Agric Res (March 2024) 13(1):124–136
https://doi.org/10.1007/s40003-023-00674-7

FULL-LENGTH RESEARCH ARTICLE

Characterising Productivity Factors Affecting Maize (*Zea mays*) Production in a Smallholder Crop-Livestock System

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Received: 6 October 2022 / Accepted: 21 September 2023 / Published online: 26 October 2023

Abstract Socio-economic factors can influence decisions and the intensity of management practices, which when appropriately considered could bridge yield gaps. The study aimed to investigate factors affecting maize (*Zea mays* L.) production in a smallholder crop-livestock system. Social and management analyses were performed to ascertain the factors influencing maize productivity using interviews and questionnaires. The study was conducted in two main maize-producing regions of Eswatini, the Highveld at Mankayane and Middleveld at Luve. Additionally, on-farm trials were established for two cropping seasons to evaluate maize response to three fertiliser regimes: cattle manure only, cattle manure plus inorganic fertiliser, and inorganic fertiliser only and lastly to determine the most economic fertiliser regime. Each fertiliser regime was replicated six times. Weed biomass and maize yield were collected from a 5 m × 1 m quadrat. Moreover, economic analysis for each fertiliser regime was performed using partial budgets comprising fertiliser and weed management costs. The social and management analyses showed that maize yield was strongly associated with household size ($p < 0.05$), land area cultivated ($p < 0.05$) and herbicide application timing ($p < 0.05$) indicating the effect of these factors on yield. On-farm trials revealed that the inorganic fertiliser only regime resulted in a significantly ($p < 0.05$) higher maize yield compared to manure only and manure plus inorganic fertiliser regimes in both study areas. Weed biomass was significantly ($p < 0.05$) lower in the inorganic fertiliser only regime at Mankayane compared to the manure only and manure plus inorganic fertiliser at both localities. The economic analysis showed that the manure only fertiliser regime had low costs that vary and high net benefits indicating that manure has the potential to improve soil conditions, reduce environmental impacts, and increase profits.

Keywords Fertiliser · Manure · Net benefit · Socio-economic · Weed management

Introduction

Integrated crop-livestock systems are a vital farming system in sub-Saharan Africa and are of benefit in resource recycling and financial preservation [31, 51]. Combining crops and livestock results in farm production that is efficient, productive, and sustainable [37, 40]. Crop residues (e.g. stover, straw, and fibrous by-products) are the primary feed sources for livestock, which in turn provide draft power for land cultivation and manure for crops' nutrient requirements [50].

Manure is an organic fertiliser that contains essential plant nutrients such as nitrogen (N), phosphorus (P), and potassium (K) as well as secondary nutrients and trace

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elements that have been linked to increased agricultural yields [12]. While the integration of manure and inorganic fertiliser could reduce input costs, it may however bring new problems, such as the infestation of cropping fields with weed seeds that have been ingested by livestock and subsequently excreted with manure [21, 41]. Uncured animal manure contains a high diversity of weed seeds, highlighting the material that cattle feed on, which is common in artificial and natural grasslands. These weeds tend to germinate during the spring and summer seasons (summer rainfall area), which is also typical of crop growth, leading to interspecific competition. Despite this, livestock manure remains a major nutrient source for smallholder farmers [38, 39].

Manure nutrient availability, for crops, is influenced by storage and handling practices [38, 39], which ultimately influence crop performance and yield. In terms of manure utilisation, farmers either use manure directly or only after composting. Composted manure has several advantages over fresh manure, including a reduced number of viable weed seeds [18]. Colbach et al. [17] observed that when the field was initially weed-free, manure spreading was the only origin of weed seeds and thus the subsequent weed infestation significantly increased with manure seed content and manuring frequency. Moreover, research has demonstrated that the application of different fertiliser regimes may influence the competition between crops and weeds [8, 10, 20, 22, 33]. Blackshaw et al. [11]. observed that many agricultural weeds are equally or more responsive to high nitrogen sources, such as manure. In addition, many weeds of agricultural importance are as responsive or more responsive to higher soil nutrition levels than crops [22]. Therefore, nutrient management is essential in controlling the nutrient release and reducing interspecific competition between weeds and crops. This means that nutrient application rate, placement, and timing can influence weed emergence, persistence and nutrient absorption rate [10, 33].

The potential of soil nutrition to encourage weed growth and persistence poses great concerns for weed management by smallholder farmers. Over recent years, herbicide application has been adopted due to ease of use, affordability and few labour requirements [36, 48]. Moreover, herbicides can reduce weed infestation even before crop emergence, from crop growth to harvesting, ultimately promoting high yields [24]. Correspondingly, variations and minimum use efficiencies of fertilisers and herbicides can impact potential crop yields.

