Integrated crop-livestock farming offers a solution to soil fertility mining in semi-arid Kenya: evidence from Marsabit County

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Abstract

Food security is a problem throughout most of sub-Saharan Africa. Sustainable intensification has been promoted as a means to address this challenge and deliver food security without negative environmental consequences. Herein lies another dimension of the challenge, since there is abundant evidence of declining soil fertility as a result of soil nutrient depletion. Soil nutrients are being mined by small-scale farmers who continue to remove large quantities of nutrients from their soils without using sufficient manure or fertilizer inputs to replenish maintain soil fertility. This low-input agriculture will not deliver future food security and a large increase in nutrient inputs is seen as a requirement for sustainable intensification.

We present here a case study from Marsabit County; the largest, most arid, and least developed region in Kenya. Evidence was gathered from field studies at four locations during 2016 and 2017 combined with a farmer survey. We show that a typical smallholder farm can achieve an acceptable nitrogen balance through better use of available livestock manure. An acceptable balance can also be achieved for phosphorus, however, there is a deficit for potassium. This case study demonstrates that an integrated crop-livestock farming system offers a potential solution to soil nutrient mining and can provide a pathway to sustainable intensification for small-scale farmers in a challenging semi-arid environment.

Key words

Sustainable intensification, soil nutrient balance, mixed farming, maize, fertilizer, manure, Kenya

1. Introduction

Food security is a problem throughout most of sub-Saharan Africa (SSA), where only two countries (South Africa and Botswana) appear in the top half of the 2018 global food security rankings (https://foodsecurityindex.eiu.com/), while 22 of the 28 countries in the bottom quartile are from SSA. Food supply is affected by recurrent risks that are well-known; farmers have always been subject to the vagaries of nature, and political conflicts have repeatedly disrupted farming and thrown markets into disarray. Faced with growing population pressure, the loss of productive land through urbanisation and land degradation, and the threat posed by climate change, the challenge will only increase in the future. Sustainable intensification has been promoted (Godfray et al., 2010; Pretty et al., 2011) as a means to address this challenge and deliver food security without negative environmental consequences. Views diverge on what is meant by sustainable intensification (Petersen & Snapp, 2015), but there is general agreement that maintenance of soil fertility is an essential component.

Herein lies another dimension of the challenge facing SSA, since there is abundant evidence of declining soil fertility as a result of soil nutrient depletion. The severity of 'nutrient mining' is apparent from various authors, who have reviewed the available data on nutrient balances across different spatial scales. Sheldrick and Lingard (2004) calculated nutrient balances from 1961 to 1998 and concluded that in most countries of SSA, nutrient depletion was accelerating. In 1998 the average annual depletion rate was 17 kg N /ha and this was projected to reach 37 kg N/ha by 2020. The corresponding data for phosphorus were 3.3 kg P /ha increasing to 6 kg P/ha, and for potassium 20 kg K /ha increasing to 36 kg K /ha by 2020. Earlier analysis by Stoorvogel et al (1993), using different methodology, for the arable soils of 38 SSA countries from 1982 to 1984 found that annual average nutrient loss was 22 kg N/ha, 2.5 kg P/ha, and 15 kg K/ha in 1982-84, and projected to be 26 kg N/ha, 3 kg P/ha, and 19 kg K/ha in 2000. A comprehensive review by Cobo et al (2010) identified 57 peer-reviewed nutrient-balance studies from SSA, most of which were at plot and farm scale. Data confirmed the expected trend of balances in the continent for nitrogen and potassium, where >75% of selected studies had negative mean values. However, for phosphorus only 56% of studies showed negative mean balances. Notably, 19 of the 57 studies were carried out in Kenya.

Soil nutrients are being mined because, over decades, small-scale farmers have removed large quantities of nutrients from their soils without using sufficient quantities of manure or fertilizer inputs to replenish the soil fertility (Sanchez, 2002). This low-input agriculture will not deliver future food security in SSA and a large increase in nutrient inputs is seen as a requirement for sustainable intensification. However, most of the countries of SSA have not achieved the target of 50 kg nutrients per hectare set in the 2006 Abuja Declaration on Fertilizer for an African Green Revolution (AU/NEPAD, 2006) and the average for SSA is still less than 20 kg/ha (Masso et al, 2017a). Reasons for low use of mineral fertilizers in the farming systems of SSA include high price, low profitability, weak fertilizer markets, inappropriate packaging sizes and knowledge constraints (Masso et al, 2017b; Chianu et al, 2012).

Given the low use of manufactured fertilizers, a greater focus on use of on-farm sources of organic nutrients might be expected, but this alternative has often been dismissed. This may be on the grounds “that no organic inputs contain a sufficient amount of readily available plant nutrients to qualify as fertilizer” (Vanlauwe et al, 2017). Alternatively, the constraint may be perceived difficulties in obtaining adequate organic resources, which can be composted (Ouédraogo, Mando, Zombréc, 2001) or livestock manure (Kiboi, Ngetich, Mugendi, 2019). Mixed crop-livestock farming systems have received relatively little attention as a solution to soil nutrient mining in sub-Saharan Africa. Yet, for the resource-constrained small-scale farmers of SSA, integrated crop-livestock systems is the only available option for sustainable soil management. We therefore present a case study from Kenya which seeks to explore sustainability of the dryland mixed farming system through a nutrient balance study.

2. Case study location

The study area is Marsabit County in northern Kenya, close to the border with Ethiopia to the North and Lake Turkana to the West (Figure 1). It is Kenya’s largest, most arid, and least inhabited region, with population density of 6 persons per square kilometre according to the recent Kenya population and housing census (GoK, 2019). Furthermore, the majority of its people were, until quite recently, nomadic pastoralists. It lies within Kenya’s Northern Region which consists of a gently sloping plateau ranging in altitude from 1200 m to the North of Mt. Kenya to barely 400 m around Lake Turkana. To the North of Isiolo, the plateau receives <250 mm annual rainfall, which is adequate to support only shrubby vegetation. A series of isolated inselbergs of volcanic origin rise from the plain, one of which is Marsabit Mountain. As a result of its high altitude (about 1680 m above sea level), the mountain receives higher rainfall (annual total between 800 and 1000 mm), which is adequate to support forest cover (Oroda et al., 2005). There is a bimodal rainfall pattern with peaks in April and November. The continuous wind direction from Northeast causes a relatively humid ecology on the eastern side of the mountain and a dry ecology on the western side of the mountain. Rainfall records for Marsabit town in the last 50 years shows considerable variability with annual mean 727 mm, median 687 mm and interquartile range of 378 mm.

