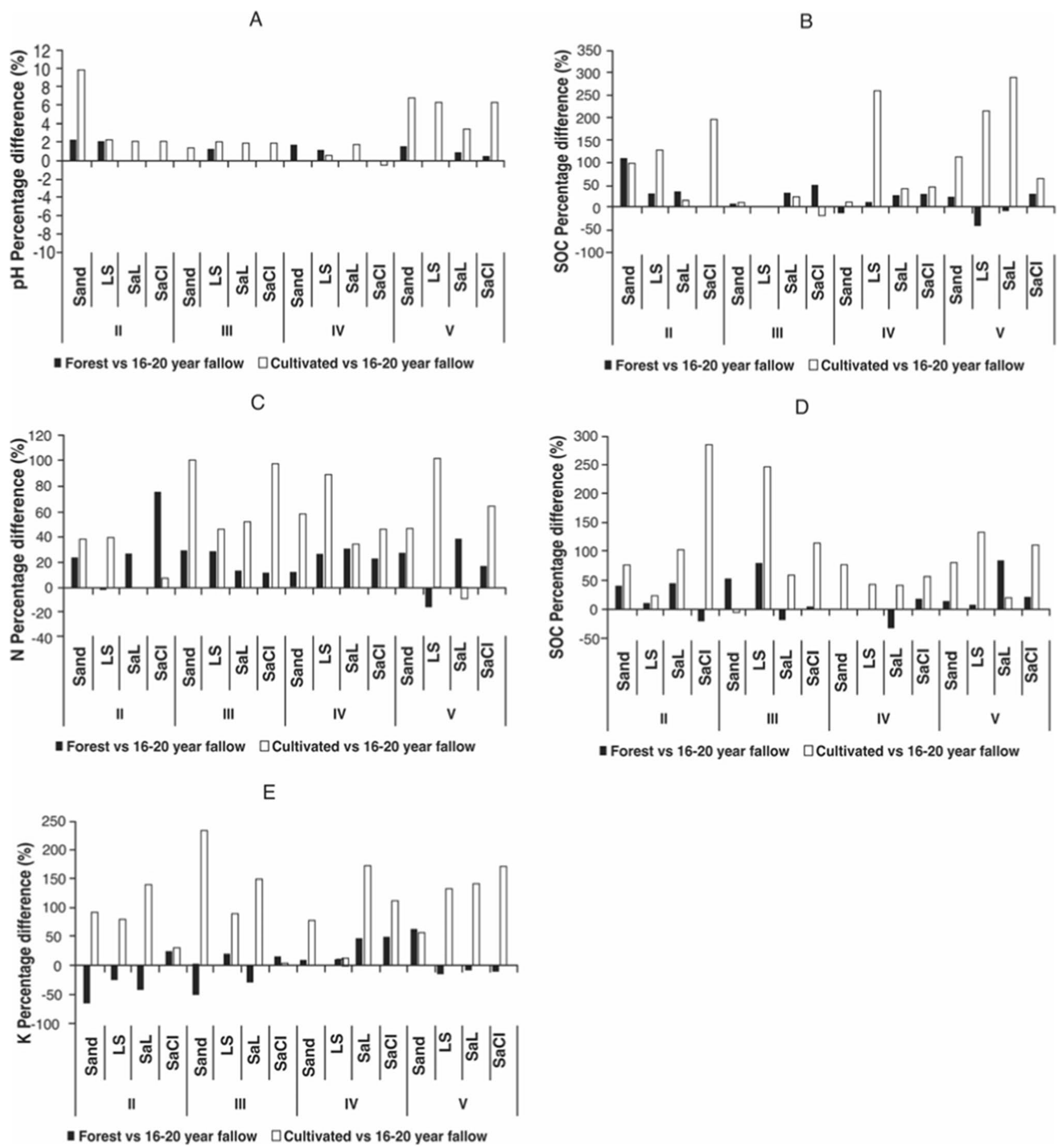

Fig. 2 Percentage differences between the two controls (forest and cultivated) and the 16–20-year fallow period for **A** soil pH, **B** soil organic carbon (SOC), **C** KCl-extractable N, **D** bicarbonate extractable P and **E** exchangeable K. Roman numerals (II, III, IV, V) represent AER. Soil textures: sand, loamy sand (LS), sandy loam (SaL) and sandy clay loam (SaCl)

