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ORIGINAL ARTICLE

Maize-bean intercrop response to nutrient application relative to maize sole crop response

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Abstract Maize-bean intercropping is important in sub-Saharan Africa. Maize sole crop (MSC) nutrient response has been much studied but data is scarce for determination of intercrop functions. A procedure for adapting MSC functions for the maize-bean intercrop was developed. Maize sole crop and intercrop responses were near parallel with notable exceptions for P in high potential areas for maize and for K. Mean intercrop bean yield with no nutrient application was about 0.4 Mg ha^{-1} and increased on average by 24, 11 and −3% with N, P and K application, respectively. Response function coefficients for MSC adjusted with the ratio of bean to maize grain value as the dependent variable accounted for nearly all variation in intercrop response coefficients providing the basis for determining intercrop response functions from MSC functions. Maize grain yield equivalent was less with MSC compared with intercrop; exceptions were for response to N in high potential areas and for bean to maize value ratios of two or less. The economically optimal rate of N and P were on average about 15% more but less for K with intercrop compared with MSC but with inconsistency. The economically optimal rate ranged widely with variation in the cost of nutrient use relative to grain value but generally without great effect on yield; an exception was a great effect on MSC yield response to N for high potential areas. Intercrop nutrient response functions can be reliably determined once maize sole crop functions are determined for a recommendation domain.

Keywords Asymptotic functions · Curvilinear to plateau · Economically optimal rate · Net return to fertilizer · Nitrogen · Optimization · Phosphorus · Potassium · Response functions · Yield equivalent

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Abbreviations

CP	The cost of using a fertilizer nutrient relative to the on-farm value of the maize grain on a (\$ kg^{-1}) (\$ $kg^{-1})^{-1}$ basis
EOR	The nutrient rate giving maximum net return per ha due to nutrient application, that is the economically optimal rate
FURP	Fertilizer Use Recommendation Project conducted in Kenya in the 1980s–90s
HP and LP	High and low potential areas for maize production
MSC	Maize sole crop
NwP, PwN and KwNP	Responses to N, P and K with uniform base applications of some level of P, N and N plus P respectively
OFRA	Optimization of Fertilizer Recommendations in Africa project

Introduction

Maize-bean intercropping is very important in eastern and southern Africa. The intercrop accounted for about 44% of the bean production area while bean sole crop accounted for about 30% of the area (Wortmann et al. 1998). Intercropping can be beneficial in productivity (Ebwongu et al. 2001; Mesfin et al. 2014), light interception (Ennin et al. 2002), profitability (Tsubo et al. 2004), weed suppression (Musambasi et al. 2002; Getachew et al. 2007; Odhiambo and Ariga 2001; Alemu et al. 1987; Workayehu and Wortmann 2011), and insect pest management (Belay et al. 2009; Nampala et al. 2002).

The relative competitive ability of the intercropped crops varies according to management (Wortmann et al. 1998). For example, in Kenya and Tanzania where maize is the primary staple food crop, intercrop management favors maize with generally full plant stands of maize but about 50% of the bean sole crop stand. In Uganda with diverse important staple crops, bean often receives preference over maize with near full plant stands of bean and low maize plant densities. Intercrop bean can add to the total value of the harvest even when bean yield is low due to the relatively high monetary value of bean (Siame et al. 1998).

Soil fertility management for the maize-bean intercrop has not been well addressed. Little biological fixation of atmospheric N by intercropped bean is expected (Stern 1993; Chalk 1996). A rotation effect of a 36% lower maize sole crop (MSC) N requirement following a maize-cowpea intercrop compared with maize sole crop was reported by Jeranyama et al. (2007) but a similar benefit was not detected with maize-bean intercrop (Waddington et al. 2007). Intercropped legumes generally benefit from fertilizer applied for the maize component (Snapp and Silim 2002). Intercrop compared with MSC productivity is commonly greater, both with and without fertilizer applied.

Results from past field research were compiled in an Optimization of Fertilizer Recommendations in Africa (OFRA) dataset with over 5800 crop-nutrient response functions, with 48% from OFRA-related research conducted since 2009 (available for download at http://agronomy.unl.edu/OFRA). The information from the OFRA dataset is relatively strong for MSC compared with other crops with 1664 MSC response functions and 178 for maize-bean intercropping (Kaizzi 2017; Wortmann et al. 2017). In creating the dataset, the response functions were standardized as curvilinear to plateau responses with an asymptotic function of $Y = a–bc^r$ where Y is yield, a is yield at the plateau for a given applied nutrient (Mg ha^{-1}), b is the maximum yield increase due to application of that nutrient (Mg ha^{-1}), c is a curvature coefficient (unitless) and r is the rate of nutrient application (kg ha^{-1}) (Kaizzi et al. 2012a, b). In constructing the OFRA dataset, it was assumed that maize yield was most constrained by deficiency of N, followed by P, followed by K and other nutrients. The information base was very weak for intercropping, as most maize intercropping studies have used fertilizer rates recommended for MSC (Onyango et al. 2002; Foundufe et al. 2001). There is, however, data for the maize-bean intercrop from numerous site-seasons of side-by-side intercrop and MSC trials conducted in Kenya during 1987–1992 (FURP 1994), and with 2013–2016 results from trials conducted under OFRA in Kenya and Tanzania.