Yields are influenced by interactions between the agro-ecological, human and economic conditions of the smallholder farmer [34]. Thus, understanding both socio-economic and management practices (fertiliser regimes and weed management strategies) and how they could impact yields is essential. This could help elucidate some of the yield gaps between the optimal yield that farmers could potentially achieve, and the actual yields obtained. The hypothesis for this study was that the factors land area cultivated, and herbicide application timing would influence maize yields. A larger cultivated land area would result in more maize plant stands and yield, while herbicide application timing would reduce weed competition enabling healthy maize crops and high yields.

This study aimed to investigate the social, economic, and management factors associated with manure and inorganic fertiliser use by smallholder farmers which could potentially impact maize yield. Maize is an energy food source for many African countries including Eswatini where it is a staple cereal. Even though the Eswatini government subsidises maize production [35], productivity is very low per unit area. Hence, the study explored the opportunities and constraints faced by farmers in Eswatini on current fertilisation practices and weed management strategies in maize-livestock cropping fields. The study also evaluated the effect of organic (manure) and inorganic fertiliser as well as weed management on maize grain yield and concomitant cost-benefits.

Materials and Methods

Study Site

A questionnaire survey was conducted during the 2020/2021 maize cropping season, and a field study was conducted during the 2020/2021 and 2021/2022 cropping seasons. The study regions were the Highveld and Middleveld of Eswatini. In the Highveld, the study area was Mankayane (26.40°S, 31.3°E, elevation 900–1800 m.a.s.l) and in the Middleveld the study area was Luve (26.19°S, 31.28°E, elevation 400–800 m.a.s.l). The total rainfall during the experimental period at Mankayane was 904 mm and 780 mm, while at Luve it was 808 mm and 505 mm for the first and second seasons, respectively. The average temperature at Mankayane was 20.9 and 18.4 °C, whereas at Luve it was 23.2 and 21.7 °C for the first and second seasons, respectively. Soil texture at Mankayane was determined as sandy clay loam with a clay content of 28% and at Luve was determined as sandy loam with a clay content of 19%.

Selection of Participants and Data Collection

Data were collected through recorded telephonic interviews. Extension officers from the study areas assisted in providing a list (with contact details) of small-scale farmers with a maize production history of more than five years.

Initially, 5320 and 4970 farmers were identified at Mankayane and Luve, respectively. Farmers were randomly selected from the list and a total of 50 farmers (25 from each region) were interviewed in the study. The questionnaire was semi-structured, with both open and close-ended questions, and comprised of three main sections: (1) the demographic profile of participants; (2) production information on maize varieties grown, fertiliser application, types and quantity of fertilisers applied, manure application, manure handling and storage, the quantity of manure applied, and costs associated with fertiliser purchase, manure purchase and application; and (3) weed management practices, which included herbicide rotations, and costs of weed control method.

From the interviews, a total of 18 participants were randomly selected from each region to participate in on-farm trials. The trials comprised of three fertiliser regimes each with six replicates. The fertiliser regimes were as follows: fields amended with cattle manure only (M), cattle manure plus inorganic fertiliser (M + F), and inorganic fertiliser only (F) (Table 1). The tillage method used by the sampled farmers was mouldboard plough followed by disc harrowing. A plot measuring 10 m × 10 m from each field was used for the study. Maize variety SC 719 (Seed-Co®, Zimbabwe) was planted at a seeding rate of 25 kg ha^{-1}, at a spacing of 0.9 m inter-row and 0.25 m intra-row. Manure was kept uncovered throughout the winter season in kraals and was later broadcasted in the field at a rate of 9 t ha^{-1} before land preparation. Basal fertiliser [N: P: K, 2:3:2 (37%)] was applied at planting with application rates of 500 kg ha^{-1} at Mankayane and 400 kg ha^{-1} at Luve. Four weeks following emergence, top-dress fertiliser Limestone Ammonium Nitrate [LAN (28% N)] was applied at application rates of 200 kg ha^{-1} for Mankayane and 150 kg ha^{-1} for Luve. Mankayane received higher fertiliser rates due to that the area receiving high rainfall amounts, which could result in nutrient leaching. Weed management in plots was through early post-emergence (EPOST) herbicide application, at four-leaf stage of the maize crop. The herbicide applied was 900 g kg^{-1} a.i, CYANAZINE (BLADEX®) (90% wettable granule formulation), at recommended dosage rates (4 L ha^{-1}). A PB-20 or PB-16 Knapsack sprayer was used, calibrated to reach and maintain the 300 kPa pressure, with a spray volume of 200 L ha^{-1}.