found to be significantly higher ($p < 0.05$) in forest and fields under more than 15 years of fallowing in AER IV and V compared to the cultivated and fields with less than 10 years of fallowing in AER II and III (Fig. 1E of supplementary file). According to classification of nutrients by the Department of Research and Specialists Services, exchangeable K ranged from acutely deficient (< 0.45 $cmol_{(+)}kg^{-1}$) to adequate (> 0.7 $cmol_{(+)}kg^{-1}$) (Table 8). All soils except for those in forests and the ones with

Table 4 Soil organic carbon variations across AER, soil textures and period of fallowing in Zimbabwe

AER	Soil texture	Period of fallowing (years)					
		Control (cultivated)	0–5	6–10	11–15	16–20	Control (forest)
II	Sand	Very low	Very low	Very low	Very low	Very low	Medium
	Loamy sand	Very low	Very low	Low	Low	Low	Medium
	Sandy loam	Very low	Low	Very low	Very low	Low	Low
	Sandy clay loam	Very low	Very low	Very low	Low	Medium	Medium
III	Sand	Low	Very low	Very low	Very low	Low	Low
	Loamy sand	Medium	Very low	Low	Low	Medium	Medium
	Sandy loam	Medium	Medium	Low	Medium	Medium	Medium
	Sandy clay loam	Low	Very low	Very low	Low	Low	Medium
IV	Sand	Low	Very low	Very low	Very low	Medium	Low
	Loamy sand	Very low	Very low	Low	Medium	Medium	Medium
	Sandy loam	Medium	Very low	Very low	Medium	Medium	Medium
	Sandy clay loam	Low	Low	Very low	Medium	Medium	Medium
V	Sand	Low	Low	Medium	Medium	Medium	Medium
	Loamy sand	Very low	Medium	Medium	Medium	Medium	Medium
	Sandy loam	Very low	Low	Medium	Medium	Medium	Medium
	Sandy clay loam	Low	Low	Medium	Low	Medium	Medium

Classification adapted from Singh et al (2018); very low (< 0.5%), low (0.5–0.75%) and medium (> 0.75%)

Table 5 Pearson correlations showing relationships among selected soil fertility properties across AER, soil textures and period of fallowing in Zimbabwe

Variable	*M*	*SD*	pH	SOC	AP	EK
pH	5.36	0.65				
SOC	0.68	0.42	0.47**			
			[.38, .56]			
MN	27.03	10.50	0.44**	0.14*		
			[.34, .53]	[.03, .26]		
AP	42.42	39.18	0.52**	0.38**	0.21**	
			[.43, .60]	[.27, .47]	[.09, .32]	
EK	0.38	0.28	0.40**	0.38**	0.29**	0.33**
			[.30, .49]	[.28, .47]	[.18, .39]	[.22, .43]

M and *SD* are used to represent mean and standard deviation, respectively. SOC is soil organic carbon, MN represents mineral nitrogen, AP refers to available phosphorus and EK means exchangeable potassium. Values in square brackets indicate the 95% confidence interval for each correlation. The confidence interval is a plausible range of population correlations that could have caused the sample correlation (Cumming, 2014)

*Indicates $p < 0.05$

**Indicates $p < 0.01$

more than 15 years of fallowing under AER IV and V are of acutely deficient (< 0.45 $cmol_{(+)}kg^{-1}$) to deficient (0.45–0.7 $cmol_{(+)}kg^{-1}$) exchangeable K status. This implies that K deficiencies are prevalent in most agro-ecologies with different treatment combinations of soil texture and fallowing period. However, the results indicate that that fallowing soils for more than 20 years can result in significantly higher ($p < 0.05$) *K* values compared to forest soil for sands, loamy sand and sandy clay loam soils in AER II as well as for loamy sands, sandy loams and sandy claim loams in AER V (Fig. 2E).