The ability to determine intercrop nutrient response functions from MSC response functions for diverse recommendation domains would be valuable. The

Nutrient Supplementation Index of Wahua (1983) for maize-cowpea intercropping based on total nutrient uptake of intercrop compared with sole crop is one approach, but it is likely that the intercrop will be relatively more efficient in nutrient recovery than the sole crop. Wortmann et al. (1996) used the FURP results to develop a method of estimating intercrop response from MSC response for N and P. With the addition of the OFRA results, the analysis can include K and also be strengthened and streamlined with more recent data and an alternative analytical approach.

The objective of this research was to determine a procedure for calculating response coefficients for maize-bean intercrop in a given recommendation domain once MSC response functions were known and apply the response functions to fertilizer use economics. This involved (1) relating maize-bean intercrop responses to MSC for applied N alone, N with some level of P uniformly applied (NwP), and K with some levels of N and P uniformly applied (KwNP); (2) determination of intercrop response functions on a maize grain yield equivalent (Mg ha^{-1}) basis (with intercrop yield expressed as the maize yield equivalent calculated as maize yield plus the product of bean yield multiplied by the bean to maize grain value ratio ($ kg^{-1} ($ kg)$^{-1}$) and hereafter referred to as maize yield equivalent); (3) development of a procedure for calculating intercrop response coefficients from MSC response functions; and (4) establishment of a basis for estimating the nutrient rate of maximum net returns ha^{-1} due to nutrient application, that is the economically optimal rate (EOR) of nutrient application, for the maize-bean intercrop.

Materials and methods

The data used were from the OFRA dataset referred to above. Maize and bean varieties and management practices differed with site-years but intercrop maize and bean were planted at about 100 and 50% of sole crop plant densities. In both Kenya-FURP and OFRA trials, fertilizers were applied near the maize rows by banding. The N and P rates for FURP trials were 0, 25, 50, and 75 kg N ha^{-1} and 11, 22, 33, and 44 kg P ha^{-1}, respectively. For OFRA, the rates were: 0, 30, 60, 90, and 120 kg N ha^{-1}; 0, 7.5, 15, and 22.5 kg P ha^{-1}; and 0, 10, 20, and 30 kg K ha^{-1}. Locations were categorized as high (HP) and low (LP) potential areas for maize production as determined by Braun (1982) and Jaetzold et al. (2006) with HP generally having a mean annual temperature between 14 and 21 °C and wetter than semi-arid with no serious edaphic constraints, and the remaining maize production area considered LP. Data from 12 HP and 9 LP locations were used in the analysis, often with several seasons of results per location. The number of trials contributing to the data ranged from 10 each for response to K with uniform application of N and P (KwNP) in both HP and LP to 37 for PwN in HP.

Using the asymptotic response functions from the OFRA dataset, yields at five nutrient levels were determined for each site-year-nutrient response function with rate increments of 30, 7.5 and 10 kg ha^{-1} for N, P and K, respectively. The means for each rate were determined and used to determine overall asymptotic response functions and the overall LSD 0.05 for MSC, maize intercrop and bean intercrop using Statistix 10 software (Analytical Software, Tallahassee, FL). These response functions were then used to determine intercrop response functions for the two crops on a maize grain yield equivalent basis with bean to maize value ratios of 1, 2, 3, 4, and 5 ($ kg^{-1}) ($ kg^{-1})$^{-1}$. Using linear regression with bean to maize value ratio as an independent variable, equations were developed for estimating intercrop asymptotic a, b and c coefficients by adapting the respective MSC coefficients.

The EOR (kg ha^{-1}) were determined for MSC and each bean to maize grain value ratio and for different fertilizer nutrient costs relative to maize grain value, that is, the cost of nutrient use relative to on-farm value of maize grain (($ kg^{-1}) ($ kg^{-1})$^{-1}$, CP). The CP for N and K were 3, 6, 9, 12, and 15 ($ kg^{-1}) ($ kg^{-1})$^{-1}$; the comparable CP of P were 5, 10, 15, 20, and 25 ($ kg^{-1}) ($ kg^{-1})$^{-1}$. Using linear stepwise regression, equations were developed for estimating intercrop EOR with the bean to maize value ratio and CP as independent variables. Next, the profit to cost ratios for nutrient applications, expressed as the net gain in maize yield equivalent, with maize and bean yield considered, per nutrient applied (kg kg^{-1}), were determined with P and K applied at 10 kg ha^{-1} and N applied at 30 kg ha^{-1}; therefore, the profit to cost ratio equaled the gain in maize yield equivalent minus the product of nutrient rate times CP, with this difference divided by the product of nutrient rate times CP. The modest nutrient application rates for determination of profit cost ratios were used realizing that most smallholder farmers of Kenya and Tanzania are severely constrained financially and are expected to get greater profit to cost ratios with rates of less than compared with equal to EOR; however, similar analysis could be done for any rate with the information reported.

