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ORIGINAL ARTICLE

Maize-nutrient response information applied across Sub-Saharan Africa

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Abstract The profit potential for a given investment in fertilizer use can be estimated using representative crop nutrient response functions. Where response data is scarce, determination of representative response functions can be strengthened by using results from homologous crop growing conditions. Maize (*Zea mays* L.) nutrient response functions were selected from the Optimization of Fertilizer Recommendations in Africa (OFRA) database of 5500 georeferenced response functions determined from field research conducted in Sub-Saharan Africa. Three methods for defining inference domains for selection of response functions were compared. Use of the OFRA Inference Tool (OFRA-IT; http://agronomy.unl.edu/OFRA) resulted in greater specificity of maize N, P, and K response functions with higher R^2 values indicating superiority compared with using the Harvest Choice Agroecological Zones (HC-AEZ) and the recommendation domains of the Global Yield Gap Atlas project (GYGA-RD). The OFRA-IT queries three soil

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properties in addition to climate-related properties while the latter two options use climate properties only. The OFRA-IT was generally insensitive to changes in criteria ranges of 20–25% used in queries suggesting value in using wider criteria ranges compared with the default for information scarce crop nutrient response functions.

Keywords Agroecological zones · Data queries · Extrapolation · Harvest Choice · Fertilizer use · Optimization · Recommendation domains · Smallholder

Abbreviations

AfSIS	Africa soil information service
AI	Aridity index
CV	Coefficient of variability
GYGA-RD	Recommendation (or climate) domains of the Global Yield Gap Atlas project
HC-AEZ	Harvest Choice agroecological zone
OFRA	Optimizing fertilizer recommendations in africa project
OFRA-IT	OFRA Inference Tool
SOC	Soil organic C
SSA	Sub-Saharan Africa
TS	Temperature seasonality

Maize is a major crop in Sub-Saharan Africa (SSA) that is grown under diverse growing conditions. Mean grain yields are low, generally 10–30% of potential rainfed yield (Wortmann et al. 2016; www.yieldgap.org). But annual variation in grain yield is high, often with coefficients of variation (CV) greater than 40% while the CV for irrigated maize in the US is typically about 7% (www.yieldgap.org). Numerous biotic and abiotic constraints contribute to the low means and high CVs of maize yield in SSA and the most limiting constraint for a field typically varies by year. Among the constraints is the inadequate availability of some soil nutrients essential to crop growth and the relatively low capacity of financially constrained smallholder farmers to manage constraints. The mean yield response to applied nutrients is limited by other biotic and abiotic constraints and these constraints contribute to high response CV.

The goal of the OFRA project was to improve farmer profitability with respect to fertilizer use, especially for financially constrained smallholder farmers (Kaizzi et al. 2017). Crop nutrient response functions, which are essential to the efficient application of economics to fertilizer use decisions, were developed from past and recent field research results using a curvilinear to plateau asymptotic response function of the form $Y = a - bc^r$ where a is the projected yield at plateau, b is the estimated maximum yield gain resulting from application of the nutrient, c is a curvature coefficient and r is the rate of nutrient application. The database had 5500 geo-referenced crop nutrient response functions at the time of this analysis, 33% of which were for maize and the remaining for 33 other crops (Table 1) (http://agronomy.unl.edu/OFRA). Results from 16 countries were included. Forty, 37 and 23% of the results were from 191 publications, recent OFRA supported research and other sources, respectively, and 48% were from research done in 2010 or later. Background information for the trials such as soil test information is included in the database when available. The 1817 maize response functions included N (43%), P (29%), K (9%), S (3%) and Zn (1%) treatments. The points in Fig. 1 represent research sites for which maize nutrient response functions were determined on a site-year basis but most sites have numerous years of results and corresponding individual response functions.

It is expected that results from areas of homologous growing conditions can be used to make decisions at a similar location of interest (Aiken et al. 2001). This can be done according to established zones or dynamically through geospatial queries based on environmental criteria. Climate variation is captured in Harvest Choice's agroecological zonation (HC-AEZ) (HarvestChoice 2010) (Fig. 1) and in the

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Table 1 Numbers (n) of compiled nutrient response functions for sub-Saharan Africa by crop and country

Crop	n	Country	N
Barley	78	Burkina Faso	230
Bean	553	Ethiopia	726
Cassava	60	Ghana	176
Cowpea	298	Kenya	1216
Faba bean	44	Malawi	156
Finger millet	129	Mali	146
Groundnut	221	Mozambique	75
Maize	1817	Niger	634
Pearl millet	286	Nigeria	357
Pigeon pea	41	Rwanda	452
Irish potato	220	Tanzania	508
Rice, lowland	221	Uganda	580
Rice, upland	85	Zambia	124
Sorghum	465	3 other countries	65
Soybean	214		
Teff	167		
Wheat	389		
17 other crops	157		

narrower more specific recommendation domains of the Global Yield Gap Atlas (GYGA-RD) project (http://wwws.yieldgap.org/web/guest/download_data) (Van Wart et al. 2013). Countries have delineated their own AEZs (Wortmann et al. (2017), http://agronomy.unl.edu/OFRA) often incorporating local soils and physiographic information.