4 Discussion

Soil type, climatic conditions and fallowing cycle can interact to influence soil pH. Soils in high potential areas with limited amounts of clay and a low fallow period tend to have a low pH buffering capacity (Six et al. 2002; Wei et al. 2019). High acidity in AERs II and III can also be attributed to relatively high rainfall compared with other AERs leading to high levels of leaching. Findings of this study are also in accordance with Selassie et al. (2015) who noted that soil pH was higher (6.05) under forest

Table 6 Soil KCl-extractable N variations across AER, soil textures and period of fallowing in Zimbabwe

AER	Soil texture	Period of fallowing (years)					
		Control (cultivated)	0–5	6–10	11–15	16–20	Control (forest)
II	Sand	Very low	Very low	Very low	Very low	Very low	Low
	Loamy sand	Very low	Low	Low	Very low	Low	Low
	Sandy loam	Very low	Low	Low	Low	Low	Low
	Sandy clay loam	Very low	Low	Low	Low	Very low	Medium to high
III	Sand	Low	Low	Low	Low	Medium to high	Medium to high
	Loamy sand	Very low	Low	Low	Low	Low	Medium to high
	Sandy loam	Low	Low	Low	Low	Medium to high	Medium to high
	Sandy clay loam	Very low	Low	Low	Low	Medium to high	Medium to high
IV	Sand	Low	Low	Low	Medium to high	Medium to high	Medium to high
	Loamy sand	Very low	Low	Low	Low	Medium to high	Medium to high
	Sandy loam	Low	Low	Medium to high	Low	Low	Medium to high
	Sandy clay loam	Low	Low	Low	Medium to high	Medium to high	Medium to high
V	Sand	Low	Low	Low	Medium to high	Medium to high	Medium to high
	Loamy sand	Low	Low	Medium to high	Low	Medium to high	Medium to high
	Sandy loam	Medium to high	Low	Low	Medium to high	Medium to high	Medium to high
	Sandy clay loam	Low	Medium to high	Low	Medium to high	Medium to high	Medium to high

Classification adapted from Mashiringwani (1983) and Nyamangara et al (2000); very low (< 20 $mgkg^{-1}$), low (20–30 $mgkg^{-1}$) and medium to high (> 30 $mgkg^{-1}$)

Table 7 Soil bicarbonate-extractable P variations across AER, soil textures and period of fallowing

AER	Soil texture	Period of fallowing (years)					
		Control (cultivated)	0–5	6–10	11–15	16–20	Control (forest)
II	Sand	Deficient	Deficient	Deficient	Marginal	Marginal	Marginal
	Loamy sand	Marginal	Deficient	Deficient	Deficient	Marginal	Marginal
	Sandy loam	Deficient	Deficient	Marginal	Deficient	Marginal	Marginal
	Sandy clay loam	Deficient	Deficient	Marginal	Deficient	Marginal	Marginal
III	Sand	Deficient	Deficient	Deficient	Deficient	Deficient	Marginal
	Loamy sand	Deficient	Deficient	Deficient	Deficient	Marginal	Marginal
	Sandy loam	Marginal	Marginal	Marginal	Marginal	Marginal	Marginal
	Sandy clay loam	Deficient	Marginal	Marginal	Marginal	Marginal	Marginal
IV	Sand	Marginal	Deficient	Marginal	Marginal	Adequate	Adequate
	Loamy sand	Marginal	Marginal	Marginal	Marginal	Adequate	Adequate
	Sandy loam	Marginal	Marginal	Marginal	Marginal	Adequate	Marginal
	Sandy clay loam	Marginal	Marginal	Adequate	Adequate	Adequate	Adequate
V	Sand	Marginal	Marginal	Marginal	Adequate	Adequate	Adequate
	Loamy sand	Marginal	Marginal	Adequate	Adequate	Adequate	Adequate
	Sandy loam	Marginal	Marginal	Adequate	Adequate	Adequate	Adequate
	Sandy clay loam	Marginal	Marginal	Adequate	Adequate	Adequate	Adequate

