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RESEARCH ARTICLE

Continuous cropping legumes in semi-arid Southern Africa: Legume productivity and soil health implications

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Abstract

Legume agronomic research in Southern Africa has often focused on integrating legumes into smallholder cereal cropping systems, but there is limited information available on the feasibility and soil health implications of continuous cropping legumes in the region. Continuous legumes may be suitable in areas with large livestock populations where a premium is placed on high-quality forage, or where efforts are underway to reclaim degraded cropland. Our objectives in this study were to (i) evaluate the performance of diverse legumes under continuous cropping and conservation tillage management with no fertility inputs and (ii) assess the response of soil health parameters to continuous legumes in a semi-arid environment. A 4-year study was conducted in Limpopo, South Africa beginning in the 2011–2012 growing season in which 10 legume and fallow treatments were imposed in the same plots for 4 growing seasons. All legumes responded negatively in varying degrees to continuous cropping in terms of biomass and nutrient accumulation. Lablab (*Lablab purpureus* L.) was the top-performing legume in the study and accumulated 4.5–13 Mg ha^{-1} of biomass and 153–345, 11–34, and 75–286 kg ha^{-1} of N, P, and K, respectively. Lablab often outperformed natural fallow, while other legumes generally performed as well as or inferior to natural fallow, depending on species and growing season. Cowpea (*Vigna unguiculata* Walp) was especially incompatible with continuous cropping and averaged less than 252 kg ha^{-1} and 2.1 Mg ha^{-1} of grain and biomass, respectively, from 2012–2013 to 2014–2015. Continuous cropping did not lead to sustained improvements in soil health. By 2014–2015, soil organic matter for all treatments had either declined or resembled baseline values. Rates of potentially mineralizable N in cowpea, lablab, vining mucuna (*Mucuna pruriens* var. *Utilis*), natural fallow, and bare ground plots fell by 70–96% during the study. There was also evidence for lower recovery of leached K by legumes compared to natural fallow species. In conclusion, legumes, such as lablab, should be considered as continuous forages on marginal land in areas where high-quality forage is in demand, but continuous cropping legumes without fertility inputs are not an effective strategy for improving soil health on degraded cropland in this semi-arid region of Southern Africa. Future research efforts may focus on the grazing strategies and baling frequencies required to optimize annual biomass accumulation of continuous lablab to meet livestock demand and support smallholder livelihoods.

Keywords: Legumes; Soil health; Southern Africa; Nutrient cycling

Introduction

Although over 26 million tonnes of maize (*Zea mays* L.) is produced annually across Southern Africa[1] (FAO, 2020), there are large tracts of land throughout the region where dryland maize production is either not possible or poses a substantial risk to growers due to land degradation, inherent soil fertility constraints, rainfall limitations, or a combination of these factors. In Malawi, for example, Li *et al.* (2017) modeled land suitability for crop production using soils and terrain data and found that 57% of cropland was either unsuitable or marginally suitable to produce crops. Recent climate reports also project that rainfall will become more erratic throughout Southern Africa in the coming decades than in previous years (Pohl *et al.*, 2017), which is not conducive to maize production. National efforts to more efficiently use cropland in marginal growing environments of Southern Africa have often focused on replacing a portion of maize production with drought-tolerant species such as cassava (*Manihot esculenta* Crantz; Barratt *et al.*, 2006; Mupakati and Tanyanyiwa, 2017; Rusike *et al.*, 2010). While high yield potential and adaptability to marginal land make cassava a suitable replacement for maize, there is a need to further explore legume cropping systems in the region as a strategy to both reclaim degraded land and identify a broader range of maize alternatives for areas where maize production is not reliable.

Grain legumes provide protein-rich pulses, while augmenting soil N pools through biological N_2 fixation (Vanlauwe *et al.*, 2019). Because of their contributions to human nutrition and soil health, legumes, such as cowpea (*Vigna unguiculata* Walp), groundnut (*Arachis hypogaea* L.), pigeon pea (*Cajanus cajan* L.), and soybean (*Glycine max* L. Merrill), have been at the forefront of efforts to diversify maize cropping systems throughout Southern Africa (Nyagumbo *et al.*, 2016; van Vugt *et al.*, 2018). In a review paper, Franke *et al.* (2018) found that mean cereal yields across the region, consisting primarily of maize, were 0.69 Mg ha^{-1} higher following grain legumes than under continuous cropping. Research in Zimbabwe has also shown that maize-legume intercropping can result in maize grain yields that rival monoculture yields but with greater stability and higher total system yield due to the inclusion of the legume (Madembo *et al.*, 2020). Compared to maize-legume rotations and intercropping, there is considerably less information available on the feasibility of continuous cropping legumes in the region, which may be suitable in areas where land degradation necessitates less frequent cultivation of maize and greater use of legumes (Mamuye *et al.*, 2020; Munthali *et al.*, 2014).

While previous research exploring the soil health implications of continuous cropping legumes in Southern Africa has been limited to short-lived perennials, those studies have yielded positive soil health outcomes that may extend to annual species. In South Africa, for example, Musokwa and Mafongoya (2021) found that soil collected from a 2-year-old pigeon pea stand had higher K concentrations, total cations, and macrofaunal species diversity and abundance compared to soil collected under continuous maize for the same time period. Similar results with regard to soil K concentrations were obtained following tephrosia (*Tephrosia vogelii* Hook) relative to maize in Malawi (Munthali *et al.*, 2014). Although information is not available regarding the impact of continuous cropping annual legumes on soil health in Southern Africa, there are several annual leguminous species that are capable of rapidly increasing soil nutrient availability and may be well-suited for continuous cropping. Cowpea, for instance, can acquire some forms of P with limited mobility through the secretion of mobilizing acids and anions (Franke *et al.*, 2018; Pypers *et al.*, 2006), while lablab (*Lablab purpureus* L.) and mucuna (*Mucuna pruriens* var. *Utilis*) have been shown to extract P from rock phosphate using a similar mechanism (Pypers *et al.*, 2007). These legumes may be viable options for continuous cropping scenarios where nutrient-rich residues are recycled with the aim of increasing nutrient availability for future cereals.