OFRA-IT (Wortmann and Milner 2015; Wortmann et al. 2017) is an ArcGIS 10.3 ArcPy script tool. It identifies crop nutrient response functions associated with areas that share similar growing conditions to those found at a point of interest (http://agronomy.unl.edu/OFRA). The tool defines similarity by querying seven rasters: aridity index (AI) (Zomer et al. 2007, 2008); temperature seasonality (TS) (Hijmans et al. 2005), elevation as a proxy for annual growing degree day accumulation (Lehner et al. 2008); distance from the equator (as degrees latitude times 1000) to distinguish between bimodal and unimodal precipitation regimes; soil pH (as pH times 10); sand content; and organic content (SOC) (Hengl et al. 2014, 2015). The three soil properties were for the 5–15 cm depth. The OFRA-IT default queries were determined in

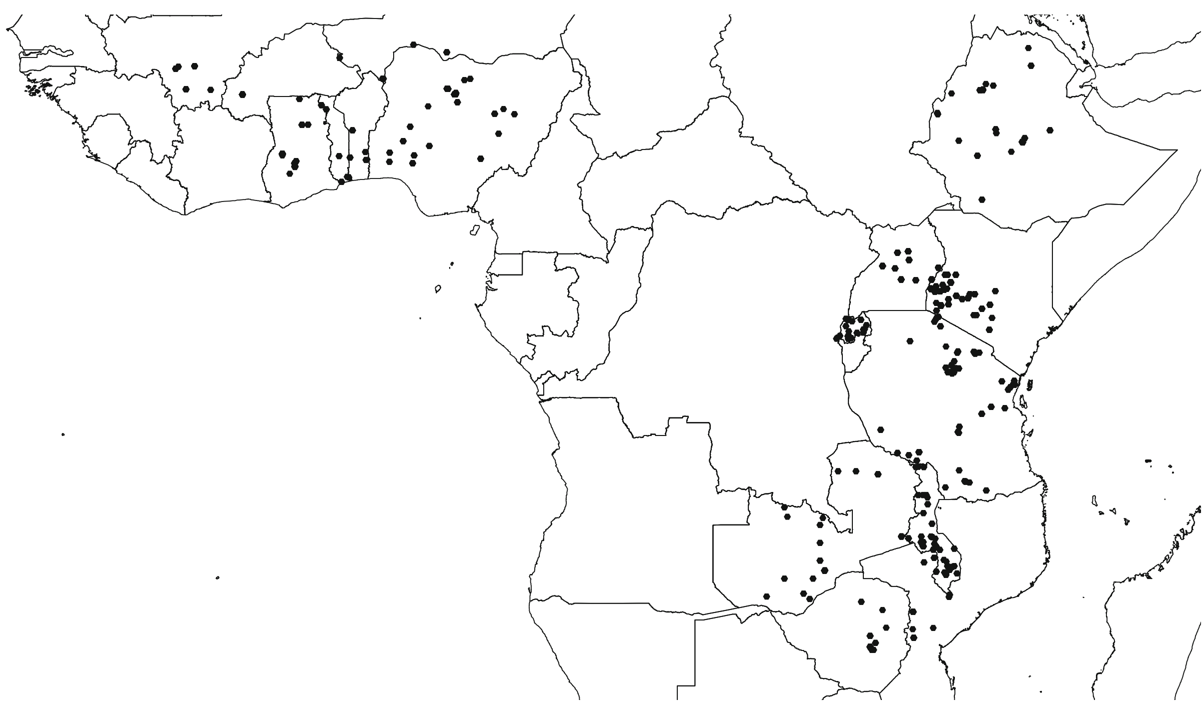

Fig. 1 Distribution of sites with research results used to determine maize response to applied nutrients