Humans have settled around the mountain because of the availability of water and good soils (Oroda et al., 2005). In contrast to the soils of the plains, which consist mainly of Vertisols, Regosols, Lithosols and Cambisols, the mountain slopes are mainly covered with humic Acrisols over the basement formations, and deep, humic Andosols in mountain areas. No source reports the presence of settlements in the area before 1900 (Adano & Witsenburg, 2005). The settlement of crop farmers was encouraged by the colonial administration during the 1930s, but in 1935, the total settled population still amounted to less than 1000 people. The population within Marsabit County, and in particular on land close to the mountain, continued to grow through the process of sedentarization of pastoralists following droughts in the 1970s. They were attracted initially to famine-relief centres and agricultural schemes established principally by religious organizations. This is also seen as a response to increasing political conflict that has made extensive grazing land less secure (Galaty, 2005). Today an estimated 80,000 people live on land close to Marsabit Mountain (GoK, 2019).

Sedentarization is the process of individuals, households, or entire communities of formerly nomadic populations settling into non-mobile, and permanent communities. Rainfed crop farming and its associated sedentary lifestyle have been adopted by the previously nomadic pastoralists in similar areas with suitable soils and sufficient rainfall for maize and beans production. These farmers often keep some livestock, though the crop and livestock components of the farming system are poorly integrated. Livestock moves seasonally to graze where there is a better pasture, in response to spatial variability in the quality of pasture. The same livestock will also graze seasonally on non-food crop biomass, thus bringing manure to crop fields and offering the prospect of avoiding soil nutrient mining. The case study site is of particular interest because its relatively recent history of settlement means firstly that nutrient mining has not advanced to the extent that soils are degraded, and secondly that the livestock population is relatively high. Together, these two attributes suggest that a possible route to achieve sustainable intensification may exist through better integration. A crucial question is to what extent can Marsabit County support further sedentarization of pastoralists in future within a sustainable mixed crop-livestock farming system?

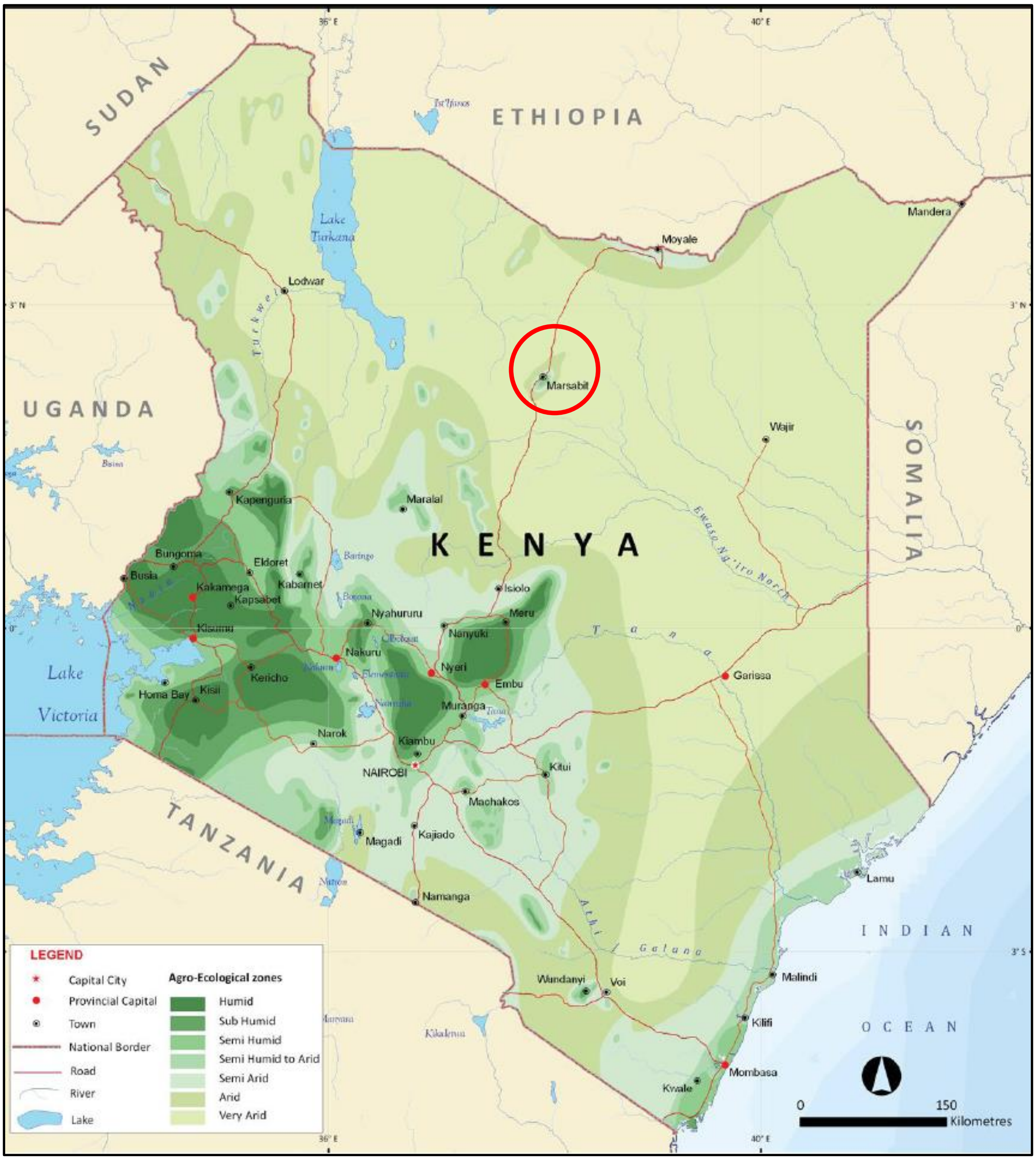

Figure 1: Agro-ecological zones in Kenya (showing case study site)

3. Methodology

3.1 Farmer interviews

In order to understand the farming system, semi-structured interviews took place in four locations within the case study area: Dakabaricha (DK), Songa (SG), Badassa (BD) and Sagante (SA) (Figure 2). In each location, ten farmers practising mixed crop-livestock systems were interviewed during 2016 and 2017 long rain seasons. They were asked questions relating to their food production systems, the number of persons living in their household, crops grown and size of land owned, the type and number of livestock owned.