Weed Biomass and Yield

Data collected from the trials were weed biomass and maize grain yield. Weeds were collected from the centre of each plot, using a 5 m × 1 m quadrat. Broadleaved weeds of 5 cm and grass weeds of 15 cm in height together with stoloniferous weeds of 5 cm in length were recognised as established plants, and their biomass was collected. Samples of weeds were collected at maize physiological maturity and oven dried at 80 °C for 48 h, and dry mass was determined. Maize grain yield was determined by harvesting maize cobs from the site where weed biomass was collected. Grains were weighed before and after oven drying (also at 80 °C for 48 h). Weed dry mass and grain yield were weighed using a Mettler Toledo scale (Model ML3002E, Switzerland) with 0.0001 g accuracy. Grain yield was adjusted to 12.5% moisture content and was determined as described by Liliane and Mutengwa [27]:

$$\mathrm{Maizeyield}(\mathrm{t\ ha^{-1}}) = [\mathrm{GrainWeight} \times 10 \times (100 - \mathrm{MC})] / [(100 - \mathrm{AdjustedMC})/(\mathrm{Plotarea})], \tag{1}$$

where grain weight is in kg, moisture content (MC) is in percentage and plot area is in m^2.

Data Analyses

Descriptive statistics were used to compute frequencies and percentages of the participants' responses. Linear regression was used to determine the association of maize yield with household size, land under cultivation, seed type, farming experience, fertiliser application, herbicide usage, herbicide application and application method, and crop rotation programs. Analysis of variance (ANOVA) was

Table 1 Treatment layout of fertiliser regimes in each study area

Fertiliser regime	Number of fields	Soil amendment	Application time
Manure only (M)	6	Cattle manure	At ploughing
Manure plus inorganic fertiliser (M + F)	6	Cattle manure	At ploughing
		NPK	Basal dressing
		LAN	Top dress
Inorganic fertiliser only (F)	6	NPK	Basal dressing
		LAN	Top dress

Table 2 Demographic profile of farmers from both study areas (Total sample $N = 50$)

Variable	Response	Frequency	Proportion of participants (%)
Gender	Male	23	46
	Female	27	54
Education level	None	3	6
	Primary	7	14
	Secondary	32	64
	Tertiary	8	16
Household size	1–5 persons	12	24
	6–10 persons	29	58
	11–15 persons	9	18

used to determine the mean differences in weed biomass and maize grain yield by fertiliser regimes, study areas, and season. Mean pairwise separation was by the least significant difference test (LSD). A linear regression analysis was done to ascertain the relationship between weed biomass and grain yield in both cropping seasons. The regression coefficient was considered a degree of sensitivity of grain yield to weed biomass. Data were analysed using the Statistical Package for Social Sciences (IBM SPSS Statistics version 28).

The economic analysis was carried out using the method described by CIMMYT [16] and were determined for the 2020/2021 cropping season only with the production costs provided by farmers from the survey questionnaire. The method included the calculation of the partial budgets, dominance, and marginal analysis for the different fertiliser regimes. The partial budget consisted of the field price of maize, total variable costs, net benefit, and total gross field benefit of each fertiliser regime. Production costs were averaged per fertiliser regime. Gross benefits for each fertiliser regime were calculated by multiplying the grain yield by the field price. The field price of maize used was \$237 (USD) per tonne as recommended by the National Maize Corporation (NMC) for the 2020/2021 cropping season. Total variable costs for each fertiliser regime were the average costs of fertiliser purchase, cost of manure procurement, cost of inorganic fertiliser and manure application, cost of labour for weed control, and the cost of herbicide purchase. All farmers who applied manure on their fields owned cattle, thus manure was sourced from the farm. However, farmers were requested to give the cost of manure if they were to purchase it from neighbours, and this cost was used in the economic analysis. The cost of labour for inorganic fertiliser, manure and herbicide application was determined by averaging the costs incurred by each farmer (to \$4.60 per individual) for each fertiliser regime. The net benefits of the fertiliser regimes were calculated by subtracting the total variable costs from the gross benefits.

To enhance farmers' income, it is necessary to consider economic net benefits rather than yield. This was done through the dominance analysis as described by CIMMYT [16]. The analysis was accomplished by listing all the fertiliser regimes in order of costs that vary. Any fertiliser regime that had net benefits equal to or less than those of a fertiliser regime with lower costs that vary was dominated, and thus eliminated from the analysis. Thereafter, the marginal rate of return was used to assess the minimal return farmers could expect after their production expenses when changing from manure only to manure plus inorganic fertiliser or inorganic fertiliser only and vice versa. The minimum marginal rate of return considered in this study was 100%, and it was determined using the following formula by CIMMYT [16]:

$$\begin{aligned}&\text{Marginal Rate of Return}\\&=[\text{Marginal benefit(Change in netbenefits)}]/\\&[\text{Marginal varying costs(change in costs)}]\times 100\end{aligned} \tag{2}$$

Results

Demographic Characteristics of Farmers

Demographic information of participating smallholder farmers revealed that female farmers were proportionately more (54%) than male farmers (Table 2). Nearly two-thirds (64%) of the farmers possessed secondary education, while a few (6%) had no formal education. The number of individuals per household varied from one person to 15 individuals, with most households (58%) consisting of 6–10 individuals.