Results

Maize and bean grain yield responses to nutrient application

Mean MSC yield for HP compared with LP was about 60 and 50% more with and without nutrients applied (Table 1). The maximum yield increase due to an applied nutrient (*b* values) for HP compared with LP were 52, 32 and 44% more for N, PwN and KwNP, respectively, but 19% less for NwP. Intercrop maize compared with MSC yield was 82 and 93% with fertilizer applied for HP and LP, respectively, and 79 and 96% with no fertilizer applied. Mean intercrop bean yield for HP compared with LP was 16 and 30% more, respectively, with and without nutrients applied. Mean intercrop bean yield responses to applied nutrients were small and negative for K for LP (Fig. 1). Both MSC and maize and bean intercrop responses to applied nutrients were positive increases except for the negative response of intercrop maize to K and no response of bean to K in LP. Maize sole crop and intercrop responses were near parallel with notable exceptions for P in HP and K in all cases.

As expected, the maize yield equivalent and the *b* values for intercropping, with and without nutrient application, increased as the bean to maize value ratio increased (Table 1). The *c* values for a given nutrient in HP or LP did not change much with changing bean to maize grain value ratio. The result was that the intercrop response curves were mostly near parallel once a low level of nutrient was applied (Fig. 2). Linear equations written to adjust MSC coefficients for intercrop with bean to maize value ratio as the dependent variable accounted for nearly all of the variation in intercrop coefficient *a* and *b* with R^2 typically >0.98 (Table 2). The mean *c* value was reported when there was too little variation in the intercrop *c* coefficient to determine an equation for adjusting the MSC value for intercrop. Therefore, the basis was established for determining intercrop response functions from the MSC response functions for a recommendation.

Table 1 Asymptotic coefficients *a*, *b* and *c* for maize sole crop, maize-bean intercropped, and the maize grain yield equivalent for the intercrop maize and bean combined with the bean to maize grain value ratio ranging from 2 (BeMz2; (\$ kg^{-1}) (\$ $kg^{-1})^{-1}$ to 4 (BeMz4) determined from research conducted in Kenya and Tanzania

Nutrient	High potential areas			Low potential areas		
	A	B	C	A	B	C
Maize sole crop						
N	5.817	1.313	0.972	3.853	0.865	0.968
NwP	6.124	0.913	0.950	4.615	1.125	0.958
PwN	6.292	0.725	0.892	3.928	0.551	0.880
KwNP	5.448	0.829	0.740	3.361	0.574	0.780
Maize intercropped with bean						
N	4.816	1.317	0.963	3.573	1.062	0.957
NwP	5.028	1.342	0.953	4.572	1.325	0.955
PwN	4.909	0.493	0.884	3.712	0.535	0.883
KwNP	4.873	0.567	0.916	2.842	−0.353	0.910
Bean intercropped with maize						
N	0.523	0.105	0.918	0.519	0.174	0.950
NwP	0.518	0.045	0.926	0.446	0.045	0.930
PwN	0.586	0.021	0.861	0.438	0.068	0.880
KwNP	0.670	0.088	0.786	0.362	−0.052	0.920
Intercrop maize yield equivalent with BeMz2						
N	5.851	1.512	0.959	4.611	1.409	0.955
NwP	5.136	1.294	0.942	5.463	1.413	0.954
PwN	6.081	0.535	0.882	4.594	0.677	0.889
KwNP	5.692	0.650	0.892	3.566	−0.457	0.912
Intercrop maize yield equivalent with BeMz3						
N	6.370	1.612	0.957	5.13	1.582	0.955
NwP	5.721	1.372	0.941	5.908	1.458	0.953
PwN	6.667	0.556	0.882	5.034	0.746	0.889
KwNP	6.334	0.727	0.883	3.929	−0.509	0.913
Intercrop maize yield equivalent with BeMz4						
N	6.890	1.712	0.955	5.649	1.756	0.954
NwP	6.307	1.451	0.940	6.354	1.502	0.953
PwN	7.253	0.577	0.881	5.473	0.815	0.888
KwNP	6.976	0.805	0.875	4.291	−0.561	0.914

Economically optimal rates and net returns for nutrient application

Responses became near parallel above a certain nutrient rate, such as 40 kg N ha^{-1}, with different