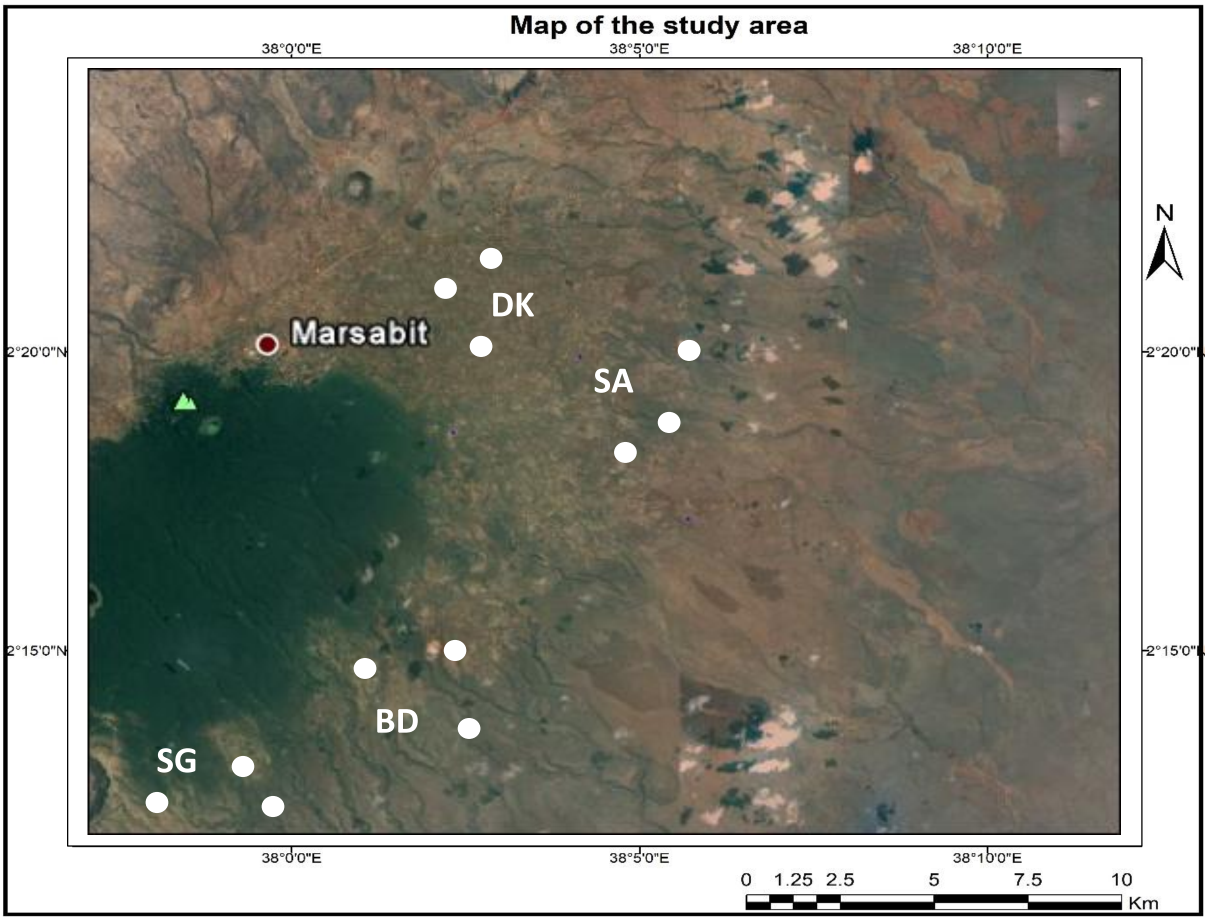

Figure 2: Location of study sites: Dakabaricha (DK), Songa (SG), Badassa (BD) and Sagante (SA)

In addition, potential nutrient pathways within the production systems were investigated. This involved identifying various subsystems within the production environment. The key materials that regulate the transfer of nutrients between the subsystems were identified through farmer interviews. These include the possible sources of nitrogen for a subsystem as well as possible pathways nitrogen is taken out of a subsystem. Farmers also provided information on the quantity of wood ash they produced and the quantity of house maintenance material (mixture of soil and manure) they used.

3.2 Soil sampling and analysis

In each study location, 3 farms with maize and bean fields were sampled. In total, soils were sampled from 12 maize fields and 12 bean fields from two depths (0-30 cm and 30-60 cm). Samples were collected from 10-15 points in each field following a zig-zag pattern. These were bulked, mixed and sub-sampled to leave 48 soil samples altogether at each time of sampling. Soil samples were then analysed for texture, total N, available P and K, total organic carbon and pH.

For total nitrogen, the Kjeldahl method was used. Dried soil samples (< 0.5 mm) were digested with concentrated sulphuric acid containing potassium sulphate, selenium and copper sulphate hydrated at approximately 350°C. Total N was determined by distillation followed by titration with diluted standardized 0.007144 N H_2SO_4 (Bremner and Mulvaney 1982). P and K analysis followed the Mehlich double acid method. The dried soil samples (< 2 mm) at 40°C were extracted in a 1:5 ratio (w/v), with a mixture of 0.1 N HCl and 0.025 N H_2SO_4. K was determined with a flame photometer. P was determined spectrophotometrically (Mehlich 1984). Organic carbon was determined using the calorimetric method. All organic C in the dried soil samples (< 0.5 mm) was oxidized by acidified dichromate at 150 °C for 30 minutes. This ensured complete oxidation. Barium chloride was added to cool digestate and after mixing thoroughly, this was allowed to stand overnight. The C concentration was read by spectrophotometer at 600 nm (Sims and Haby 1971, Anderson and Ingram 1993).

Soil pH was determined in a 1:1 (w/v) soil – water suspension, with a pH meter. Soil texture was determined using the hydrometer method. 50 g of dried soil (< 2 mm) was weighed and transferred into a 500ml plastic shaking bottle. 300 ml of distilled water and 50 ml of dispersion agent (calgon) were added. After shaking, the soil suspension was transferred into a sedimentation cylinder and topped up to the 1 L mark. It was then mixed thoroughly with a plunger to bring the soil particles into suspension. A hydrometer was lowered into the solution and a reading taken and recorded 40 seconds after stirring ceased. After 2 hours, a second reading was taken. The first hydrometer reading indicated percentage for silt and clay. The second reading indicated the density of sandy particles and the percentage sand was calculated (Klute 1986).