Production Information of Maize

Of the 50 farmers surveyed, only one produced maize on leased land, while the rest produced maize on their own land (Table 3). The highest experience the farmers had in maize production was more than 30 years (54%), with a few (8%) having 10 years or less experience. Nearly two-thirds (64%) of the farmers cultivated hybrid maize varieties, while the rest used local landrace seeds. Only a few (6%) obtained yields of more than 5 t ha^{-1}, with the majority harvesting between 0.5 and 1.5 t ha^{-1}.

Only a quarter of the participants practiced crop rotation, with a 12-month rotation cycle (22%) and common

Table 3 Production information of maize from both study areas (Total sample $N = 50$)

Variable	Response	Frequency (N)	Proportion of participants (%)
Land ownership	Own	49	98
	Rented	1	2
Maize production experience	0–10 years	4	8
	11–20 years	9	18
	20–30 years	10	20
	> 30 years	27	54
Land under maize cultivation (ha)	0–0.5	10	20
	0.5–1	30	60
	1–1.5	1	2
	1.5–2	3	6
	2–2.5	2	4
	2.5–3	2	4
	3–4	1	2
	4–5	1	2
Type of seed	Landraces	18	36
	Hybrid	32	64
Maize yield (t ha^{-1})	0–0.5	7	14
	0.5–1	16	32
	1–1.5	12	24
	1.5–2	3	6
	2–4	5	10
	4–5	4	8
	5–8	3	6
Crop rotation	Yes	13	26
	No	37	74
Crops rotated	Dry beans	1	2
	Peanuts	7	14
	Sweet potato	5	10
Rotation period	6 months	2	4
	12 Months	11	22
Apply inorganic fertiliser only	Yes	37	74
	No	13	26
Apply manure only	Yes	25	50
	No	25	50
Apply manure and inorganic fertiliser	Yes	13	26
	No	37	74
Herbicide application	Yes	47	94
	No	3	6
Herbicide application timing	Pre-emergence	4	8
	Early post-emergence	38	76
	Pre- and post-emergence	5	10
Herbicide applied	BLADEX®	33	66
	2, 4-D AMINE	11	22
	CLEAROUT®	3	6

Table 4 Socio-economic factors in relation to maize yield (Total sample $N = 50$)

		Unstandardised B	SE	*B*-coefficients	*t*-value	*p*-value
Maize yield	Household size	0.745	0.348	0.214	2.144	0.039
	Land cultivated	0.732	0.164	0.519	4.471	0.001
	Land ownership	1.583	1.722	0.102	0.919	0.364
	Farming experience	0.345	0.244	0.156	1.414	0.166
	Seed type	0.526	0.540	0.110	0.974	0.337
	Inorganic fertiliser application	−0.586	0.590	−0.116	−0.994	0.327
	Weed control method	0.503	0.301	0.178	1.668	0.104
	Herbicide application timing	1.355	0.632	0.264	2.145	0.039
	Herbicide applied	0.266	0.232	0.148	1.149	0.258
	Crop rotation	−0.266	0.568	−0.048	−0.468	0.642