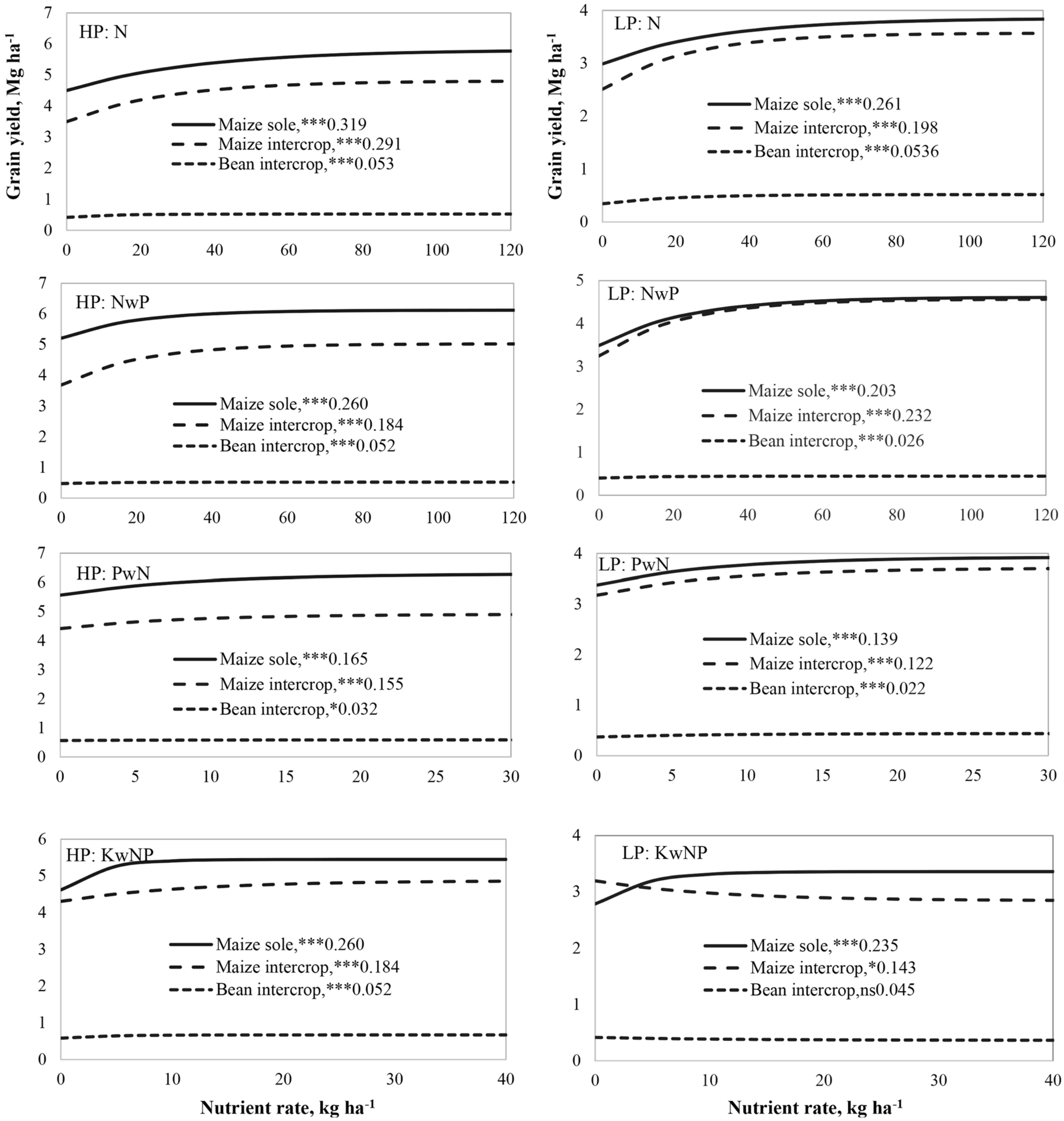

Fig. 1 Grain yield responses to K, N, and P application for maize sole crop and maize-bean intercrop for high (HP) and low (LP) potential maize production areas of Kenya and northern Tanzania. The level of significance (ns, *, *** indicating not significant and significant at P = 0.05 and 0.001, respectively) and LSD 0.05 vales are presented in the legends

bean to maize value ratios, and therefore EOR were similar for a given CP across these value ratios (Fig. 2). The yield increase from the application of 40 kg ha^{-1} N applied increased with bean to maize value ratio for both LP and HP. There was no EOR for KwNP in LP for intercrop due to the negative response to K.

Maize yield equivalent was less with MSC compared with intercrop with the exception of response to N and NwP in HP where MSC and intercrop with a bean to maize value ratio of 2 had similar maize yield equivalent (Fig. 2). Generally, EOR were less with MSC compared with intercrop. However, EOR ranged higher for MSC at lower CP for response to N in HP