[1]For the purposes of this paper, Southern Africa includes the following countries: Botswana, Eswatini, Lesotho, Malawi, Mozambique, Namibia, South Africa, Zambia, and Zimbabwe.

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Continuous cropping legumes may also find acceptance in areas with smallholder dairy operations where a premium is placed on the availability of protein-rich fodder. In Zimbabwe, for example, surveys among smallholder dairy producers have shown that legumes, such as cowpea, lablab, and mucuna, are grown by approximately 80% of producers solely for the purpose of providing feed for dairy cattle (Mapiye *et al.*, 2006). Smallholder dairy producers in Zimbabwe have also successfully cultivated these species in limited rainfall (<600 mm) areas (Mapiye *et al.*, 2007). Nonetheless, smallholder dairy producers in South Africa and Zimbabwe still point to shortages of quality feed, lack of technical knowledge, and grazing land as leading constraints in milk production (Mapiye *et al.*, 2006, 2009; Nkonki-Mandleni *et al.*, 2019). Under some circumstances, reallocating portions of marginal land from maize to forage legumes may be warranted to help overcome some of these milk production constraints. Economic tradeoff analysis in Zimbabwe has shown that reassigning a portion of maize land to mucuna production is potentially more profitable than continuous maize, with the largest impact felt by smallholders (Tui *et al.*, 2015). While the responsiveness of annual forage legumes to continuous cropping is not well understood in Southern Africa, limited research has suggested that such an alternative cropping system would be well-adapted to marginal lands in the region. In Zimbabwe, Jingura *et al.* (2001) showed that lablab biomass production consistently produced approximately 5.9 t ha^{-1} over three seasons of continuous cropping in smallholder-managed trials that received no inputs. There is a need to build upon these findings with additional research that explores the effects of longer-term continuous cropping on legume performance stability and soil health.

Given the poor status of soil health throughout Southern Africa, priority should be given to evaluating continuous legumes under conservation tillage practices that aim to improve long-term soil health. Our objectives in this study were to (i) evaluate the performance of diverse legumes under continuous cropping and conservation tillage with no fertility inputs and (ii) determine the response of soil health parameters to continuous legumes under semi-arid environmental conditions in Southern Africa. We hypothesized that legume performance would depend on species, and positive soil health outcomes would be proportional to legume biomass and nutrient accumulation.

Materials and Methods

Site description

A field study was conducted from 2011 to 2015 at the Ukulima Farm Research Center in Limpopo, South Africa (24°31’ 48” S, 28°06’ 08”E, elevation 1263 m above sea level) on a loamy fine sand containing 87% sand, 9% silt, and 4% clay (Table 1). The site has a semi-arid climate with average annual temperatures ranging from 12 to 23 °C. Annual precipitation amounts to 630 mm, falling primarily between October and April.

Experimental setup and treatments

In September of each growing season, the field site was weeded manually using hoes. Following weeding, planting basins (150 mm width × 150 mm depth) were constructed at 0.50 m spacing in 3 × 5 m plots. Planting basins did not receive amendments and were used for water conservation purposes only. An experiment was arranged in a randomized complete block design with four replications. Each plot is receiving one of the following legumes: bush mucuna (cv. ECHO-1), cowpea (cv. IT98D-1399), horse gram [*Macrotyloma uniflorum* (Lam.) Verdc., cv. unknown], jack bean [*Canavalia ensiformis* (L.) DC., cv. Comum], lablab (cv. Highworth), sunn hemp (*Crotalaria juncea* L., IAC-1), tephrosia (cv. unknown), and vining mucuna (cv. Tropical). Note: Bush and

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Table 1. Baseline soil properties at the study site

Soil property	Units	Baseline values
Sand	%	87
Silt	%	9
Clay	%	4
pH (H_2O)		5.7
Organic C	g kg^{-1}	3.8
EC	dS m^{-1}	0.06
NO_3^- + NH_4^+	mg kg^{-1}	7.27
P	mg kg^{-1}	25.9
K	cmol kg^{-1}	0.16
Ca	cmol kg^{-1}	1.5
Mg	cmol kg^{-1}	0.40
S	mg kg^{-1}	4.6
Fe	mg kg^{-1}	6.8
Mn	mg kg^{-1}	6.7
Zn	mg kg^{-1}	4.4
B	mg kg^{-1}	0.39
Cu	mg kg^{-1}	0.47

Nutrient testing was conducted using Bray 1 (P), 1 molar ammonium acetate (Ca, Mg, and K), 0.1 molar hydrochloric acid (Cu, Zn, Mn, and Fe), hot water (B), calcium phosphate (S), and 1 molar potassium chloride (NH_4^+ + NO_3^-) extraction methods.

vining mucuna are the same species but have different growth habits. The former grows compactly, while the latter has a spreading growth habit.

Legumes were planted at a rate of three seeds per basin from 25 September to 27 October depending on growing season and were thinned to one plant per basin approximately 1 month after planting. In addition to legumes, each block contained natural fallow and plant-free bare ground plots. Natural fallow plots contained both grass and broadleaf species, including but not limited to *Chloris gayana* Kunth, *Commelina benghalensis* L., *Hibiscus sp*., and *Tagetes minuta* L. Species composition in natural fallow plots was not manipulated in any way during the study. Plants in natural fallow plots were allowed to grow undisturbed during each growing season. All plots, except natural fallow, were weeded manually as needed using hoes. The treatments were located in the same plots each growing season to assess the impact of continuous cropping on legume performance and soil health parameters. All legume and natural fallow residues were left on the surface of plots after plants completed their life cycle at the end of each growing season. This experiment was surrounded by other experiments that received supplemental irrigation via a center pivot, which inevitably resulted in our experiment receiving approximately 100 mm of irrigation during each growing season.