3.2 Nitrogen balance for crop fields

Nitrogen balance is the difference between nitrogen input and the nitrogen output. The various potential sources of nitrogen inflows and outflows are indicated in Figure 3. The subsystems include: cropping, homestead, livestock and grazing land subsystems. Each subsystem affects the productivity and sustainability of every other subsystem. This work quantified the key materials to provide a partial nitrogen balance.

$$\text{Partial nitrogen balance} = (IN1 + IN2) – (OUT1 + OUT2).$$

The primary inputs were mineral fertilizer (IN1) and manure (IN2), while primary outputs were through crop grains (OUT1) and non-food crop biomass (OUT2). The partial balance was considered at field level, involving maize and bean fields in each farm.

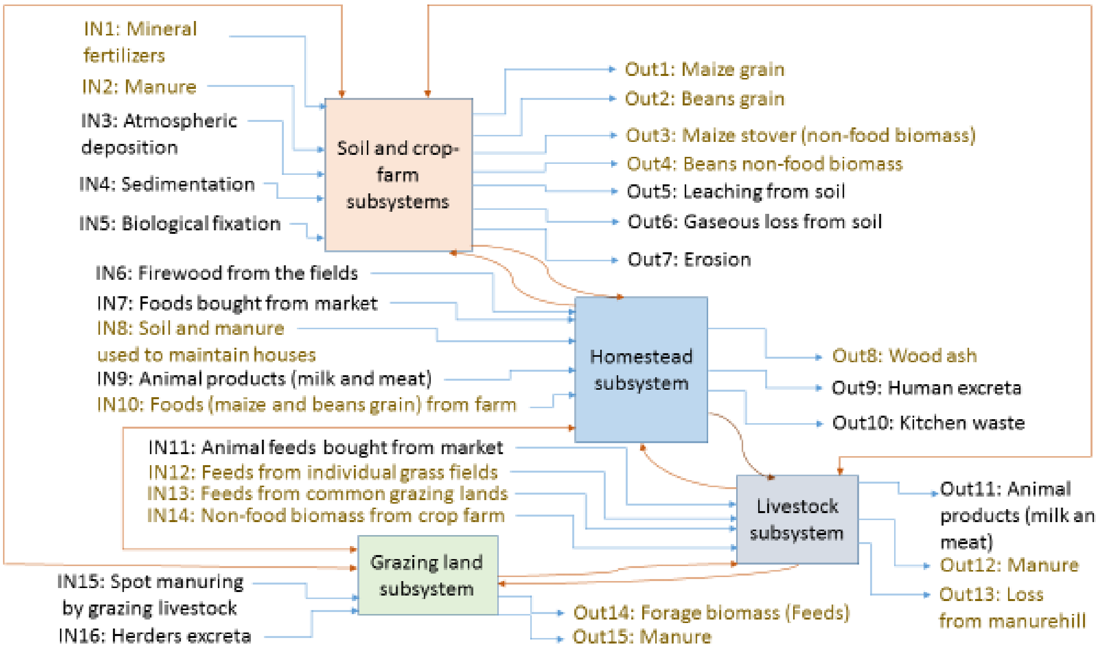

Figure 3: Indicative nitrogen pathways within the farming system

3.3 Quantification of nitrogen output from crop fields (OUT1 + OUT2)

The maize and bean crops in the selected sample farms were monitored throughout the growing period of 2016 and 2017 long rain seasons. At the maturity stage of each crop, 3 quadrats, each measuring 3 m x 3 m were randomly sampled in all maize and bean fields. The harvestable crop and non-food biomass were collected and weighed separately using a field balance. Samples for determining dry matter and samples for laboratory analysis were collected. The samples for dry matter analysis were dried in an oven at 105oC for 24 hours and dry weight determined. Other samples were transported for laboratory analysis.

The samples were dried at 40°C and milled in preparation for laboratory analysis. In the laboratory, samples were weighed to about 50 mg into a foil cup. The cup was carefully folded and squashed into a pellet to expel the air. The analysis itself was carried out using the CN cube. This involved using a combustion, post combustion and reduction tube in the furnace of the cube analyser. The combustion tube was at 960°C and a sample was dropped into this via a carousel and ball valve. Oxygen is used to burn the sample and the gas is carried off in helium through both the post combustion (900°C) and reduction tubes (830°C) (which are also heated) to the detectors housed within the analyser. Nitrogen element is analysed and a % figure is then obtained. Before each run, a set of standards were run which ensures that the analyser is working correctly. Standards are also run halfway through a sample run as well. To check that the analyser was operating correctly, there is a daily factor figure which was worked out after each run. Runs that did not achieve a factor between 0.9 and 1.1 were discarded.

Nitrogen output in crop (ie. maize or bean grains) (kg/ha/season) was determined as:

% N concentration in the crop grains x 10 x crop grain yields (t/ha/season)

Nitrogen output in non-food biomass (maize and beans stover) (kg/ha/season) was determined as:

% N concentration in the non-crop biomass x 10 x non-food biomass yield (t/ha/season)

3.4 Quantification of nitrogen inputs to crop fields (IN1 + IN2)

The 12 maize farmers and 12 bean farmers, whose crop production practices were studied, were also interviewed during the long rain seasons of 2016 and 2017 to determine the quantities of mineral fertiliser and livestock manure they applied to the crop fields per hectare per season. Wheelbarrow-load was the unit of measurement of manure use by the farmers. In other similar studies, a dried wheelbarrow load of manure was estimated at 40 kg to 50 kg (Dovie, Witkowski et al. 2003, Savala, Omare et al. 2003, Kearney, Fonte et al. 2012). For this work, a conversion factor of 46 kg was used. Manure used by the farmers was analysed in the laboratory and nitrogen concentrations was determined using the method described above.