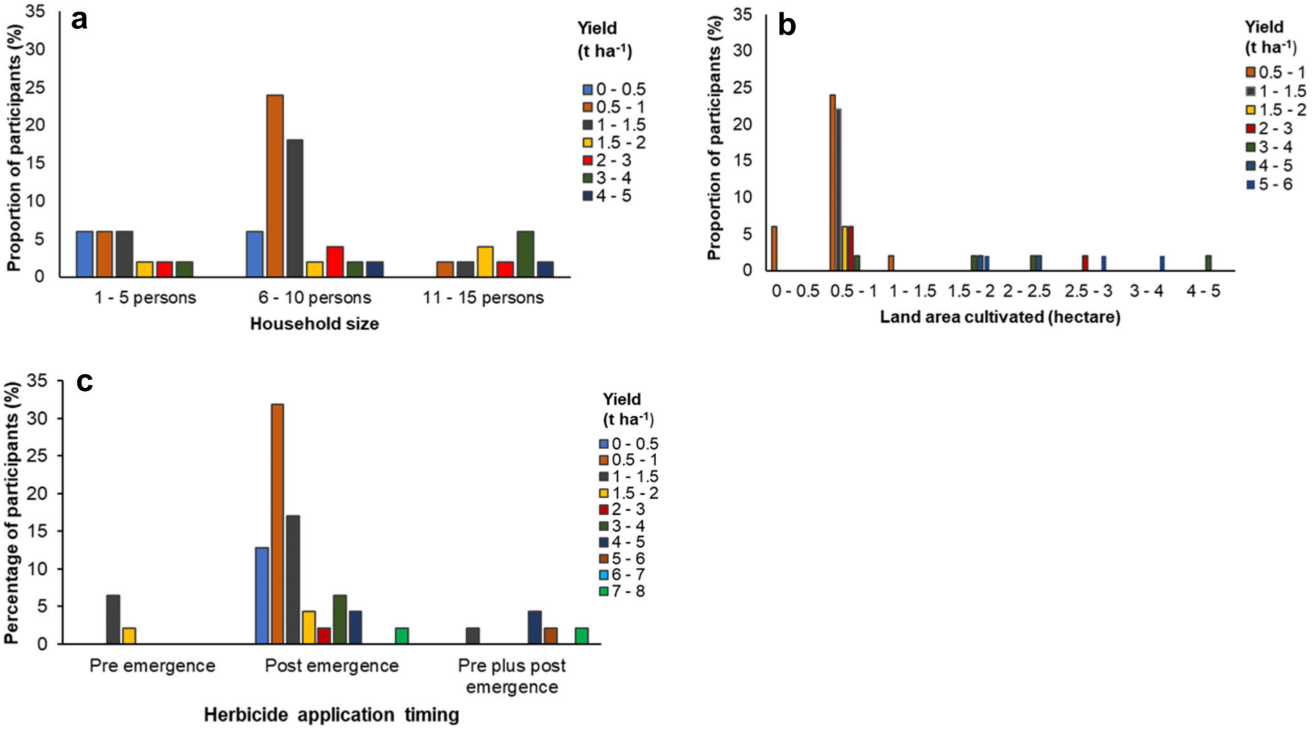

Fig. 1 Impact of household size (**a**), land area cultivated (**b**) and herbicide application timing (**c**) on maize yield at both study sites

crops included peanuts (*Arachis hypogaea* L.), sweet potato [*Ipomoea batatas* (L.) Lam.], and sometimes common beans (*Phaseolus vulgaris* L.) (Table 3). The majority (94%) of the farmers managed weeds using herbicides, and the remainder practiced manual weeding. Few farmers applied pre-emergence herbicides, while the majority (76%) applied post-emergence herbicides. Specifically, 66% of the farmers applied 900 g kg^{-1} a. i. Cyanazine (BLADEX®) (90% wettable granule) as an early post-emergence herbicide, while the rest either applied 360 g L^{-1} Glyphosate (CLEAROUT® 41 PLUS) or 2,4-D AMINE as a post-emergent herbicide, applied a few weeks before planting for pre-plant weed control and to obtain a weed free seed bank. With regards to fertiliser regimes, most farmers (74%) supplied their maize crop with inorganic fertiliser only while a few supplied both manure and inorganic fertiliser (26%).

Regression analysis showed that maize yield was positively influenced (Adjusted $R^2 = 0.62$, $p < 0.05$) by household size, total land area cultivated by farmers and herbicide application timing (Table 4).

Most of the participants who attained 0.5–1 t ha^{-1} of maize yield were part of the medium household size (6–10 individuals) (Fig. 1a). They cultivated maize on 0.5–1 ha

Table 5 Partial budgets of fertiliser regimes for both Mankayane and Luve

Production costs (USD)	Mankayane			Luve		
	Manure only	Manure plus inorganic fertiliser	Inorganic fertiliser only	Manure only	Manure plus inorganicfertiliser	Inorganic fertiliser only
Average yield ($t.ha^{-1}$)*	1.98	2.23	2.72	1.85	2.04	2.77
Gross field benefits ($)	469.07	528.44	643.73	437.33	483.73	654.47
Cost of Manure ($)	52.13	52.13		89.33	89.33	
Cost of Tractor-trailer for manure transportation ($)	16.67	16.67		16.67	16.67	
Cost of labour for manure application ($)	24.43	24.43		23.33	23.33	
Cost of fertiliser (NPK) ($)		172.43	172.43		105.87	105.87
Cost of NPK labour for application ($)		16.93	16.93		18.40	18.40
Cost of fertiliser (LAN)		89.07	89.07		66.80	66.80
Cost of LAN labour for application ($)		18.40	18.40		17.33	17.33
Cost of Herbicide ($)	34.67	34.67	34.67	34.67	34.67	34.67
Cost of labour for herbicide application ($)	14.72	14.72	14.72	18.40	18.40	18.40
Total costs that vary ($)	142.49	439.45	346.22	182.40	390.80	261.47
Net Benefits ($)	326.58	88.99	297.51	254.93	92.93	393.00

*Field price of maize per tonne = $ 236.67

Table 6 Dominance and marginal analysis of fertiliser regimes at Luve

Fertiliser regime	Costs that vary ($)	Net benefits ($)	Marginal rate of return
Manure only	182.40	254.93	174%
Inorganic fertiliser only	261.47	393.00	
Manure plus inorganic fertiliser	390.80	92.93 ^{Dm}	

Dm Dominated alternative; Minimum rate of return = 100%

Table 7 ANOVA output explaining the effect of fertiliser regimes, study areas and seasons on maize yield and weed biomass

Source of variance	Maize yield ($t\ ha^{-1}$) *p*-value	Weed biomass ($g\ m^{-2}$) *p*-value
Fertiliser regimes (Fr)	0.001	0.001
Study areas (Sa)	0.239	0.350
Seasons (Se)	0.540	0.905
Fr x Sa	0.972	0.015
Fr x Se	0.986	0.001
Sa x Se	0.709	0.303
Fr x Sa x Se	0.572	0.013

of land (Fig. 1b) and applied post-emergence herbicides (Fig. 1c).