agronomic consideration of environmental effects on crop adaptation and distribution. The default queries were: if the selected point's AI value is <6000, then similarity equals the selected AI value ±1000, else similarity equals AI values >5000; temperature seasonality similarity equals the selected value ±1000; if the selected SOC value is ≤35 g kg^{-1}, then similarity equals the selected SOC value ±10, else similarity equals SOC > 25; if the selected pH × 10 value is <54, then similarity equals the selected pH × 10 value ±4, else similarity equals pH × 10 values >50; if the selected sand value is >75, then similarity equals the selected sand value ±20, else similarity equals sand values <80; if the selected elevation value is >700 m, then similarity equals the selected elevation value ±250, else similarity equals elevation <1000; and distance from equator (|degrees| × 1000) similarity equals the selected distance value ±3000. Research locations that meet all the criteria fall in the inference, or recommendation, domain of the selected point.

The objectives of this research were to: compare the use of HC-AEZ, GYGA-RD, and OFRA-IT inference domains for determining representative maize nutrient response functions; apply spatial information to determine location specific S and Zn response functions; and to evaluate the sensitivity of OFRA-IT criteria ranges.

Materials and methods

The georeferenced maize crop nutrient response functions associated with each of the study's HC-AEZs, GYGA-RDs and OFRA-IT inference domains were extracted using ArcMap 10.3. Due to the number and distribution of maize response functions, analysis was restricted to N, P and K and to four tropical HC-AEZ and four GYGA-RD. The four HC-AEZ were warm semi-arid (312), warm sub-humid (313), cool sub-humid (323), and cool humid (324) (Table 2). The four GYGA-RDs were 6701, 7501, 9501, and 10,301 where the first one or two numbers (6, 7, 9, 10) represent annual growing degree day accumulation, the next number (7, 5, 5, 3) represents AI with lower numbers representing more aridity, and the rightmost number (1) represents TS (Van Wart et al. 2013). Nine sites were selected within the study's HC-AEZ and GYGA-RD boundaries for determination of OFRA-IT inference domains (Table 3).

Table 2 The number of response functions available for selected Global Yield Gap Atlas recommendation domains (GYGA-RD) and Harvest Choice agroecological zones (HC-AEZ)

RD/AEZ	N	P	K	S	Zn
GYGA6701	43	37	6		
GYGA7501	95	51	21	16	
GYGA9501	70	10	16		3
GYGA10301	43	59	27		
HC312	156	77	174	26	12
HC313	177	118	37	28	7
HC323	158	97	14		
HC324	155	144	20		

The sensitivity of OFRA-IT query criteria was evaluated by comparing the representative response functions determined from different ranges of criteria. Wider and narrower ranges resulted in larger and smaller inference domain, respectively. The three sets of plus and minus values, relative to the site value, were: 800, 1000, and 1200 for both AI and TS (e.g. for site AI of 7000, the respective ranges would be 6200–7800, 6000–8000, and 5800–8200 for narrow, intermediate and wide queries); 8, 10 and 12 g kg^{-1} SOM; 0.3, 0.4, and 0.5 for pH; 16, 20, and 24 g kg^{-1} sand; 200, 250, and 300 m elevation; and 2, 3, and 4 degrees latitude. The analysis was done at Farako-ba, Achefer, Wenchi, Siaya, and Kapchorwa (Table 3).

The yield response for each selected response function was determined for six nutrient levels using 25, 5, and 10 kg ha^{-1} increments for N, P, and K, respectively, using Excel. Non-linear regression analyses were done for the datasets created by the HC-AEZ, GYGA-RD, and the OFRA-IT selection methods according to $Y = a - bc^r$ as defined above using Statistix 10 (Analytical Software, Tallahassee FL). Since the analysis was for response to applied nutrient only, coefficient a and b were equal. Standard errors and standard deviations of the b and c coefficients, the estimated R^2 values, and differentiation of response functions were considered in the comparisons of selection methods and criteria ranges.

Results

Nutrient application did not result in increased yield in some cases. The percent of cases with yield changes

Table 3 Locations used for query with the OFRA Inference Tool

Country	Location	Lat[†]	Long	Elev	HC-AEZ	GYGA-RD	Data sources[‡]
Burkina Faso	Farako-ba	11.100	−4.333	405	312	10,301	BF GH NG ZM
Ethiopia	Achefer	11.341	36.939	2020	323	6701	ET TZ
Ghana	Wenchi	7.690	−2.100	130	313	9501	GH ML NG TZ TO
Kenya	Siaya	−0.094	34.235	1260	324	7501	KE RW TZ UG
Malawi	Mwanza	−15.600	34.500	680	312	7501	MW ZM
Mali	Bougouni	11.387	−7.477	329	313	10,301	BF GH ML NG
Tanzania	Mlingano	−5.140	38.870	80	313	9501	GH NG TZ
Tanzania	Nyakunguru	−1.417	34.517	1392	313	7501	KE RW TZ UG
Uganda	Kapchorwa	1.400	34.610	1877	324	6701	KE RW UG