3.5 Manure production by farmers

The traditional enclosure where livestock are kept at night is known locally as a '*boma*'. It is fenced with locally available brushwood. The floor is mainly earth and this influences the quantity of collectable manure. To investigate how much manure can be collected from the livestock *boma*, an enclosure similar to farmers' *boma* with a size of 12.56 square metre (adequate for two mature zebu cattle) was constructed. Two typical mature zebu cattle from the study area were allowed to graze outside in the field according to farmer practice and taken back to the *boma* each evening at 6.30pm. In the morning at 7.30am, the manure in the *boma* was collected and fresh weight taken. A sub-sample of manure was placed in an oven for 24 hours at 105°C and dry weight determined. The measurement of manure was done in this way for 14 days.

Additionally, 25 cattle farmers were interviewed on the quantity of manure produced. The farmers gave estimates on the wheelbarrow-loads of manure produced per month. The farmers were also asked the number of cattle they own. This information was then converted to daily manure production per TLU.[1]

Farmers in the study area store manure for at least 4 months on the ground in the open air before applying it to their crop fields. An ancillary study was conducted to investigate the change in nutrient content during storage. Manure was collected from 3 locations (SG, BD and SA); in each location, fresh manure of about 90 kg was collected from 3 different livestock *bomas.* Thus, fresh manure weighing 270 kg was collected from each location of the study. Three alternative storage treatments were investigated: (1) under roof on plastic sheet, (2) outside on plastic sheet, (3) outside on the ground (i.e. the de facto farmer's practice in the study area). Storage treatments were conducted for four months. Initially and at the end of every month, samples of manure were collected and analysed in the laboratory for total organic carbon, total nitrogen, total phosphorous and total potassium.

3.6 Laboratory analysis of manure and house maintaining material

The samples were dried at 40°C then digested in tubes with H_2SO_4, salicylic acid, H_2O_2 and selenium. The larger part of organic matter is oxidised by hydrogen peroxide at relatively low temperature (100°C). After decomposition of the excess H_2O_2 and evaporation of water, the digestion is completed by concentrated sulphuric acid at elevated temperature (330°C) under the influence of Se as a catalyst. Potassium was determined with a flame photometer, phosphorus was determined calorimetrically on spectrophotometer, N-total was measured by distillation followed by titration with standardized 0.01 N HCl. Calorimetric method was used for analysing total organic carbon.

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[1] Total livestock units (TLU) are calculated on the basis of: cattle = 1.0 TLU; sheep = 0.1 TLU; goat = 0.1 TLU; 1 TLU is equivalent to live animal weighing 250kg.

3.7 Quantifying crop yields under manured and unmanured treatments

The same four locations where farmer's crop production practices were monitored were selected for a manure input experiment in 2017. In each location, 3 farms were sampled. In each farm, 6 maize experimental plots and 6 beans experimental plots were laid out at the beginning of the long rain season. Each experimental plot measured 5 m x 5 m (25 m^2). Treatments were with/without manure, with three replicates. The rate of manure application in maize plots was 200 kg total nitrogen/ha (equivalent to 25 kg of cattle manure per plot or 10 t/ha). The rate of manure application in bean plots was 100 kg total nitrogen/ha (equivalent to 12.5 kg of cattle manure per plot or 5 t/ha). These experimental plots were then monitored throughout the growing season. At the end of growing season, the fresh weight of maize and bean grains and their non-food biomass were measured. Sub-sample of grains and non-food biomass were then dried in an oven at 105^oC for 24 hours and dry matter recorded.

4. Results and discussion

4.1 Household and farm enterprise data

The farmer survey (n=40) indicated that the mean household size of 6 persons is sustained from a crop area of 1.5ha with 0.7 ha under maize and 0.5 ha under beans. Similarly, the Kenya 2019 census results (GoK, 2019) indicated average household size of 5.8 persons, in Marsabit. Cattle (East African zebu, mainly of Boran breed) represent the main livestock holding with 16 per household, while also goats and sheep are kept. The mean total livestock holding is 19 TLU per household.

4.2 Soil properties at study sites

Soil sample analysis (Tables 1 & 2) confirmed that all sites are dominated by slightly acid, clay soils. These Acrisols are known to have poor chemical properties with low base saturation (i.e. low nutrient content) and with problems of Aluminium toxicity and P sorption. Low levels of total C are indicative of inadequate soil organic matter content. Nitrogen is the most limiting nutrient while P and K levels are generally adequate. These finding are consistent with an assessment of the soil fertility status of Marsabit Sub- County by Kenya's National Accelerated Agricultural Inputs Access Program (2014).

Table 1: Physical characteristics of soils at study sites

	BD location (n=48)	DK location (n=48)	SA location (n=48)	SG location (n=48)
Clay (%)				
0-30cm (topsoil)	64.67(3.53)b	67.67(1.31)b	62.00(3.61)b	69.33(1.69)b
30-60cm (subsoil)	72.00(3.22)a	73.33(1.69)a	71.67(1.58)a	75.33(0.99)a
Silt (%)				
0-30cm (topsoil)	22.00(1.71)a	21.67(1.41)a	21.00(1.34)a	22.33(1.50)a
30-60cm (subsoil)	15.33(0.99)a	18.67(2.17)a	19.00(1.69)a	19.00(1.00)a
Sand (%)				
0-30cm (topsoil)	13.33(1.84)ab	10.67(0.84)ab	17.00(3.61)a	8.33(0.80)b
30-60cm (subsoil)	12.67(2.35)a	8.00(1.46)ab	9.33(0.84)ab	5.67(1.41)b

Means in each row that do not share a letter are significantly different at *P*≤0.05 by Tukey's HSD test. Values are given as mean at each location with SE in parentheses.