Classification adapted from Mashiringwani (1983) and Nyamangara et al (2000); deficient (< 20 $mgkg^{-1}$), marginal (20–40 $mgkg^{-1}$) and adequate (> 40 $mgkg^{-1}$)

compared to cultivated lands (5.44). The lowest value of pH under the cultivated land compared to fallowed lands and undisturbed forests could be due to the depletion of basic cations due to crop harvest which reduce organic input to the soil and leaching to streams in runoff generated from accelerated erosions (Parwanto and Alan 2019; Vortr et al. 2021). Soil pH was significantly and weak positively correlated with SOC (Table 5). This could be due to the ability of SOC and soil organic matter hydroxyl groups released during stabilization to buffer against acidity (Tonon et al., 2010). Contrary, Zhang et al. (2015) noted that pH was significantly and negatively correlated

Table 8 Soil exchangeable K variations across AER, soil textures and period of fallowing

AER	Soil texture	Period of fallowing (years)					
		Control (cultivated)	0–5	6–10	11–15	16–20	Control (forest)
II	Sand	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Deficient	Acutely deficient
	Loamy sand	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient
	Sandy loam	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Deficient	Acutely deficient
	Sandy clay loam	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient
III	Sand	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Deficient	Acutely deficient
	Loamy sand	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Deficient
	Sandy loam	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Deficient	Acutely deficient
	Sandy clay loam	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient
IV	Sand	Acutely deficient	Acutely deficient	Acutely deficient	Acutely deficient	Deficient	Adequate
	Loamy sand	Acutely deficient	Acutely deficient	Acutely deficient	Deficient	Deficient	Adequate
	Sandy loam	Acutely deficient	Acutely deficient	Deficient	Deficient	Adequate	Adequate
	Sandy clay loam	Acutely deficient	Deficient	Deficient	Deficient	Adequate	Adequate
V	Sand	Deficient	Acutely deficient	Deficient	Acutely deficient	Adequate	Adequate
	Loamy sand	Acutely deficient	Acutely deficient	Deficient	Deficient	Adequate	Adequate
	Sandy loam	Acutely deficient	Acutely deficient	Deficient	Adequate	Adequate	Adequate
	Sandy clay loam	Acutely deficient	Acutely deficient	Deficient	Deficient	Adequate	Adequate

Classification adapted from Mashiringwani (1983) and Nyamangara et al (2000); acutely deficient (0.45–0.7 $cmol_{(+)}kg^{-1}$), deficient (0.45–0.7 $cmol_{(+)}kg^{-1}$) and adequate (> 0.7 $cmol_{(+)}kg^{-1}$)

with SOC and concluded that acidification inhibits SOC decomposition. The divergence may be attributed to variations in soil type and climatic conditions. The low soil pH (< 5.5) in most fields and under different periods of fallowing in the diverse AERs is not considered ideal for optimal nutrient availability for most crops including maize, the staple crop (Shehu et al. 2018). This means that natural fallowing is of limited potential and effectiveness in restoring soil pH to original levels even if done to a period of 20 years. Therefore, liming to increase soil pH using either locally available material (i.e. ash, termite mound soils) or inorganic commercial materials (i.e. calcitic or dolomitic lime) could be adopted when converting the fallowed land to cropping (Olego et al. 2021). Application of phosphate rock and dolostone fractions shown to have a liming effect on tropical soils is another option to reduce acidity (Rafael et al. 2018). Moreover, improved fallows with N_2-fixing trees, such as *Acacia angustissima*, *Cajanus cajan*, *Tephrosia vogelii* and *Sesbania sesban*, that have been shown to be effective for improving soil fertility such as pH within a shorter time period of 8 months to 3 years may also be an option to consider in the smallholder sector of Zimbabwe (Partey et al. 2017).