Legume and natural fallow performance

Approximately 6 months after planting, legume and natural fallow biomass was sampled from representative areas of each plot using a 1 × 1 m quadrat. One biomass sample per plot was cut at ground level and dried at 40 °C to a constant weight. Samples of dried biomass from each plot were ground to pass a 2-mm mesh screen (Wiley Laboratory Mill, Model 4 3375-E10; Thomas Scientific, Swedesboro, New Jersey, USA) and analyzed for N, P, and K concentrations. Samples were analyzed for N concentrations using a LECO instrument by the Dumas dry combustion method (AgriLASA, 2007a). Biomass P and K concentrations were determined using acid-microwave digestion followed by inductively coupled plasma spectrometry (AgriLASA, 2007b).

Edible species, which included cowpea, horse gram, and lablab, began producing grain at different periods. Cowpea was harvested by hand on a weekly basis beginning in February, while

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logistical challenges and climatic conditions prevented harvest of other species. Horsecgram forms a dense layer of biomass with pods located underneath at ground level. While there is no history of horse gram production in Southern Africa, standard pod harvest procedures in South Asia, where the species is typically grown, consist of cutting and removing horse gram biomass from the field and inverting it on a tarp to facilitate pod drying. When pods begin opening, biomass is struck, and grain accumulates on the tarp. Although horse gram biomass could have been removed from plots and returned after grain harvest, this procedure would have disrupted biomass decomposition and nutrient mineralization processes. We initially attempted to harvest pods from horse gram plants in the field, but the time taken to harvest, as well as the disturbance caused to plants when searching for pods at ground level, made this alternative harvest method unfeasible. Since an important component of this study was to assess legume effects on soil health, we decided against harvesting horse gram grain. Lablab began producing harvestable pods toward the end of the rainy season. Annual freezing temperatures in May damaged developing pods, which were also attacked by pod-boring lepidopteran pests. Because of the damage to pods caused by frost, it was not worthwhile to use pesticides in an attempt to control pests. The end result was that lablab yield data were not collected. We also harvested all seed from bush and vining mucuna as well as jack bean to both plant and distribute during subsequent years.

Soil health assessment

Soil samples were collected to 150 mm depth 1 day before planting in the first season and, subsequently, at the end of each season (~ 6 months after planting) using a 25.4 mm diameter soil probe. Eighteen samples were collected per plot in a "W" walking pattern, homogenized manually, and bulked. A 500 mL subsample was taken from homogenized soil in each plot, from which soil organic matter (SOM) content, inorganic N, P, and K concentrations, and potentially mineralizable N (PMN) were measured as indicators of soil health. Immediately after sampling, fresh soil was sieved using a 4-mm mesh screen to remove large plant debris. Sieved soil was used to measure all soil health indicators. For SOM measurements, soil was first air-dried on a laboratory bench at 22 °C to a constant weight and then manually ground to pass a 2-mm mesh screen. Ten-gram samples were analyzed for SOM by loss on ignition at 430 °C for 24 hours as described by Davies (1974).

Soil used to measure inorganic N, P, and K concentrations was dried to a constant weight at 40 °C, then manually ground to pass a 2-mm mesh screen. For inorganic N measurements, 5-g soil samples were extracted with 25 mL of 2 M KCl and shaken for 1 hour. After shaking, samples were placed to settle for 30 minutes before filtering. Extracts were stored at 4 °C until analyzed for NO_3^- and NH_4^+ using steam distillation and colorimetric methods. Samples were run in duplicates and compared against prepared standards at $R^2 > 0.99$. Soil inorganic P and K concentrations were determined using Bray 1 and 1 M ammonium acetate extraction methods. All methods used to measure inorganic N, P, and K concentrations are described in AgriLASA (2004).

PMN refers to the fraction of soil organic N mineralized during a specific time period and indicates the ability of a soil to provide plant available N during a crop cycle (Natural Resources Conservation Service, 2014). Given the expected annual soil N contributions from legume biomass, we anticipated PMN would relate closely to legume performance. The process used to determine PMN consisted of a 7-day anaerobic incubation during which NH_4^+ production was tracked as an indicator of N mineralization (Gugino *et al.*, 2009). After initial sieving through a 4-mm mesh screen, soil used to determine PMN was stored fresh at 4 °C until ready for use. Samples were removed from storage within 1 week and sieved to pass a 2-mm mesh screen. Two 8-g samples were placed in 50 mL centrifuge tubes. One tube received 40 mL of 2.0 M KCl solution and was agitated on a mechanical shaker for 1 hour. Samples were then allowed to settle for 30 minutes before filtering. Pre-incubation NH_4^+ concentrations were determined from 20 mL of filtrate collected from the shaken tube. The second tube received 10 mL of distilled water, was manually shaken, capped with a gaseous N atmosphere, and incubated for

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7 days at 30 °C. After the incubation, the second tube received 2.67 M KCl, creating a 2.0 M solution. The tube was mechanically agitated and filtered as described previously and filtrate was analyzed for NH_4^+ concentration. The difference between pre-incubation and post-incubation NH_4^+ concentrations was considered PMN.

Due to cost limitations, PMN was only measured in bare ground, cowpea, lablab, natural fallow, and vining mucuna plots. These legumes were selected because of their multi-purpose function as food, fodder, or green manures in Southern Africa (Franke *et al.*, 2018; Odhiambo, 2011). Bare ground and natural fallow treatments were included to enable PMN comparisons among legume and non-legume plots.

Weather conditions

Weather data were collected with an on-site HOBO® U30 Remote Monitoring System (Onset Computer Corporation, Bourne, MA, USA; Model H21-001) equipped with a Rain Gauge Smart Sensor (Part No. S-RGB-M002) and a Temperature Smart Sensor (Part No. S-THB-M008). During legume growth, temperatures ranged from 2 to 38 °C, with maximum and minimum temperatures generally occurring in October and April, respectively (Figure 1). Total rainfall ranged from 497 to 730 mm and was unevenly distributed during each growing season. This uneven rainfall distribution was especially apparent in 2013–2014 when 226 mm, or 31% of total rainfall, occurred in March. Early-season rainfall during each growing season was adequate for legume stand establishment, including in 2014–2015 when rainfall amounted to only 26 mm in October.