Table 2: Chemical characteristics of soils at study sites

	BD location (n=48)	DK location (n=48)	SA location (n=48)	SG location (n=48)	Deficiency level for chemical characteristics	Sources for deficiency level
pH						Adapted from: Muya, Gitau et al. (2010) Berazneva, McBride et al. (2016)
0-30cm (topsoil)	6.6(0.15)a	6.1(0.06)b	6.1(0.02)b	6.2(0.11)b	<5.5	
30-60cm (subsoil)	6.3(0.16)b	6.1(0.07)b	6.0(0.05)b	6.1(0.10)b		
Total N (%)						Adapted from: Muya, Gitau et al. (2010); Berazneva, McBride et al. (2016)
0-30cm (topsoil)	0.12(0.020)a	0.12(0.005)a	0.13(0.003)a	0.13(0.007)a	<0.20%	
30-60cm (subsoil)	0.12(0.007)ab	0.10(0.007)b	0.13(0.005)a	0.13(0.005)a		
Available P (ppm)						Adapted from: Muya, Gitau et al. (2010)
0-30cm (topsoil)	33.33(5.43)a	54.17(11.93)a	52.50(14.24)a	19.17(4.36)a	<20.00 ppm	
30-60cm (subsoil)	20.83(2.01)b	31.67(9.46)b	40.83(10.44)b	27.50(3.82)b		
Available K (%)						Adapted from: Muya, Gitau et al. (2010)
0-30cm (topsoil)	1.09(0.11)a	1.09(0.06)a	0.99(0.06)a	0.88(0.20)a	<0.83%	
30-60cm (subsoil)	0.76(0.19)b	0.62(0.08)b	0.64(0.02)b	0.62(0.15)b		
Total C (%)						Adapted from: Muya, Gitau et al. (2010)
0-30cm (topsoil)	1.23(0.23)a	1.02(0.06)a	1.37(0.04)a	1.37(0.12)a	<1.08%	
30-60cm (subsoil)	1.11(0.13)ab	0.73(0.09)b	1.17(0.05)a	1.15(0.10)a		

Means in each row that do not share a letter are significantly different at P≤0.05 by Tukey's HSD test. Values are given as mean at each location with SE in parentheses

4.3 Crop performance

Raingauges installed at the study sites indicated considerable spatial variation, but with a close relationship to altitude (Golicha, 2018). The amount of rainfall in the crop season of 2016, was higher than in 2017 (Table 3). Analysis of the 50-year record for Marsabit Town (Golicha, 2018) indicates that the 2016 year was relatively wet (corresponding to a 15% probability of exceedance) while 2017 was relatively dry (corresponding to 90% probability of exceedance).

Grain yields (Table 4) were highly variable with a mean of 1.27 t/ha for maize and 0.80 t/ha for beans in 2016. The low rainfall in 2017 meant that the crop grain yields were not measurable in all study farms. Crop production data for Marsabit are sparse but a household survey by Adano and Witsenburg (2005) indicates that a typical household expects to produce around 1 tonne of maize per year. Analysis of other arid and semi-arid counties in Kenya by Omoyo et al (2015) indicates that the data for 2016 represent a relatively good year.

Manure inputs by farmers to the monitored maize fields averaged 12.6 kg N per hectare in 2016 with maximum value 45.5 and minimum value 2.7 kg N per hectare. In 2017 the corresponding mean value was 10.1 kg N per hectare with a range 2.7 to 27.2 kg N per hectare. Farmers' manure inputs to their bean crop was slightly less than this in both years. These are low values and crop grain yields and above-ground crop biomass were substantially higher in the experimental plots receiving greater manure inputs (Table 5). However, 2017 season received low rainfall and crop production was adversely affected.

Table 3: Long rain season (April – August) rainfall at study sites (mm)

Location	Altitude (m)	2016 Rainfall	2017 Rainfall
Marsabit Town	1353	598.2	151.7
BD	1010	N/A	267.3
DK 1	1251	565.6	155.3
DK 2	1268	572.0	149.6
DK 3	1281	541.2	158.8
SG 1	1015	501.9	378.0
SG 2	1007	488.0	299.2
SG 3	1002	446.4	312.3
GL 1	738	359.9	95.5
GL 2	642	364.9	69.9
GL 3	1143	410.9	83.0

Table 4: Maize and beans grain DM yields (kg/ha)

Location	Farm	Maize		Beans	
		2016	2017	2016	2017
DK	1	2.29(0.38)		1.15(0.28)	
	2	3.35(0.48)		1.37(0.49)	
	3	0.92(0.00)		1.32(0.00)	
SG	1	1.61(1.59)	0.14(0.05)	0.20(0.09)	0.64(0.20)
	2	0.72(0.36)	0.86(0.16)	0.78(0.60)	0.42(0.09)
	3	1.59(0.56)	1.46(0.62)	1.46(0.00)	0.61(0.23)
SA	1	1.09(0.54)		0.26(0.21)	
	2	0.68(0.00)		0.11(0.00)	
	3	0.59(0.00)		0.94(0.00)	

BD	1	0.45(0.27)	1.11(0.25)	0.19(0.10)	0.44(0.11)
	2	1.07(0.46)	0.76(0.28)	1.43(0.48)	0.75(0.27)
	3	0.91(0.39)		0.42(0.32)	

Values are given as mean at each farm with SD in parentheses.

Table 5: Maize and bean production (t/ha) in manured and unmanured fields (n=12)

Manure treatment	Maize		Beans	
	Grain	Total Biomass	Grain	Total Biomass
With	1.70 (0.23) a	4.42 (0.43) a	0.92 (0.04) a	2.56 (0.17) a
Without	0.65 (0.09) b	2.87 (0.34) b	0.59 (0.08) b	1.44 (0.12) b

Means in each column that do not share a letter are significantly different at *P*≤0.05, by Tukey's HSD test. Values are given as mean for each treatment with SE in parentheses.

4.4 Nitrogen balance

The farmer survey found that mineral fertilizer was not used for the food crop fields of the study area. The only source of nutrient input was livestock manure which was applied in relatively small quantities. By combining yield data (Table 4) with nitrogen content data (Table 6) it is possible to compute nitrogen offtake.

Table 6: Nitrogen concentrations and material flows at study sites

Material	Total nitrogen concentration in this material (%)	Sample size (n)	Average quantity produced or used during 2016 and 2017
Maize grain	1.54 (0.55)	94	1070 kg/ha per season
Maize non-food biomass	1.34 (0.97)	109	5850 kg/ha per season
Bean grain	4.01 (0.92)	131	680 kg/ha per season
Bean non-food biomass	1.80 (0.99)	109	1020 kg/ha per season
Material for maintaining houses	1.75 (0.35)	3	32 kg per household per month
Forage grass (Livestock feeds)	0.98 (0.71)	9	6000 kg/ha in wet season
Wood ash	0.13 (0.06)	9	8 kg per household per month
Cattle manure	2.22 (0.54)	20	1.71 kg per day per TLU

Note: reported total nitrogen concentrations are mean of each material with SD in parentheses.