Long period of fallowing was found to have a positive effect on SOC (Fig. 1B of supplementary file). This is in agreement with the finding of Bravo-Garza and Bryan (2005) who noted that more than 20 years of natural fallowing had beneficial effect on SOC. Similarly, Masse et al. (2004) noted that natural fallowing showed no evidence of increasing SOC in a short 10-year period in a sandy soil in Bolivian Altiplano. According to Yemefack et al (2002), SOC increases slightly but gradually with the age of the natural fallow. This build-up of SOC in lengthy fallow period and in undisturbed forests could be attributed to decomposition of above ground and root biomass of established trees, shrubs, perennial grasses and native leguminous species (Partey et al. 2017). Cultivation especially on sandy soils exposes the little available SOC to microbial activity and soil degradation processes as such low values were observed under cultivation (Biinemann et al. 2020; Yavitt et al. 2021). According to Six et al. (2002), it is also important to consider soil texture in SOC dynamics as sand fractions have limited capacity to protect SOM from microbial mineralization. This study showed that fallowing land even for up to 20 years does not return the SOC to the levels of undisturbed soil. In Mexico, a natural fallow of 22 years only recovered SOC by 16% compared to the cultivated fields (Aguilera et al. 2013). This illustrates that SOC restoration through natural fallowing is a slow process that requires extended period of time. Unfortunately, this may not be possible to adhere to given the land shortage as a result of an increasing world population which increase demand for food (Molotoks et al. 2020). According to UN (2015) estimates that African population will double from 1.2 to 2.5 billion by 2050 putting pressure on the land resource. This therefore means that farmers may need to consider applying organic manure or use of improved fallows to boost their soil carbon stocks. According to Gross and Glaser (2021), continuous application of manure induces an increase in SOC and soil fertility. Improved fallows containing forage N-fixing legumes such as *Lablab purpureus* and *Cajanus cajan* have potential to increase SOC from 2.6 to 194 kg ha^{-1} $year^{-1}$ (Masikati et al. 2014; Nord et al. 2020).

Short period of natural fallowing has limited capacity to increase N, the most limiting nutrient for sustainable crop intensification in the smallholder areas of Zimbabwe and SSA in general, to adequate levels required to support crop growth (Kaizzi et al. 2017). Short natural fallow periods do not provide enough time for SOM built up to supply enough N especially if there are limited nitrogen fixing plant species within the natural fallow. Low KCl-extractable N levels in short-term fallows with low clay content soils could also be attributed to rapid SOM mineralization with relatively high rainfall inducing leaching on KCl-extractable N in high rainfall areas (Six et al. 2002; Tadele, 2017). Similarly, Masse et al. (2004) also noted that short period of fallowing (< 5 years) in a sandy soil in Senegal did not significantly influenced increment of soil N. However, longer period of fallowing in low potential areas with soils containing high clay content has high KCl-extractable N accumulation possibly due to limited leaching and increase cation exchange capacity (CEC) and WHC (Chipomho et al. 2020). The positive interaction between AER and soil type on KCl-extractable N was also observed by Mtali-Chafadza et al. (2020) who also noted that N varied significantly with soil type and AER, with clay soil and soil from low rainfall potential area having significantly high N content. This makes long natural fallows comparable to improved fallows with N fixing forage legumes such as *Lablab purpureus*, *Medicago sativa* and *Cajanus cajan* which have capacity to increase N from 6 to 14 kg ha^{-1} $year^{-1}$ (Getachew 2013; Masikati et al. 2014). Furthermore, SOC was positively correlated with KCl-extractable N (Table 3) in accordance with the results reported by Metwally et al. (2019). This shows that SOC is an important parameter of the soil which influences soil N availability (Behera et al. 2018).