Statistical analyses

Analysis of variance was conducted using PROC MIXED (SAS Statistical Software, Cary, NC, USA) to determine how treatments, growing season, and their interactions affected aboveground biomass and nutrient accumulation and soil health parameters. Legume and fallow treatments were treated as fixed effects, block as a random effect, and growing season as a repeated measures factor. The subject upon which repeated measures were taken was a combination of block × treatment and was accounted for with the REPEATED statement in SAS (Loughin, 2006). SLICE statements in PROC MIXED were used to partition treatment by growing season interactions. Treatment means within and between growing seasons were separated using Waller-Duncan's multiple range test ($p < 0.05$).

Results

Biomass accumulation

Biomass accumulation varied by treatment and growing season. Within each growing season, there was a general trend showing highest biomass accumulation in natural fallow, lablab, and vining mucuna plots (Table 2). In 2011–2012, lablab accumulated 13 Mg ha^{-1} of biomass, which exceeded natural fallow by 4.8 Mg ha^{-1}. Vining mucuna biomass accumulation amounted to 10 Mg ha^{-1} during this time, which was statistically similar to lablab and natural fallow biomass accumulation. Other legumes that accumulated similar amounts of biomass as natural fallow in 2011–2012 included bush mucuna, cowpea, horse gram, and sunn hemp, all of which accumulated close to or over 5 Mg ha^{-1}. During subsequent growing seasons, lablab and vining mucuna continued to accumulate at least as much biomass as natural fallow, with lablab outperforming natural fallow in 2014–2015. It should be noted that tunnels created by burrowing animals were observed in some natural fallow plots in 2014–2015, which may have hindered natural fallow biomass accumulation than growing season.

Biomass accumulation for most treatments was either stable or declined over the study. The reduction in biomass accumulation from 2011–2012 to 2012–2013 ranged from 37% in lablab plots to as high as 94% in sunn hemp plots. With the exception of lablab, biomass accumulation

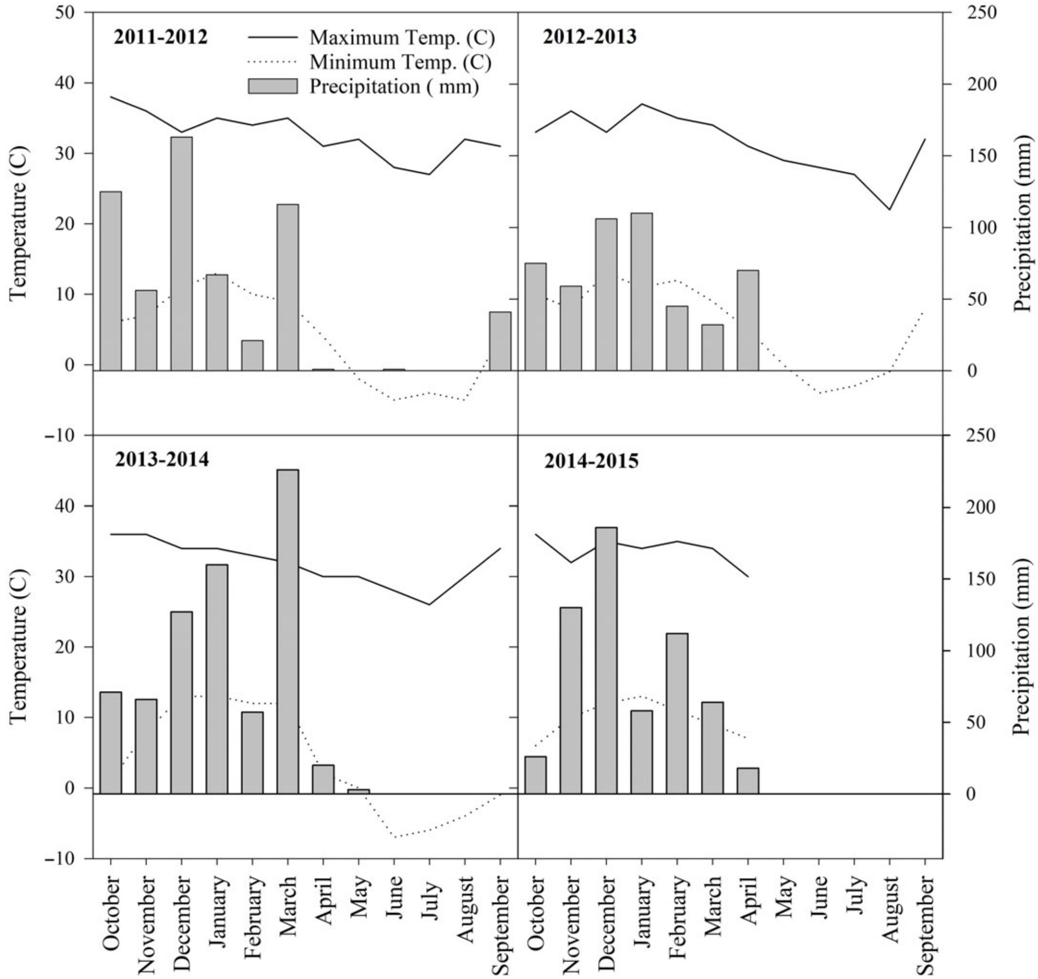

Figure 1. Daily maximum (solid lines) and minimum (dotted lines) air temperatures at 2 m above the soil surface and monthly precipitation (mm). Data were collected from an on-site weather station (Onset Computer Corporation).

by these species remained at 2012–2013 levels during subsequent growing seasons. Lablab was the only species that showed improvement in biomass accumulation relative to a previous growing season, increasing by 4.5 Mg ha^{-1} from 2013–2014 to 2014–2015. Although jack bean and tephrosia biomass accumulation remained stable throughout the study, these species were among the least productive legumes, accumulating less than 2 and 1 Mg ha^{-1} of biomass, respectively, in three out of four growing seasons.