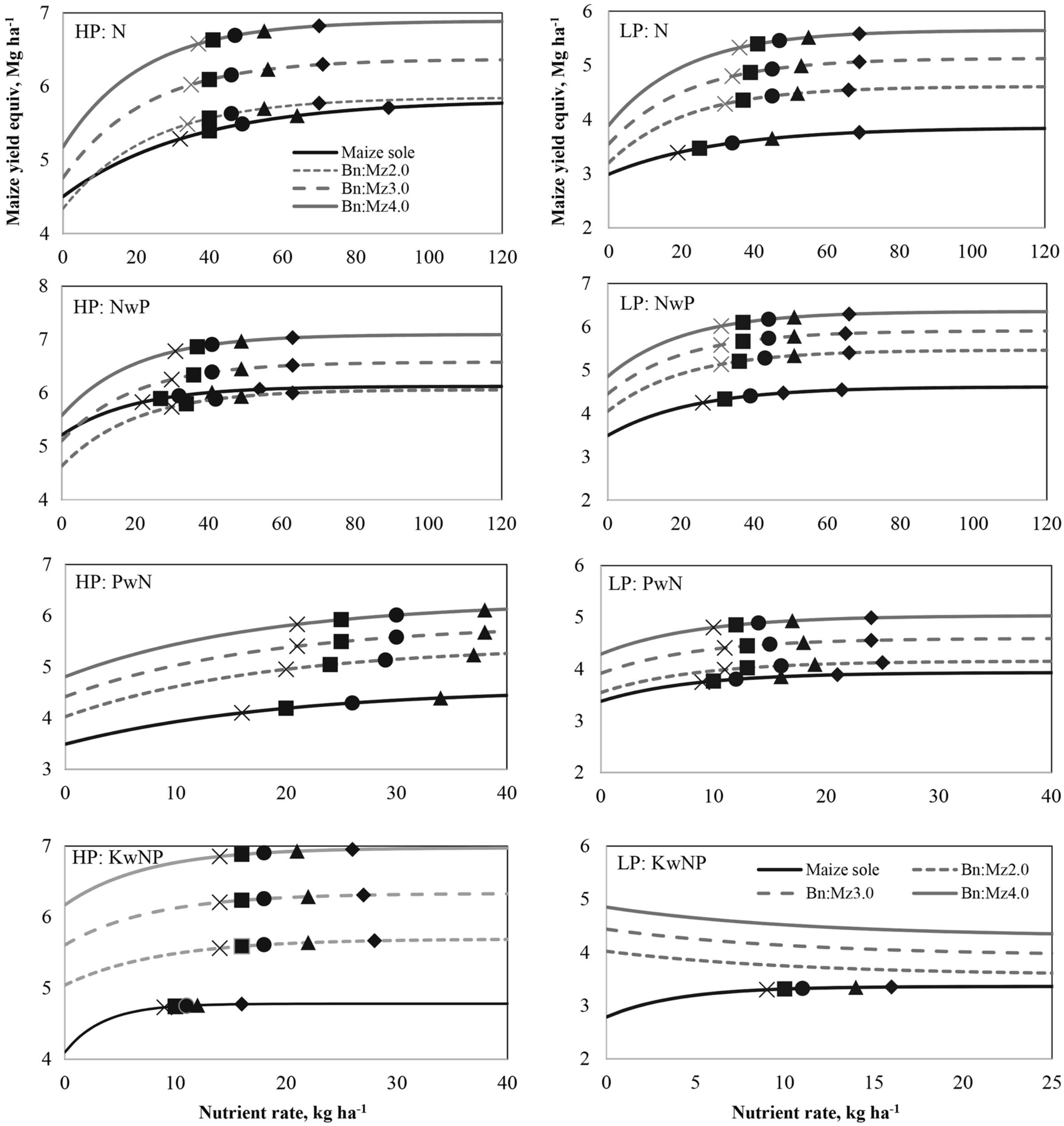

Fig. 2 The maize sole crop and the maize-bean intercrop grain yield response on a maize grain yield equivalent with the bean relative to maize grain value ratio (\$ kg^{-1}) (\$ kg^{-1})$^{-1}$ ranging from 2 (BeMz2.0) to 4 (BeMz4.0) for high (HP) and low (LP) potential maize production areas of Kenya and northern Tanzania. The symbols indicate the economically optimal nutrient rate with the diamond, triangle, circle, square and X representing the cost per kg of N or K use equal to 2, 4, 6, 8, or 10 kg of maize grain and the cost per kg of P use equal to 5, 10, 15, 20, and 25 kg of maize grain, respectively. NwP and KwNP mean that the responses to N and K were determined with 22.5 kg ha^{-1} P applied and with 22.5 kg ha^{-1} P and 30 kg ha^{-1} N applied, respectively

and was similar to intercrop EOR at high CP for both N and NwP in LP. The EOR ranged widely in some cases due to changing CP such as from 32 to 89 and from 19 to 69 kg ha^{-1} in the cases of MSC response to N in HP and LP, respectively, resulting in 0.42 and 0.37 Mg ha^{-1} respective differences in yield. In the

Table 2 Equations for estimating maize-bean intercrop (MBI) coefficients from maize sole crop (MSC) nutrient response functions for high and low potential maize production areas of eastern Africa with the bean to maize value ratio (Be:Mz; ($ kg^{-1}) ($ kg^{-1})$^{-1}$) as the independent variable