The nitrogen removal by maize stover (non-food biomass) was higher than the nitrogen removal by maize grains. This is due to higher quantity of non-food maize biomass produced. The non-food crop biomass forms part of livestock feed. Nitrogen removal by bean grains is higher than removal by non-food biomass. This is due to higher nitrogen concentrations in bean crop grains than non-food bean biomass.

The partial nitrogen balance for maize and bean fields in 2016 and 2017 long-rain cropping seasons is shown in Figure 4. The maize fields recorded nitrogen balance ranging from -0.2 to -76.5 kg/ha/season and from -21.8 to -118.2 kg/ha/season in 2016 and 2017, respectively. These are consistent with values proposed by Sheldrick and Lingard (2004), De Jager et al (1998), Shepherd and Soule (1998), Van den Bosch (1998) and Stoorvogel et al (1993). The bean fields recorded a partial nitrogen balance ranging from 3.3 to -72.9 kg/ha/season and from -11.0 to -62.6 kg/ha/season in the seasons of 2016 and 2017, respectively. However, this does not allow for any contribution from atmospheric N fixation, which has been shown to be 50% to 60% of total N use by the crop (Wilker et al, 2019; Franke et al, 2018).

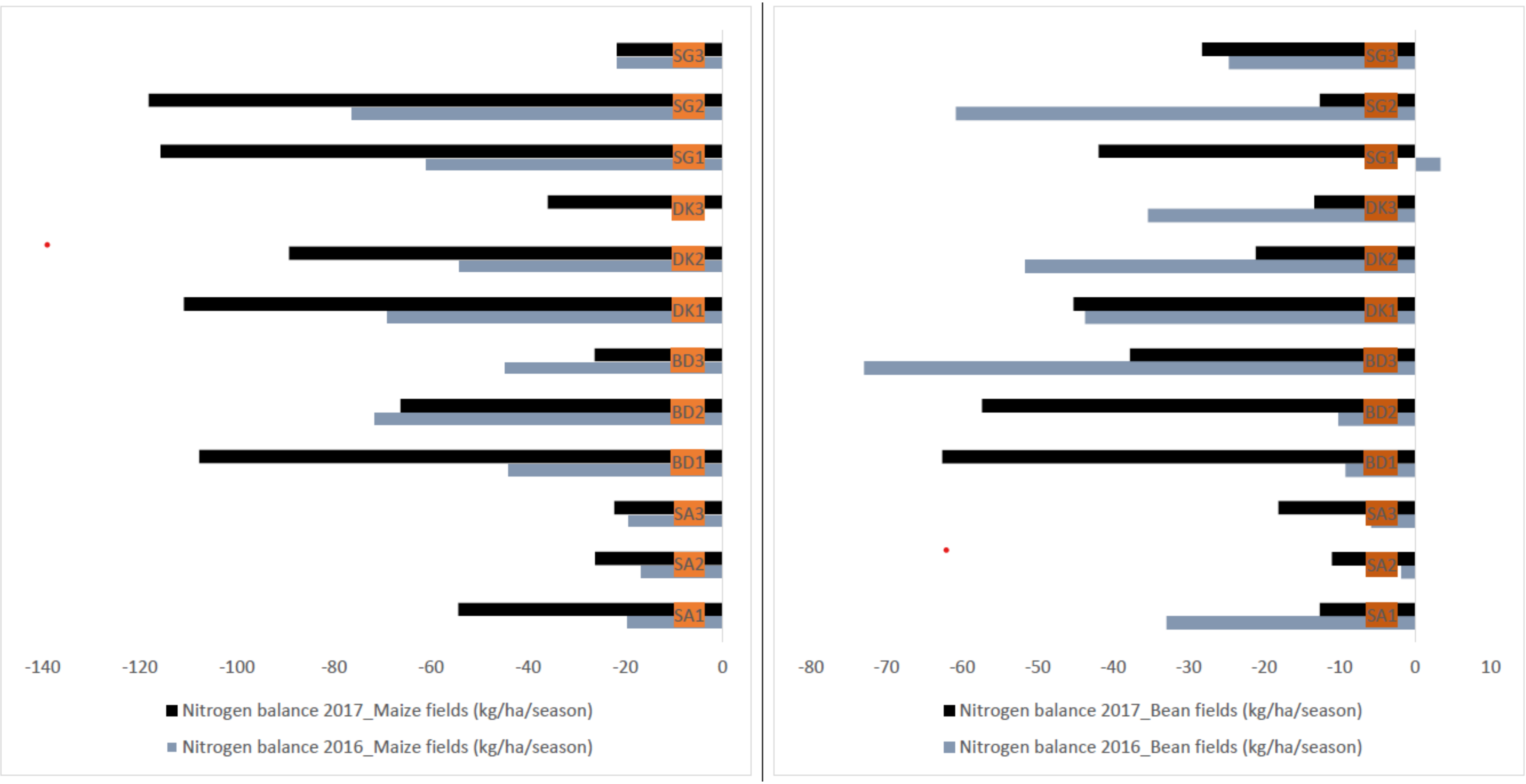

Figure 4: Nitrogen balance in maize and bean fields in 2016 and 2017 long rain cropping seasons

4.5 Manure production and its nutrient content

The manure production was 1.71±0.1 kg DM manure per day per TLU, which accords with previous studies, which report values between 1.1 to 2.7 kg per day per TLU in various African countries (Ayantunde, Fernandez-Rivera et al. 2002) (Khombe and Dube 1992). There were no significant differences in the chemical compositions of fresh manure between locations (Table 7).

The manure storage experiment indicated that age had significant impact on the total organic carbon, total phosphorous and total potassium (Table 8). A similar trend was apparent for total nitrogen content, but this was not significant at p=0.05 level. Different storage treatments did not have any significant effect (Table 9).

Table 7: Nutrient content of dry manure (%)

Location	Total organic carbon	Total nitrogen	Total phosphorous	Total potassium
SG	7.41(2.33)	2.28(0.66)	0.42(0.13)	1.14(0.69)
SA	7.20(1.92)	2.28(0.69)	0.34(0.15)	1.30(0.92)
BD	7.08(2.33)	2.16(0.34)	0.36(0.08)	0.97(0.60)

Note: values are given as mean at each location with SD in parentheses.