Cowpea grain yields were relatively low and ranged from 118 to 552 kg ha^{-1} over the study. Seed production in bush mucuna, jack bean, and vining mucuna plots ranged from 1846 to 2601, 880 to 1261, and 1535 to 3168 kg ha $^{-1}$, respectively (data not shown) and was ended each year by frost.

Nutrient accumulation

As with biomass accumulation, legume and natural fallow nutrient content depended on treatment and growing season. Lablab was consistently the top nutrient-accumulating legume throughout the study, with its biomass containing the most N, P, and K in three (P and K) or four (N) growing seasons. Lablab was also highly resilient, accumulating 345 kg N ha^{-1} in 2014–2015, which marked a 107 and

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Table 2. Aboveground biomass accumulation collected 6 months after planting for each growing season

	2011–2012	2012–2013	2013–2014	2014–2015
Legume		Biomass accumulation (Mg ha^{-1})		
Bush mucuna	6.1 cd A	4.0 c AB	3.0 bc AB	2.1 cd B
Cowpea	4.9 cd A	2.0 d B	2.1 cd B	0.8 d B
Natural fallow	8.2 bc A	7.2 ab A	6.2 a AB	3.1 bc B
Horse gram	7.7 bc A	3.6 c B	4.4 ab B	3.5 bc B
Jack bean	3.8 de A	1.3 de A	1.9 cd A	1.2 d A
Lablab	13.0 a A	8.2 a BC	4.5 ab C	9.0 a AB
Sunn hemp	5.1 cd A	0.3 e B	0.1 d B	1.6 cd B
Tephrosia	0.8 e A	0.3 e A	0.6 d A	2.4 bcd A
Vining mucuna	10.0 ab A	6.3 b B	5.4 a B	4.0 b B

Within each row, means with the same uppercase letter were not significantly different at a significant level of 0.05 according to Waller-Duncan's multiple range test.

Within each column, means with the same lowercase letter were not significantly different at a significance level of 0.05 according to Waller-Duncan's multiple range test.

125% increase compared to 2012–2013 and 2013–2014 totals, respectively (Table 3). Apart from lablab, vining mucuna also accumulated large amounts of nutrients, matching lablab N accumulation for two growing seasons. Vining mucuna and horse gram were highly stable in terms of N accumulation, as neither species varied in N content throughout the study. Jack bean and tephrosia showed even greater stability, with each respective legume accumulating similar amounts of N, P, and K during each growing season. However, as with biomass accumulation, these species were among the least productive legumes in the study, accumulating as little as 9–29 kg N ha^{-1}, 1–3 kg P ha^{-1}, and 3–11 kg K ha^{-1}, depending on growing season.

A visual inspection of natural fallow plots during each growing season indicated the absence of leguminous species. However, natural fallow biomass contained 67–166 kg N ha^{-1} during the study, which exceeded annual N accumulation by one to five legumes in three of four growing seasons. Natural fallow P and K accumulation during the study was more stable than N accumulation and only declined in 2014–2015. However, for most legumes, P and K accumulation declined considerably following 2011–2012 and remained relatively low moving forward. Legumes that were stable N accumulators, such as horse gram, lablab, and vining mucuna, accumulated 41–52 and 54–66% less P and K, respectively, in 2012–2013 than in 2011–2012.

Soil health assessment

SOM under all treatments had either declined or resembled baseline values by the end of the study (Table 4), suggesting that biomass contributions from the different treatments may have been insufficient to increase SOM within the time frame of the study. Although vining mucuna was a top biomass accumulator, SOM declined in vining mucuna plots by 59% over the study, falling from a baseline value of 7.1 g kg^{-1} to a final concentration of 2.9 g kg^{-1} in 2014–2015. Bare ground plots, which always contained negligible biomass, lost a similar amount of SOM as vining mucuna plots, while in bush mucuna, horse gram, lablab, and tephrosia plots, SOM at the end of the study resembled baseline values, despite the variation in biomass accumulation among those legumes. At the end of the study, treatment effects were limited to lablab plots where SOM concentrations were 48% higher than in bare ground and vining mucuna plots.

Soil inorganic N concentrations varied widely by growing season and treatment, with values peaking for all treatments in 2012–2013 before declining by 51–73% in 2013–2014. By the end of the study, N concentrations for all treatments resembled baseline values (Table 5). Within each growing season, lablab, cowpea, horse gram, bush mucuna, and vining mucuna plots had N concentrations that were high or higher than in other plots.

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Table 3. Nitrogen (N), phosphorous (P), and potassium (K) accumulation in aboveground biomass collected 6 months after planting for each growing season

	2011–2012	2012–2013	2013–2014	2014–2015
Legume		N content (kg ha^{-1})		
Bush mucuna	174 b A	96 bc AB	103 bc AB	79 bcd B
Cowpea	129 bc A	51 de BC	72 cd B	23 d C
Natural fallow	143 bc A	70 d B	166 a A	67 bcd B
Horse gram	159 bc A	74 cd A	120 abc A	125 bc A
Jack bean	91 cd A	29 ef A	62 cde A	50 cd A
Lablab	252 a AB	167 a B	153 ab B	345 a A
Sunn hemp	126 bc A	9 f C	4 e C	69 bcd B
Tephrosia	25 d A	9 f A	22 de A	104 bc A
Vining mucuna	188 ab A	118 b A	139 ab A	130 b A
		P content (kg ha^{-1})		
Bush mucuna	23 b A	13 bc AB	8 cde B	8 bc B
Cowpea	17 bcd A	6 d B	6 def B	2 d B
Natural fallow	21 bc A	15 b AB	25 a A	10 b B
Horse gram	21 bc A	10 c B	14 b B	10 b B
Jack bean	10 de A	3 de A	6 ef A	4 cd A
Lablab	34 a A	20 a B	11 bcd B	19 a B
Sunn hemp	12 cde A	1 e B	<1 g B	5 bcd B
Tephrosia	4 e A	1 e A	2 fg A	7 bcd A
Vining mucuna	25 ab A	14 b B	12 bc B	6 bcd B
		K content (kg ha^{-1})		
Bush mucuna	89 cd A	37 cde B	25 def B	10 d B
Cowpea	92 cd A	27 def B	34 cde B	12 cd B
Natural fallow	173 b A	102 b AB	119 a A	28 bc B
Horse gram	126 bc A	47 cd B	53 bcd B	36 b B
Jack bean	55 de A	16 efg A	20 ef A	11 cd A
Lablab	286 a A	132 a B	75 b B	108 a B
Sunn hemp	59 de A	4 fg B	1 f B	15 cd B
Tephrosia	12 e A	3 g A	5 ef A	22 bcd A
Vining mucuna	167 b A	57 c B	60 bc B	13 cd C

Within each row, means with the same uppercase letter were not significantly different at a significance level of 0.05 according to Waller-Duncan's multiple range test.