High potential[a]	Low potential
$a_{MBI_N} = a_{MSC_N} - 0.774 + 0.551$Be:Mz	$a_{MBI_N} = a_{MSC_N} - 0.280 + 0.52$Be:Mz
$b_{MBI_N} = b_{MSC_N} + 0.0079 + 0.094$Be:Mz	$b_{MBI_N} = b_{MSC_N} + 0.198 + 0.17$Be:Mz
$c_{MBI_N} = c_{MSC_N} - 0.0125 - 0.0017$Be:Mz	$c_{MBI_N} = c_{MSC_N} - 0.0117 - 0.0005$Be:Mz
$a_{MBI_NwP} = a_{MSC_NwP} - 0.821 + 0.50$Be:Mz	$a_{MBI_NwP} = a_{MSC_NwP} - 0.045 + 0.45$Be:Mz
$b_{MBI_NwP} = b_{MSC_NwP} + 0.370 + 0.043$Be:Mz	$b_{MBI_NwP} = b_{MSC_NwP} + 0.200 + 0.044$Be:Mz
$c_{MBI\_NwP} = 0.951$	$c_{MBI\_NwP} = 0.953$
$a_{MBI_PwN} = a_{MSC_PwN} - 1.382 + 0.59$Be:Mz	$a_{MBI_PwN} = a_{MSC_PwNP} - 0.217 + 0.44$Be:Mz
$b_{MBI_PwN} = b_{MSC_PwN} - 0.232 + 0.021$Be:Mz	$b_{MBI_PwN} = b_{MSC_PwN} - 0.0158 + 0.069$Be:Mz
$c_{MBI\_PwN} = 0.882$	$c_{MBI\_PwN} = 0.889$
$a_{MBI_K} = a_{MSC_K} - 0.621 + 0.67$Be:Mz	$a_{MBI_K} = a_{MSC_K} + 0.520 - 0.36$Be:Mz
$b_{MBI_K} = \mathrm{b}_{MSC_K} - 0.270 + 0.083$Be:Mz	$b_{MBI_K} = b_{MSC_K} - 0.270 + 0.083$Be:Mz
$c_{MBI_K} = c_{MSC_K} + 0.171 - 0.008$Be:Mz	$c_{MBI_K} = c_{MSC_K} - 0.130 - 0.0008$Be:Mz

[a] The R^2 values for these equations were typically >0.98

case of MSC response to K in HP, the range of EOR was narrow from 9 to 15 kg ha^{-1} with a yield difference of only 0.05 Mg ha^{-1}.

The mean EOR with intercrop compared with MSC for HP and LP, respectively, were 19 and −9% more for N, −9 and 27% more for NwP, and 36 and 19% more for PwN. The EOR of intercrop compared to MSC for K was 97% more in HP. Once maize-bean intercrop nutrient response functions have been determined for a recommendation domain, intercrop EOR can be estimated with CP and the bean to maize value ratio as independent variables (Table 3) with R^2 of 0.96 or higher. The independent variables accepted to give the best fit equation varied but CP and CP^2 were always present and bean to maize value ratio was present for five of eight equations.

The net returns to modest rates of nutrient application, measured as kg of maize yield equivalent, ranged from 11 to 50, 17 to 62, and negative to 64 kg ha^{-1} maize yield equivalent for N, P and K, respectively, with 25, 10 and 10 kg ha^{-1} applied (Table 4). Net returns to these rates were higher with intercrop compared with MSC and increased as the bean to maize value ratio increased but decreased as CP increased. Net returns to K for MSC were high due to the abrupt mean response to low rates but with very little added yield increase with rates beyond 10 kg ha^{-1} (Fig. 1).

Table 3 Equations for estimating the economically optimal nutrient rate (EOR) for maize-bean intercropping in consideration of the bean to maize value ratio (Be:Mz; ($ kg^{-1}) ($ kg^{-1})$^{-1}$) and the ratio of nutrient application cost to maize grain value (CP; ($ kg^{-1}) ($ kg^{-1})$^{-1}$) for eastern Africa

High potential production areas	
N	EOR_N = 91.3 − 0.910Be:Mz − 10.13CP + 0.421CP^2 + 0.205Be:MzCP, R^2 = 0.99
NwP	EOR_NwP = 61.6 + 9.70Be:Mz − 8.44CP − 1.26Be:Mz^2 + 0.379CP^2, R^2 = 0.98
PwN	EOR_PwN = 77.1 − 4.52CP + 0.0920CP^2, R^2 = 0.96
KwNP	EOR_KwNP = 34.44 − 2.59CP + 0.0814CP^2, R^2 = 0.97
Low potential production areas	
N	EOR_N = 80.94 − 6.65CP + 1.94Be:Mz − 0.215CP^2, R^2 = 0.97
NwP	EOR_NwP = 75.06 − 5.14CP + 0.820Be:Mz + 0.971CP^2, R^2 = 0.97
PwN	EOR_PwN = 33.04−2.46CP + 0.720Be:Mz + 0.0746CP^2, R^2 = 0.99
KwNP	EOR_KwNP = 0

Table 4 Net returns expressed as net gain in maize grain yield equivalent value per nutrient applied (kg kg^{-1}) for different bean to maize grain value ratios (BeMZ; (\$ kg^{-1}) (\$ kg^{-1})$^{-1}$) with intercropping and different nutrient cost to maize grain value ratios (CP; (\$ kg^{-1}) (\$ kg^{-1})$^{-1}$) determined from results of field research conducted in Kenya and Tanzania. Rates are low in consideration of the financially constrained smallholder farmer who needs to get high returns on small investments