Table 8: Influence of storage on quality of manure

Age of manure	Total organic carbon (%)	Total nitrogen (%)	Total phosphorous (%)	Total potassium (%)
4 months	5.79(0.34)b	1.98(0.10)a	0.33(0.04)b	0.63(0.12)b
2 months	5.84(0.42)b	1.98(0.08)a	0.42(0.02)ab	1.64(0.21)a
One month	5.92(0.55)b	2.10(0.15)a	0.42(0.03)ab	1.95(0.21)a
Fresh	8.66(0.62)a	2.49(0.21)a	0.53(0.03)a	2.50(0.27)a

Note: means in each column that do not share a letter are significantly different at $P \leq 0.05$, by Tukey's HSD test. Values are given as mean with SE in parentheses.

Table 9: Influence of different manure storage treatments after 1 month

Storage treatment	Total organic carbon (%)	Total nitrogen (%)	Total phosphorous (%)	Total potassium (%)
Outside on ground	5.99(0.15)	2.22(0.15)	0.47(0.04)	2.09(0.22)
Outside on plastic	6.34(0.29)	2.57(0.48)	0.38(0.02)	2.18(0.30)
Inside on plastic	6.90(0.46)	2.16(0.19)	0.39(0.04)	2.48(0.19)

Note: values are given as mean for each treatment with SE in parentheses.

4.6 A sustainable mixed crop-livestock system

It is apparent from Figure 4 that the current farming system delivers a negative nitrogen balance for all farms studied at all sites. This is not sustainable and would have severe negative effects in the long run. It is therefore pertinent to consider whether this can be reversed through better use of available livestock manure without need for mineral fertiliser inputs.

Three model farms are considered in order to illustrate the analysis:

Farm A comprises 1.5 ha crop land which is divided between 50% maize and 50% beans; livestock holding is 20 TLU. This represents the average condition as determined in the farmer survey.

Farm B comprises 1.5 ha crop land with livestock holding is 20 TLU (both as for Farm A) but all crop land is allocated to maize production.

Farm C comprises 1.5 ha crop land which is divided between maize and beans (as for Farm A) but livestock holding is only 10 TLU.

The computed nitrogen balance for each case is shown in Table 10. Grain yield is assumed to be 1.75 t/ha for maize and 1.5 t/ha for beans. Non-crop biomass is computed on the basis of a harvest index of 0.3 for both crops. These are considered to be reasonable long term crop performance values under conditions of improved soil fertility based on our experimental evidence. Nitrogen offtake for the bean crop is reduced by 50% to reflect the ability of this crop to fix atmospheric nitrogen (Unkovich et al, 2008; Franke et al, 2018; Wilker et al, 2019). Based on our experimental evidence, manure production is assumed to be 1.7 kg/d/TLU with 2% nitrogen content, which is collected over a 180 day season.

Table 10: Computed nitrogen balance per cropping season for a representative 1.5 ha farm

Farm type	Crop	Yield (t/ha) of		N offtake (kg) by		Availability (kg) of		Balance of N (kg/ha)
		Grain	Stover	Grain	Stover	Manure	Nitrogen	
Farm A	Maize	1.75	4.1	20.2	41.2	6,120	122.4	9.4
	Beans	1.5	3.5	23.1	23.6			
Farm B	Maize	1.75	4.1	40.4	82.4	6,120	122.4	-0.3
	Beans	-	-	-	-			
Farm C	Maize	1.75	4.1	20.2	41.2	3,060	61.2	-31.3
	Beans	1.5	3.5	23.1	23.6			

It is evident from Table 10 that farm types A and B both deliver an acceptable nitrogen balance for the average household with a livestock holding of 20 TLU. However, this represents a tenfold increase in manure use from the current average of around 600 kg/ha. Our evidence shows that the required amount of livestock manure can be produced, however farmers currently lack capability to transport the required amount from their ‘boma’ to their crop fields.

A similar balance computation for phosphorus and potassium is shown in Table 11, based on grain and stover concentrations of phosphorus and potassium quoted by van den Bosch et al (1998) from their work in Kenya. Manure samples from our own work indicated that corresponding nutrient contents were 0.4% and 1.1% for phosphorus and potassium respectively. Farm types A and B again deliver an acceptable balance for phosphorus while type C delivers a small deficit. However, all farm types deliver a deficit for potassium.

Table 11: Computed K and P balance per cropping season for representative 1.5 ha farm

Farm type	Crop	Yield (t/ha)		Offtake (kg)		Availability (kg) of			Balance (kg/ha)	
		Grain	Stover	P	K	Manure	P	K	P	K
Farm A	Maize	1.75	4.1	8.7	89.5	6,120	24.5	67.3	1.8	-71.1
	Beans	1.5	3.5	13.1	84.4					
Farm B	Maize	1.75	4.1	17.5	179.0	6,120	24.5	67.3	4.7	-74.5
	Beans	-	-	-	-					
Farm C	Maize	1.75	4.1	8.7	89.5	3,060	12.2	33.7	-6.4	-93.5
	Beans	1.5	3.5	13.1	84.4					

5. Conclusion

There is clear evidence of nutrient mining in all crop fields in the study area under current farming practice. None of the 50 farmers interviewed are using mineral fertilizer and the non-use of mineral fertilizer was confirmed by local government officials. Mineral fertilizer is not available in Marsabit and the nearest place for a farmer to buy fertilizer is Meru County which is about 290km away. High cost, poor availability and fear of adulteration are deterrents to utilization of mineral fertilizer across much of Kenya (Misiko, et al. 2011). Hence, mineral fertilizer use in Kenya, hardly exceeds 10 kg/ha per growing season.

Long term food security requires the adoption of a sustainable intensification strategy that addresses the fertility constraint. The mixed crop-livestock farming system that prevails within the study area offers a potential solution to soil nutrient mining. We have shown that a typical smallholder farm can achieve an acceptable nitrogen balance through better use of available livestock manure. An acceptable balance can also be achieved for phosphorus, however, there is a deficit for potassium.

This proposed sustainable intensification strategy requires a tenfold increase in manure use from the current average of around 600 kg/ha. Our evidence shows that the required amount of livestock manure can be produced by a typical smallholder farm, however external intervention is needed to overcome the constraint that farmers face in transporting the required amount from their ‘boma’ to their crop fields. The analysis is based on existing livestock numbers and availability of forage has not been considered as a constraint. A spatial analysis of land use and forage biomass production is required in order to determine the potential to extend these farm-scale analyses to larger landscape-scales.

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