Within each column and separated by nutrient, means with the same lowercase letter were not significantly different at a significance level of 0.05 according to Waller-Duncan's multiple range test.

Compared to N concentrations, there was substantially less variability in soil inorganic P concentrations both over and within growing seasons (Table 5). Phosphorus concentrations in cowpea and natural fallow plots resembled baseline values throughout the study, while in vining mucuna plots, P concentrations only deviated from baseline values in 2014–2015, when they were 20% less than initial values. As with N concentrations, there were no treatments resulting in sustained higher P concentrations relative to baseline values for the duration of the study.

Soil inorganic K concentrations were either equal to or less than baseline values in all treatment plots by the end of the study. However, within each growing season, treatments had a notably different effect on K concentrations compared to their effects on N and P concentrations. Soil in natural fallow plots consistently had higher K concentrations than soil in all other treatment plots throughout the study (Table 5). Baseline K concentrations rose from 64 to 133 mg kg^{-1}, or 108%, in natural fallow plots by 2011–2012, while there were no detectable increases observed in any other treatment plots during this time. While K concentrations in natural fallow plots declined over time, they were still over 50% higher than in treatment plots containing the second highest K concentrations at the end of the study.

There was a substantial decline in PMN in all tested plots following 2011–2012 that lasted through 2013–2014 (Table 6). Depending on treatment, PMN declined by 70–96% during this time. While PMN was relatively low in all tested plots in 2012–2013 and 2013–2014, there were

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Table 4. Soil organic matter (SOM) concentrations at the beginning of the study before planting legumes (baseline) and at the end of the study

	Baseline	2014–2015
Legume	SOM (g kg^{-1})	
Bare ground	8.1 a A	2.7 c B
Bush mucuna	6.5 a A	4.8 abc A
Cowpea	5.8 a B	3.8 abc B
Natural fallow	7.2 a A	3.6 abc A
Horse gram	6.7 a A	4.6 abc A
Jack bean	6.4 a A	3.3 bc A
Lablab	7.6 a A	5.4 ab A
Sunn hemp	6.9 a A	3.3 bc A
Tephrosia	7.2 a A	3.7 abc A
Vining mucuna	7.1 a A	2.9 c B

Within each row, means with the same uppercase letter were not significantly different at a significance level of 0.05 according to Waller-Duncan's multiple range test.

Within each column, means with the same lowercase letter were not significantly different at a significance level of 0.05 according to Waller-Duncan's multiple range test.

some notable treatment differences detected during those growing seasons. In 2012–2013, PMN in lablab and natural fallow plots was approximately 95% higher than in bare ground plots. Similar results were observed in 2013–2014 when PMN in vining mucuna and natural fallow plots was approximately 88% higher than in bare ground plots. There were similar levels of PMN in cowpea and bare ground plots throughout the study.

Discussion

Based on annual biomass accumulation, lablab appears most suitable for use as a continuous forage legume in this region of South Africa. Although lablab biomass accumulation showed some variation by growing season, annual accumulation averaged 8.7 t ha^{-1} over the study, which was 47% higher than the average amount accumulated by continuous lablab over three growing seasons in on-farm trails in Zimbabwe (Jingura *et al.*, 2001). While lablab is well-adapted to a wide range of soils in areas receiving 650–3000 mm of annual rainfall (Cook *et al.*, 2020), there is a lack of information regarding the rainfall range required to optimize biomass accumulation on sandy soils in semi-arid regions of Southern Africa. The performance of lablab in our study suggests this optimal range is relatively low, which is further supported by previous research at the same study location that showed lablab intercropped at a low density with *Moringa oleifera* accumulated 6.4 and 4.0 t ha^{-1} of biomass under 496 and 594 mm of rainfall, respectively (Motis *et al.*, 2017).

Smallholders in Southern Africa who consider adopting lablab as a continuous forage legume and intend to save seed must consider a pest management program to protect pods from insect pests. As previously noted, pod-boring insects attacked lablab and, along with freeze events, prevented pod harvest in our study. Smallholder surveys in Tanzania have revealed that insect pests and pesticide costs are leading factors hindering lablab adoption (Chawe *et al.*, 2019; Forsythe, 2019). In Southern Africa, smallholders would likely face similar challenges given that lablab insect pests are widespread throughout the region (Mhere *et al.*, 2002). If implementing a lablab insect pest management program is not feasible, then smallholders should consider vining mucuna as an alternative continuous forage legume. Vining mucuna matched lablab in terms of biomass accumulation in two of four growing seasons but, unlike lablab, did not sustain notable pod damage, likely due to the impenetrable thickness of vining mucuna pods. As a result, vining mucuna produced high-quality seed every growing season. Throughout the study, neither lablab

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Table 5. Soil inorganic nitrogen (N), phosphorous (P), and potassium (K) concentrations at the beginning of the study before planting legumes (baseline) and 6 months after planting for each growing season