Economic Analysis of Fertiliser Regimes

The partial budget for Mankayane shows that manure only and inorganic fertiliser only applications, had costs that vary, that were 67.55 and 21.22% lower than manure plus inorganic fertiliser regime (Table 5). Similar observations were made at Luve, where the manure only and the inorganic fertiliser only applications had costs that vary, that were 53.33 and 33.1% lower than manure plus inorganic fertiliser regime. The lower costs that vary in the application of manure only and inorganic fertiliser only resulted in high net benefits compared to manure plus inorganic fertiliser regime.

To select the most economic fertiliser regime in maize cultivation, the dominance analysis was conducted. The results showed that, at Mankayane, all the fertiliser regimes

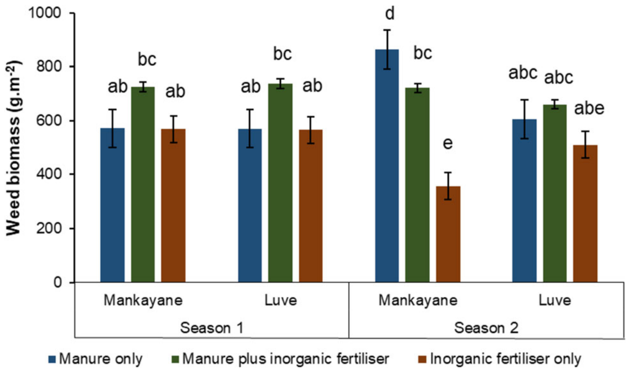

Fig. 2 Mean (± SD) weed biomass (g m^{-2}) showing the interaction of fertiliser regimes, study areas and cropping seasons. Superscripts denote significant differences per fertiliser regime, study area and cropping season

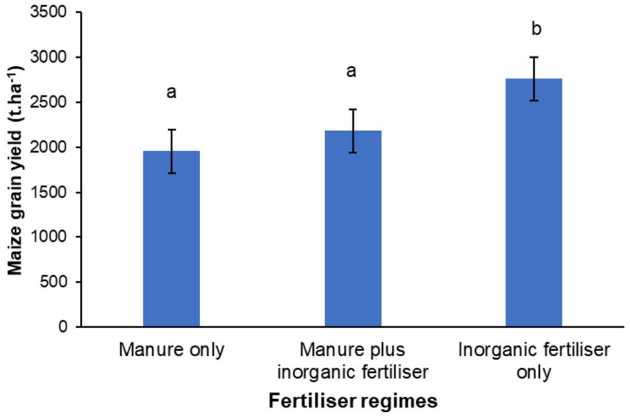

Fig. 3 Mean (± SD) maize grain yield (t ha^{-1}) between fertiliser regimes. Superscripts denote significant differences per fertiliser regime

were dominated, thus no marginal analysis was conducted. Conversely at Luve, the manure plus inorganic fertiliser regime had high varying costs, thus low net benefits and was therefore dominated by the other fertiliser regimes and was eliminated from the analysis. The inorganic fertiliser only regime was the most economical, with a marginal rate of return of 174% over manure only applied fields (Table 6).

Weed Biomass and Maize Yield

Weed biomass differed significantly between fertiliser regimes, study areas and cropping seasons ($F(72, 2)$ 4.648, $p < 0.05$) (Table 7). There was a significant weed biomass decrease, in the application of inorganic fertiliser only at Mankayane, in the second season compared to the application of manure only and manure plus inorganic fertiliser, in both study areas and both seasons (Fig. 2). The manure only fertiliser regime at Mankayane in the second season, showed a significant weed biomass increase compared to the manure only fertiliser regime at Luve, in both cropping seasons.

Maize yield showed a significant difference between the fertiliser regimes only ($F(72, 2)$ 18.032, $p < 0.05$) (Table 7). Specifically, at both Mankayane and Luve, inorganic fertiliser only regime showed a significant increase in maize yield compared to manure only and manure plus inorganic fertiliser regimes (Fig. 3).

Regression analysis indicated no significant ($p > 0.05$) relationship between weed biomass and maize yield in season 1 (Mankayane Adjusted $R^2 = -0.814$; Luve Adjusted $R^2 = -0.074$) and season 2 (Mankayane Adjusted $R^2 = -0.226$; Luve Adjusted $R^2 = -0.116$) (Table 8).