Soil bicarbonate-extractable P, in higher rainfall areas (AER II), was found to be generally low compared to low potential areas (AER V) (Fig. 1C of supplementary file). This could be attributed to limited SOM which could help mask acidity-induced P-fixation in the soil found in high potential areas (Nziguheba et al. 2016). Chipomho et al. (2020) also noted that low pH (acidic) sandy soils due to increased levels of leaching in high potential areas with limited SOC affect the availability of nutrient elements like P. Forests and fields with more than 15 years of fallowing had higher soil bicarbonate-extractable P compared to cultivated and fields with a short period of fallowing due to increased accumulation of SOC of the soil over time (Six et al. 2002; Nziguheba et al. 2016). However, contrary to these findings, Gebeyaw (2007) and Selassie et al. (2015) noted that ageing of a natural fallow and undisturbed forests reduces P availability due to absorption and storage in the biomass of plants. Soils with higher clay content were found to have higher amounts of bicarbonate-extractable P (Fig. 1C of supplementary file). High amount of clay fraction in a soil positively contribute to availability of nutrients such as P (Kihara et al. 2016; Soropa et al. 2018). Thus, long period of natural fallowing in soils with high clay content has potential to increase bicarbonate-extractable P, the second most limiting nutrient to crop growth in most arable fields in Zimbabwe and in SSA (Nziguheba et al. 2016). Similarly, Yemefack et al. (2002) noted that long (> 8 years) natural fallows on clay soil positively influence bicarbonate-extractable P levels to become similar or more to that of the virgin forest. However, natural fallowing could be difficult to adopt as a low-cost strategy to increase bicarbonate-extractable P in resource-constrained smallholder farming systems due to increased population densities and land shortage (Molotoks et al. 2020).

Exchangeable K was significantly influenced ($p < 0.05$) by the interaction effect of AER and period of fallow (Fig. 1D of supplementary file). This is in agreement with the work of Aguilera et al. (2014) who noted that fallowing in dry regions for long period of time (> 10 years) significantly increased concentration of nutrients like exchangeable K. The prevalent exchangeable K deficiencies in most AERs with different treatment combinations of soil texture and fallowing period are worrisome and need attention as K is considered the third most important nutrient for crop productivity in SSA (Kihara et al. 2020). Andrews et al. (2021) noted that high exchangeable K deficiency levels in agricultural soils are possible due to poor K retention on soil exchangeable complex caused by strong acidity and leaching. Low soil pH results in reduction in CEC and deficiency of exchangeable K (Nyamangara et al. 2000; Nziguheba et al. 2016). Therefore, K fertilizer additions, liming and soil and water conservation techniques should be considered in these areas. However, the result on acutely deficient to deficient exchangeable K status on most soils under in this study especially in high potential areas with short fallows is contrary to previous studies that indicate adequate concentrations of the exchangeable K in most soils, even those under cultivation in Zimbabwe (Kurwakumire et al. 2014; Nyamangara et al. 2000). The low levels of K could be attributed to leaching especially in high rainfall AER II. The results on K illustrate that long fallow fields (> 10 years) in low potential areas have the potential to recover exchangeable K. However, just like with all other nutrients, it will be difficult for farmers to leave their fields to fallow for long periods of time due to limited cropping land and the ever rising population.

5 Conclusion

In conclusion, the study revealed that natural fallowing has limited capacity to restore soil fertility status to original levels on contrasting soils in the short to medium term (< 15 years) across different agro-ecological regions (AERs) once the land has been cleared for cultivation in Zimbabwe. Therefore, with the increasing population and land shortage, other low input strategies known to improve soil fertility over a short period are highly recommended. Policy makers should encourage smallholder farmers to adopt farming practices that help improve soil pH, soil organic carbon (SOC), macronutrient availability such as improved fallows, liming of acidic soils, application of soil organic matter (SOM) and inorganic fertilizers for increased crop productivity, profitability and sustainability.

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Author Contribution GS was involved in research design and layout; performed data collection, analysis and interpretation; and was the major contributor in writing the manuscript. MAM was involved in data analysis and interpretation of soil pH, OC and macronutrients. NM was involved also in study site map development, data analysis and interpretation. LM was involved in datasets presentation, analysis and interpretation. All authors read, edited and approved the final manuscript.

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Code Availability Not applicable.

Declarations

Competing Interests The authors declare no competing interests.

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