	Baseline	2011–2012	2012–2013	2013–2014	2014–2015
Legume			N concentration (mg kg^{-1})		
Bare ground	7.3 a B	11.0 b AB	18.4 b A	9.0 a B	5.6 a B
Bush mucuna	5.9 a B	13.3 ab B	26.6 ab A	7.5 a B	6.5 a B
Cowpea	7.9 a B	22.0 a AB	28.4 ab A	14.3 a AB	10.5 a B
Natural fallow	8.7 a BC	13.6 ab AB	17.1 b A	6.7 a C	6.4 a C
Horse gram	6.7 a B	16.7 ab AB	25.9 ab A	10.6 a B	9.6 a B
Jack bean	8.8 a B	11.9 b B	29.3 ab A	8.8 a B	6.8 a B
Lablab	6.3 a C	21.8 a B	36.9 a A	13.0 a BC	7.4 a BC
Sunn hemp	6.7 a B	15.1 ab AB	20.6 b A	8.6 a AB	5.0 a B
Tephrosia	6.7 a B	10.8 b B	18.5 b A	7.0 a B	5.2 a B
Vining mucuna	7.1 a B	16.8 ab AB	28.3 ab A	7.6 a B	5.5 a B
			P concentration (mg kg^{-1})		
Bare ground	25.7 a B	33.6 a A	32.8 a A	31.8 ab A	24.5 a B
Bush mucuna	26.4 a BC	31.5 a A	30.2 a AB	28.5 ab ABC	24.9 a C
Cowpea	26.8 a A	27.0 a A	28.4 a A	28.2 ab A	23.7 a A
Natural fallow	25.2 a A	27.5 a A	28.2 a A	25.4 b A	25.6 a A
Horse gram	28.4 a BC	29.5 a BC	33.3 a A	30.3 ab AB	26.9 a C
Jack bean	27.0 a AB	31.2 a A	30.4 a A	31.7 ab A	23.8 a B
Lablab	26.0 a AB	27.5 a AB	28.5 a AB	30.5 ab A	24.1 a B
Sunn hemp	25.9 a AB	31.2 a A	32.4 a A	31.1 ab A	22.1 a B
Tephrosia	26.8 a BC	31.3 a AB	31.4 a AB	33.4 a A	23.7 a C
Vining mucuna	26.6 a A	29.3 a A	30.1 a A	28.1 ab A	21.6 a B
			K concentration (mg kg^{-1})		
Bare ground	71.0 a A	68.6 bcd A	53.7 bcd AB	40.3 c AB	29.7 d B
Bush mucuna	59.3 a A	53.7 cd AB	42.9 d BC	40.7 c BC	35.3 cd C
Cowpea	56.0 a ABC	74 bcd AB	75.0 bcd A	50.9 bc BC	55.3 b BC
Natural fallow	64.0 a C	133 a A	124.4 a AB	97.1 a ABC	95.5 a BC
Horse gram	60.2 a A	81.7 bc A	71.7 bcd A	66.1 b A	50.5 bc A
Jack bean	57.9 a A	55.2 cd A	43.3 d AB	42.8 c AB	27.7 d B
Lablab	66.4 a AB	91.9 b A	86.1 b A	47.8 bc B	52.5 bc B
Sunn hemp	67.4 a A	65.9 bcd AB	49.1 cd BC	46.3 bc C	36.7 bcd C
Tephrosia	56.4 a A	48.5 d A	45.5 cd AB	49.3 bc A	28.8 d B
Vining mucuna	67.6 a AB	68.1 bcd AB	80.3 bc A	47.5 bc BC	37.4 bcd C

Within each row, means with the same uppercase letter were not significantly different at a significance level of 0.05 according to Waller-Duncan's multiple range test.

Within each column and separated by nutrient, means with the same lowercase letter were not significantly different at a significance level of 0.05 according to Waller-Duncan's multiple range test.

Table 6. Potentially mineralizable nitrogen (PMN) measured 6 months after planting in bare ground, cowpea, fallow, lablab, and vining mucuna plots from 2011–2012 to 2013–2014

	2011–2012	2012–2013	2013–2014
Legume		PMN (μg N per g dry soil per week)	
Bare ground	7.6 a A	0.13 b B	0.37 b B
Cowpea	9.41 a A	1.72 ab B	1.44 ab B
Natural fallow	10.99 a A	2.42 a B	3.34 a B
Lablab	8.96 a A	3.27 a B	2.17 ab B
Vining mucuna	8.06 a A	1.36 ab B	2.72 a B

Within each row, means with the same uppercase letter were not significantly different at a significance level of 0.05 according to Waller-Duncan's multiple range test.

Within each column, means with the same lowercase letter were not significantly different at a significance level of 0.05 according to Waller-Duncan's multiple range test.

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nor vining mucuna experienced substantial foliar damage from insect pests or disease, furthering their case as continuous forage legume options for smallholders in some regions of Southern Africa.

Our results showed that cowpea was not compatible with continuous cropping, which was important to demonstrate since it is the third most widely grown legume in Southern Africa (FAOSTAT, 2020). Bagayoko *et al.* (1996) similarly reported a sustained decline in cowpea biomass accumulation following the first of a 5-year continuous cropping study in Mali. Crop monitoring during our study revealed only minor insect or disease damage to cowpea pods and foliage, suggesting other causes of cowpea decline. We suspect root-knot nematodes (genus *Meloidogyne*) may have been responsible for poor cowpea performance due to the early and lasting presence of several root-knot nematode symptoms, such as galled and knotted roots, stem discoloration, foliar chlorosis, and rapid crop decline (Abad *et al.*, 2003). While soil and plant tissue were not tested to confirm root-knot nematode damage, these symptoms, along with the widespread presence of root-knot nematodes in maize growing regions of South Africa (Reikert and Henshaw, 1998), suggest the pathogen may have been at least partially responsible for cowpea decline. Nematicides, like carbofuran, can effectively control root-knot nematode populations (Adegbite and Agbaje, 2007; Adegbite, 2011), but their high toxicity toward non-target organisms, humans, and animals hinders their adoption, especially among smallholders (Mishra *et al.*, 2020). Given the poor performance of cowpea in this study, along with the toxic measures needed to better ensure acceptable biomass and grain yields, we do not recommend cowpea as a continuous legume in the region. Other possible forage legumes, such as bush mucuna, horse gram, and sunn hemp, did not accumulate large enough quantities of biomass on an annual basis to justify their use over lablab or mucuna as continuous forage legumes.