Discussion

The study set out to investigate social, economic and management aspects that may influence maize productivity when smallholder farmers use cattle manure and inorganic fertilisers. The application of manure only and manure plus inorganic fertiliser, indicated a significantly reduced maize yield compared to the fertiliser only regime. The low yields from the application of manure only can be attributed to the slow and prolonged release of nutrients from manure, which could have failed to meet the nutrient requirements of the maize crop. The reduced yields in the manure plus inorganic fertiliser application could be due to over fertilisation which did not guarantee nutrient use by the maize crop resulting in luxury resource consumption by weeds [29]. The results contradict those of Baghdadi et al. [5], Abid et al. [1] and Chipomho et al. [15] who reported increased maize yield benefits with manure plus inorganic fertiliser applications.

Low maize yields in the manure applied fields could also be due to the manure handling and storage methods implemented by farmers which may have compromised nutrient availability to the crop. Nutrient losses occur during storage and application practices which directly affect the quantity and quality of nutrients available for crops [26]. Farmers tend to store their manure uncovered throughout the year which exposes it to sunshine and rainfall. Storing manure in uncovered heaps results in volatilisation, leaching and denitrification [44]. Castellanos-Navarrete et al. [13] observed increased nutrient retention and value with manure stored in roofed and hard-floored stalls. Thus, to benefit from manure nutrients, farmers need to invest in manure storage and application methods that allow better nutrient retention and availability to crops. Furthermore, nutrient losses can occur during communal grazing where stocking rates are not observed,

Table 8 Regression analysis of weed biomass and maize yield in season 1 and season 2 at both Mankayane and Luve

Effect of weed biomass	Unstandardised B	SE	β-coefficients	t-value	p-value
Season 1					
Mankayane					
Biomass – M yield	−1.157	0.789	−0.591	−1.467	0.216
Biomass – M + F yield	−2.035	1.096	−0.680	−1.856	0.137
Biomass – F yield	1.618	1.081	0.599	1.496	0.209
Luve					
Biomass – M yield	−1.839	2.751	−0.317	−0.669	0.540
Biomass – M + F yield	−2.012	1.323	−0.605	−1.520	0.203
Biomass – F yield	−2.811	3.406	0.381	−0.825	0.456
Season 2					
Mankayane					
Biomass – M yield	0.143	0.119	0.516	1.204	0.295
Biomass – M + F yield	−0.247	0.154	−0.625	−1.604	0.184
Biomass – F yield	0.102	0.101	0.449	1.006	0.371
Luve					
Biomass – M yield	−0.045	0.146	−0.152	−0.307	0.774
Biomass – M + F yield	−0.037	0.053	−0.327	−0.692	0.527
Biomass – F yield	0.031	0.034	0.410	0.900	0.419

M manure only, *M + F* manure plus inorganic fertiliser, *F* norganic fertiliser only

resulting in the dominance of unpalatable species [52], and restricting nutrient transfer [20].

In the second season, the manure only fertiliser regime, at Mankayane, recorded significantly high weed biomass compared to the manure plus inorganic fertiliser and inorganic fertiliser regimes at Luve for both cropping seasons (Fig. 2). This could have been due to the large number of viable seeds contained in uncured manure [21, 32, 42], which could have germinated and contributed to the increased weed biomass. Weeds, especially nitrophilous and phosphophilous weeds [8, 9, 15] those having a high nutrient usage efficiency, may have benefited from manure's gradual and slow release of nutrients [8, 29], thus increasing weed biomass. The results correspond with those of Abid et al. [1] and Salikhov et al. [43]. who reported increased weed biomass with cattle manure applications in maize and potato (*Solanum tuberosum* L.) production, respectively. In addition, manure is a soil conditioner that improves soil chemical and physical qualities and may allow weeds to grow and compete effectively [30]. Moreover, nitrogen contained in the manure may break seed dormancy [47, 53] resulting in the germination of weed seeds and in the subsequent successful establishment of weed seedlings.

Weed biomass did not affect maize yield which demonstrated the effectiveness of the early post-emergence herbicide applied. The impact of weeds after the critical growth period of maize and post-emergence herbicide control is minimal. However, strong association between maize yield and the management aspect of herbicide application timing was established. The pre-emergence, post-emergence and pre- plus post-emergence herbicide application timing, gave maize yields of 0.5–7 t ha^{-1} in the different cultivated farm sizes. The results correspond with studies by Khan et al. [23] and Kumar et al. [25], which revealed that the application of pre-, post- and pre- plus post-emergence herbicides influenced maize yields positively. This also indicated that chemical weed control has the potential to increase maize yields. Additionally, herbicide application has increasingly been adopted by smallholder farmers and has become the easiest and cheapest weed control method [36]. Also, the different timings of herbicide application could still influence herbicide efficacy and efficiency and may result in greater weed reduction and increased crop competitiveness [2, 54].