CP	High potential production areas						Low potential production areas					
	Maize sole	Intercrop_BeMz					Maize sole	Intercrop_BeMz				
		1	2	3	4	5		1	2	3	4	5
25 kg ha^{-1} N												
3	23.7	32.6	36.2	40.0	43.8	47.3	16.2	30.4	35.5	40.3	45.6	50.4
6	20.7	29.6	33.2	37.0	40.8	44.3	13.2	27.4	32.5	37.3	42.6	47.4
9	17.7	26.6	30.2	34.0	37.8	41.3	10.2	24.4	29.5	34.3	39.6	44.4
12	14.7	23.6	27.2	31.0	34.8	38.3	7.2	21.4	26.5	31.3	36.6	41.4
15	11.7	20.6	24.2	28.0	31.8	35.3	4.2	18.4	23.5	28.3	33.6	38.4
25 kg ha^{-1} NwP												
3	23.3	36.1	37.6	39.2	40.7	42.2	26.6	34.9	36.1	37.8	39.0	40.8
6	20.3	33.1	34.6	36.2	37.7	39.2	23.6	31.9	33.1	34.8	36.0	37.8
9	17.3	30.1	31.6	33.2	34.7	36.2	20.6	28.9	30.1	31.8	33.0	34.8
12	14.3	27.1	28.6	30.2	31.7	33.2	17.6	25.9	27.1	28.8	30.0	31.8
15	11.3	24.1	25.6	27.2	28.7	30.2	14.6	22.9	24.1	25.8	27.0	28.8
10 kg ha^{-1} PwN												
5	38.8	51.3	53.7	56.0	58.4	61.9	55.1	37.1	41.8	46.6	51.7	56.4
10	33.8	46.3	48.7	51.0	53.4	56.9	50.1	32.1	36.8	41.6	46.7	51.4
15	28.8	41.3	43.7	46.0	48.4	51.9	45.1	27.1	31.8	36.6	41.7	46.4
20	23.8	36.3	38.7	41.0	43.4	46.9	40.1	22.1	26.8	31.6	36.7	41.4
25	18.8	31.3	33.7	36.0	38.4	41.9	35.1	17.1	21.8	26.6	31.7	36.4
10 kg ha^{-1} KwNP												
3	61.5	33.9	41.4	48.9	56.5	64.1	49.6	−27.6	−30.5	−33.4	−36.3	−39.4
6	58.5	30.9	38.4	45.9	53.5	61.1	46.6	−30.6	−33.5	−36.4	−39.3	−42.4
9	55.5	27.9	35.4	42.9	50.5	58.1	43.6	−33.6	−36.5	−39.4	−42.3	−45.4
12	52.5	24.9	32.4	39.9	47.5	55.1	40.6	−36.6	−39.5	−42.4	−45.3	−48.4
15	49.5	21.9	29.4	36.9	44.5	52.1	37.6	−39.6	−42.5	−45.4	−48.3	−51.4

Discussion

Maize and bean grain yield responses to nutrient application

Land productivity on a maize yield equivalent basis was generally increased through the intercropping of maize and bean as compared to MSC (Table 1; Fig. 1) confirming the results over diverse conditions of Clark and Francis (1985), Davis and Garcia (1983), Tsubo et al. (2004), Workayehu and Wortmann (2011), and Mesfin et al. (2014). The greater intercrop compared with MSC productivity generally occurred with and without fertilizer applied agreeing with Snapp and Silim (2002). The results also demonstrate the responsiveness of the intercrop compared with MSC to applied N and P. The intercrop gave higher rates of return to applied N, and higher and lower rates of return to applied P for HP and LP, respectively.

Intercrop response to K was less promising and negative for LP (Fig. 1). Yield losses with K application for situations of adequate soil test K are not uncommon. Wortmann et al. (2017) found maize yield decreases of greater than 0.1 Mg ha^{-1} in 18% of the trials captured in the OFRA dataset. Even in high yield environments with an average of about 15 Mg ha^{-1}, mean maize yield loss to unneeded K application has been reported with reference to other studies with similar reduction (Dobermann et al. 2011). There is unpublished evidence of reduced N uptake with KCl application for situations of adequate soil test K. A major concern with KCl application is the salt effect when placed near the seed, including below the seed, and especially with crops such as many pulse crops that produce taproots. However, research teams were advised to band apply KCl at least 5 cm to the side of the row. Also, the decline occurred even with the low 10 kg ha^{-1} rate indicating a problem other than salt effects. It is interesting but unexplained that the negative effect of K for the LP was greater for intercrop maize compared with intercrop bean.

Mean MSC and intercrop yields were higher with HP compared with LP but the effect on the response to applied nutrients was inconsistent (Table 1; Fig. 1). Responses to N and K were greater with HP compared with LP but responses to NwP and PwN were inconsistent. Maize yields were high compared with the national average maize yield of 1.9 Mg ha^{-1} and 1.8 Mg ha^{-1} for Kenya and Tanzania, respectively (DTM 2014), and about 69% of the estimated mean water limited rainfed potential yield of 7.1 Mg ha^{-1} estimated for Kenya (www.yieldgap.org). Many biotic and abiotic constraints in addition to water deficits and nutrient related constraints affect maize yield, especially for financially constrained smallholders with little capacity to control constraints. The most limiting constraint to yield is expected to vary depending on the relative importance in a given site-year of nutrient deficiency, soil water deficit, the effect of some insect pest or disease problem, or the effect of other biotic or abiotic constraints. Yields and responses are expected to increase as control of major constraints improves.