In addition to evaluating legumes as possible forage options for smallholders, we also sought to better understand the impact of continuous cropping legumes on soil health parameters. The inability of productive legumes, such as lablab and vining mucuna, to enhance SOM after 4 years of continuous cropping may be explained by a combination of legume decomposition dynamics, annual biomass inputs, and soil physical properties. Legume biochemical composition was not reported in this study, but research elsewhere has shown that several of the species that were investigated have low carbon-to-nitrogen ratios (Odhiambo, 2010), which results in rapid decomposition and reduces the effectiveness of legumes, compared to cereals, in making lasting contributions to SOM (Franzluebbers *et al.*, 1994; Stallings *et al.*, 2017; Blanco-Canqui and Jasa, 2019). On the rare occasions where legumes have successfully increased SOM in Southern Africa, they have been integrated into maize cropping systems resulting in a combined total of approximately 15 t ha^{-1} of maize and legume biomass contributed annually to soil containing at least 20% clay (Dube *et al.*, 2012). The combination of high biomass inputs and clay content might explain the SOM increase over time in the aforementioned study since clay particles often bind closely to SOM and are an integral component of soil aggregates in which SOM is protected from microbial decomposition (Hassink *et al.*, 1993; Bronick and Lal, 2005). The loamy sand soil used in our study contained only 4% clay and was poorly structured, which would have left SOM vulnerable to microbial consumption and would explain the lack of SOM accumulation, even in productive lablab and mucuna plots.

Nitrogen mineralization dynamics from leguminous residues, along with soil texture, may explain soil inorganic N levels observed in the study. The onset of rains in growing seasons two through four likely ushered in a period of rapid N mineralization from leguminous residues accumulated during the previous growing season. Research in Kenya has shown that lablab residues on the soil surface can mineralize up to 60% of residue N within 8 weeks (Njunie *et al.*, 2004). Using a loamy sand soil collected near our study site, Odhiambo (2010) found that lablab and mucuna residues mineralized 50 and 60% of residue N, respectively, during a 16-week laboratory incubation. Considering the low nutrient holding capacity of the loamy sand soil used in our study, a large portion of N mineralized from leguminous residues was probably leached before

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soil samples were collected at the end of each growing season. This explanation is supported by previous research in Zimbabwe that showed soil nitrate concentrations from 0 to 1.2 m depth declined by 77% from the beginning of the rainy season to 1 week after planting maize (a 6-week span) in fields planted to vining mucuna the previous growing season (Jiri and Mafongoya, 2018).

Considering that management practices, such as no-till, crop residue additions, and the use of legumes are all effective strategies for increasing PMN in cropping systems (Mahal *et al.*, 2018), we did not expect the low rates of PMN detected in this study. Some combination of rapid legume N mineralization as described previously, low SOM content, and poor soil structure may explain these results. Previous studies have shown SOM is an important source of inorganic N and is positively associated with PMN (Sahrawat, 2006; Wang *et al.*, 2019). Because SOM remained low throughout the study, its contributions to PMN were likely negligible.

This study provided important information regarding soil P and K cycling under continuous legumes. As noted previously, legumes, such as cowpea, lablab, and mucuna, may acquire soil P with limited mobility by secreting mobilizing acids (Franke *et al.*, 2018; Pypers *et al.*, 2006, 2007). Because soil P mobilization by legumes was not reported in this study, soil P concentrations should not be interpreted as providing support for or against soil P mobilization by legumes. There were no treatments that resulted in higher soil P concentrations at the end of the study compared to initial concentrations. However, for several legumes in which seed was harvested each season, including cowpea, bush mucuna, jack bean, and lablab, baseline and end of study soil P concentrations were similar, which is worth noting since seed harvest can represent a substantial P export from soil (Kyei-Boahen *et al.*, 2017; Okogun *et al.* 2005). While these findings do not substantiate soil P mobilization by legumes, they do suggest this area of study warrants further exploration.

The most consistent soil-related treatment effect found in this study was the higher soil inorganic K concentrations following natural fallow compared to all other treatments at the end of each growing season. These results suggest the species comprising natural fallow plots were more capable of scavenging soil inorganic K than the legumes in the study. Bagayoko *et al.* (1996) also found that soil inorganic K concentrations were higher after 4 years of natural fallow compared to continuous cowpea in Mali. Although root morphology was not explored in our study, previous research in South Africa has shown that endemic and naturalized plants in semi-arid areas can develop root systems well beyond 3 m in depth (Snyman, 2005, 2009). The grass and broadleaf species that made up natural fallow plots may have had deep and extensive roots capable of recovering K leached deep in the soil profile, as K leaching is probable in soils high in sand and subjected to intense rainfall events (Dovey *et al.*, 2014). These results point to the need to more fully characterize the root architecture, morphology, and growth patterns of the legumes used in this study to more fully understand their limitations as nutrient scavengers. Additionally, in areas where high-quality forages are desired, planting nutritious cereal/legume mixtures may be a suitable alternative to legume monocultures or natural fallow. The mixtures could be more efficient than legume monocultures in recovering K due to the presence of the cereal root system and would also provide higher quality forage than natural fallow. The productivity and nutrient scavenging capabilities of cereal/legume mixtures have not been widely explored in Southern Africa but warrant investigation.

Conclusions

Our hypothesis that legume biomass and nutrient accumulation would vary by species and that positive soil health outcomes would be proportional to legume performance was only partially supported by results from this study. While legumes, such as lablab and vining mucuna, often outperformed several other species in terms of biomass and nutrient accumulation, their use did not lead to sustained improvements to soil health based on the parameters measured in this study. We conclude that lablab and vining mucuna warrant consideration as continuous forages in areas where livestock populations place a premium on nutritious fodder. However, additional research is needed to determine the best grazing strategies and baling frequencies to optimize annual biomass accumulation by continuous legumes to meet livestock demand and support smallholder livelihoods.

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Competing interests. The authors declare none.

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