The study further identified strong relationships between maize yield and household size and land area cultivated (Table 4). The results are in accordance with Banerjee et al. [6] and Sheng et al. [45] who reported that household size and farm size significantly influenced maize yield. The strong association between household size and maize yield could be indicative of increased labour availability and efficiency of family members as well as overall management of the maize crop. It could also suggest that farmers are better able to feed their families and thus ensure food security. The strong association between land area cultivated and maize yield could imply that farmers are able to effectively manage their maize crop, through timely input supply and weed control. Input use efficiency is elevated even in small farm sizes (below one hectare) and yield increases with increasing cultivated land. Besides the influence of weeds, crop yields could also be affected by the interaction of genotypic, management and environmental factors [28], which include climatic (temperature, rainfall) conditions that the farmer may not have control over, soil conditions (texture, pH, nutrients), as well as pests and diseases.

Also, socio-economic factors can influence the input intensification by farmers [46, 49]. The economic analysis revealed that the manure only applied fields had the lowest costs that vary, and high net returns specifically at Mankayane. This was because manure is a cheap source of fertiliser that farmers utilise for nutrient supply. Manure is a readily available fertiliser that is usually obtained at no cost by farmers [4]. This may lead to the high net benefits observed in the manure only fertiliser regime in this study. The results correspond with Cen et al. [14] who observed increased economic returns with cattle manure applications.

The manure plus inorganic fertiliser applied fields had the highest variable costs and low economic returns due to the consideration of the little to no cost of manure. This could be due to the probable over- or under application of both manure and inorganic fertiliser, which can result in unproductive nutrient use by the crop and low net return from maize cultivation [1]. At Mankayane the inorganic fertiliser only regime had net benefits which were lower than those of the manure only regime. This could be due to the possibility of nutrient leaching as a result of the area's high rainfall [55]. Furthermore, inorganic fertiliser only provides nutrients and has no beneficial effects on soil physical properties that promote crop growth [3, 7]. At Luve the inorganic fertiliser only applied fields showed the highest net benefits. This could have been due to the fact that inorganic fertilisers immediately provide crops with nutrients and the maize crop could have utilised them efficiently and increased yield. The results corroborate with Dhakal et al. [19], who observed increased net returns with a benefit cost ratio of 1:54 in recommended inorganic fertiliser applications. The marginal rate of return showed a benefit of 174% at Luve if the farmers were to change from the manure only to inorganic fertiliser only regime. The results imply that inorganic fertiliser application brings both economic and yield benefits.

Conclusion

The results obtained in this study showed that maize yield was not influenced by weed biomass but by socio-economic and management factors, i.e. household size, farm size, and herbicide time of application. Household size represented labour availability, which can further impact decisions on the intensity of management practices, such as fertiliser and weed management. Moreover, the analysis showed that the manure only fertiliser regime is characterised by high net returns, low input costs and low yields. Therefore, manure may have the potential to increase maize yield when properly managed and correctly handled to conserve nutrients, increase nutrient availability for maize, increase crop competitive ability, and increase yields. Integration of manure and inorganic fertiliser were characterised by high input costs, low yields, and minimal economic returns. Inorganic fertiliser only applied fields especially at Luve, showed high yields and high economic returns. However, inorganic fertiliser application only may not be sustainable and may reduce soil quality, crop yield and productivity in the long term. The socio-economic and management factors evaluated in this study, when appropriately considered, may bridge yield gaps for many smallholder farmers, allowing them to produce surplus maize. This calls for smallholder farmers to consider their maize production as an enterprise and to invest in quality nutrient preservation and application. Nonetheless, maize–legume rotations could assist in enhancing nitrogen availability and improve soil fertility. Maize–legume rotations can also suppress the number and type of weeds that are highly competitive during maize production.

Research Ethics

This research was conducted in accordance with the Stellenbosch University's ethical research policy. Permission to conduct the study was granted prior to data collection by the University Research Ethics Committee (REC: FES-CAGRI-2020-18829). Respondents of the study were sent a consent form through a link via WhatsApp messaging or by email, where they had an opportunity to either accept or decline participation. Farmers who participated in on-farm trials further signed another consent form granting permission to access their fields and allowing participation in the study. The anonymity of respondents and confidentiality were assured for each participant. Sensitive information such as personal contact details was kept separate and only the authors had access to it.

Author Contribution TLM, EEP, HRM, and PJP conceptualised, conceived and designed the experiment. TLM, PNM and JTR analysed the data and interpreted the results. TLM drafted the manuscript. EEP, PJP, JTR, HRM, and PNM critically revised and edited the manuscript.

Funding Open access funding provided by Stellenbosch University.

Declarations

Conflict of interest The authors have no conflicts of interest to declare and no financial interest to report.

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