Economically optimal rates and net returns for nutrient application

Knowledge of how a sole crop or intercrop responds to a range of nutrient rates is essential to the application of economics to fertilizer use, including for determination of EOR and the expected mean profitability at application rates less than EOR (Jansen et al. 2013). The demonstrated ability to use MSC response functions in the determination of intercrop response functions has great potential in advancing the economic efficiency of fertilizer use for intercrop across diverse recommendation domains without much additional field research (Table 3). The range of inference for these results cannot, however, reliably include maize-bean intercropping where bean is managed as the priority crop. The equations for estimating EOR (Table 4) may need to be determined again once the intercrop response functions are developed for another recommendation domain as demonstrated by the difference in the equations for HP and LP. The results reported here apply to maize and bean, realizing that other crops respond differently to applied nutrients such as a greater probability of positive response of cassava and potato to applied K (Kibunja et al. 2017; Senkoro et al. 2017).

The importance of CP in determination of EOR for improved profitability has been repeatedly demonstrated by several authors including Dobermann et al. (2011), Kaizzi et al. (2012a, b, c) and Jansen et al. (2013), and is further demonstrated by the results of this study including for intercrop (Fig. 2). The EOR for all CP were beyond the rate of rapid yield increase and the yield change from the lowest to highest CP rate was a mean increase of 5.9 and 4.6% for MSC and intercrop, respectively, with similar effects for HP and LP. The corresponding mean change in nutrient rate was about 100%. The implications of a reduction in nutrient rate are much greater for financially constrained compared with non-financially constrained farmers. This is because the financially constrained are likely to gain relatively more from an alternative investment using the saved fertilizer money, such as in fertilizer use for another crop, in another enterprise, or in household or family livelihood improvement.

Fertilizer application generally offers great profit opportunity, especially at below EOR as shown in Table 4, and profit from fertilizer use was greater than 100% with the exception of N applied to MSC at higher CP for HP and for intercrop response to K for LP. While 100% net returns on investment within a year has been considered adequate to be financially attractive to smallholder farmers (CIMMYT 1998), it is likely that other smallholders need much better returns on their small budget capacity for fertilizer use. The results demonstrate the potential to achieve such high returns.

The procedure presented in this paper for determining maize-bean intercrop nutrient response functions from those of MSC (Table 2) can be applied in the development of fertilizer use tools such as the OFRA fertilizer optimization tools developed for 67 recommendation domains across 13 nations of sub-Saharan Africa (Jansen et al. 2013; Kaizzi 2017). The OFRA tools use linear optimization for determination of crop-nutrient-rate choices for profit maximization considering the relative costs and the farmer's budget for fertilizer use and land allocation to different crops. The OFRA fertilizer optimization tools are available for download at www.agronomy.unl.edu/OFRA with the tool for elevations above 1400 m for Western Kenya providing an example of including the maize-bean intercrop (Kibunja et al. 2017).

The above results provide the means for optimizing fertilizer nutrient application for maize-bean intercropping. The right source and the right method and time of fertilizer application for intercrop should be similar to those for MSC as that was what was practiced in the field research underlying this analysis. Therefore, band application of P, K and some N at or near planting time with bands at least 5 cm to the side of maize and bean rows, with the remaining 50% or more of the N sidedress applied and covered at about six weeks after planting is likely to be appropriate. As stated above, not much N fixation by bean is expected with the maize-bean intercrop (Stern 1993; Chalk 1996) and inhibition of fixation by applied N is not a concern while bean is often highly responsive to some N applied at planting (Kaizzi et al. 2012c).

Conclusion

The maize-bean intercrop is more productive on a maize yield equivalent basis compared with MSC and the intercrop value is enhanced as bean to maize value ratio increases. Both MSC and intercrop productivity can be increased with N and P application but the response with intercrop is primarily with the maize component while intercrop bean is not very responsive. The coefficients for intercrop nutrient response functions can be estimated with high confidence from the coefficients of MSC functions. This reduces the field research requirement to optimize fertilizer use for the maize-bean intercrop. The procedure presented was developed using data from diverse production environments and should be robust for a wide inference range of maize-bean intercropping such as from the Hararghe Highlands of Ethiopia south to maize-bean intercropping areas of Malawi and Zambia, and likely east to Madagascar and west to Cameroon. The procedure cannot be applied directly to other nutrients due to insufficient information such as for applied S to which MSC is highly responsive in parts of the Southern Highlands of Tanzania and parts of Malawi. For other nutrients, the intercrop rate might be similar to or up to 20% more compared with the MSC rate. The EOR for MSC and intercrop are very dependent on CP with an average 100% higher EOR at the lowest compared to the highest CP, but this EOR range affects yield by only 4–6%. There is great profit potential with nutrient application at modest rates and generally very good profit potential at EOR.

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