[†] Lat., Long., and Elev. are latitude and longitude in decimal degrees (WGS 84) and elevation (m above sea level). GYGA-RD refers to the Global Yield Gap Atlas recommendation domains. HC-AEZ refers to the Harvest Choice agroecological zones

[‡] BF, GH, KE, ML, MW, NG, RW, TO, TZ, UG, and ZM refer to Burkina Faso, Ghana, Kenya, Mali, Malawi, Nigeria, Rwanda, Togo, Tanzania, Uganda, and Zambia, respectively

for applied N, P, K, S, and Zn, were respectively: for increases of >0.1 Mg ha^{-1}, 87, 69, 57, 87, and 84%; for positive or negative yield changes of <0.1 Mg ha^{-1}, 12, 27, 24, 13, and 11%, and for yield decreases of >0.1 Mg ha^{-1}, 1, 4, 18, 0, and 5%. The frequent negative response to K is not well understood but the negative responses often occurred even with rates of 10 kg ha^{-1}; salt effects of KCl placed too close to the seed may have been a factor.

Use of soil test results may improve prediction of response to applied nutrients. Soil pH of <5.3, 5.3–7.3, and >7.3 occurred in 25, 74, and 1% of the cases. Soil organic matter of <13, 13–25, and >25 mg kg^{-1} occurred in 23, 22, and 54% of the cases. Soil Mehlich-3 and Bray-1 P distribution include 80 and 20% of cases with <15 and >15 mg kg^{-1}, respectively, with many of the high P sites being from research centers. Exchangeable K was >130, 80–130, and <80 mg kg^{-1} for 14, 76, and 12% of the cases, respectively, with most cases of <80 occurring with sandy soils in the Sahel. The low soil pH may inhibit response to applied nutrients, especially in cases of Al toxicity. Soil organic matter may contribute to prediction of response to N and other nutrients but the very low levels are mostly from areas of severe soil water deficits and a large proportion of soil organic matter is resistant to decomposition as indicated by evidence of low release of N (Kaizzi et al. 2012, 2013). The probability of low soil test P with smallholder annual crop fields is very high unless near the household and livestock holding areas. Exchangeable K is high enough on most smallholder fields that not much response to applied K should be expected in most maize production areas of SSA. Therefore, soil test results may not account for much variation in crop nutrient responses.

Comparison of HC-AEZ, GYGA-RD, and OFRA-IT inference domains

The OFRA-IT sites, Wenchi and Mlingano, are in the same GYGA-RD (9501) and HC-AEZ (313) although separated by about 4700 km (Table 3). The inference domain selection for each was associated with response functions from Ghana, Nigeria and Tanzania, but Wenchi's inference domain also encompassed a few functions from Mali and Togo. The remaining 7 OFRA-IT sites are located in unique GYGA-RD and HC-AEZ combinations. The Nyakunguru and Siaya OFRA-IT queries selected response functions from the same four countries with some much overlap in response functions.

The overall potential yield response to applied N (coefficient b) was 1.38 Mg ha^{-1} but values ranged from 0.91 to 2.28 Mg ha^{-1} for GYGA-RD 9501 and the Achefer inference domains, respectively (Table 4). Mlingano and Wenchi, both under GYGA-RD (9501) and HC-AEZ (313), had b values of 0.99 and 1.14 Mg ha^{-1}, respectively. Bougouni, Mlingano, Nyakunguru and Wenchi were in HC-AEZ 313 which had a b value of 1.28 Mg ha^{-1} while the respective values determined from the OFRA-IT

Table 4 Maize N response function results for selected Harvest Choice (HC) AEZs, Global Yield Gap Atlas (GYGA) recommendation domains and OFRA Inference Tool domains in Sub-Saharan Africa

Zone/site	B	B_se	C	C_se	Function (n)	Pseudo R^2
All	1.378	0.038	0.970	0.002	786	0.24
GYGA6701[†]	1.623	0.169	0.963	0.010	43	0.27
GYGA7501	1.598	0.091	0.970	0.005	95	0.38
GYGA9501	0.914	0.107	0.971	0.009	70	0.17
GYGA10301	2.070	0.168	0.976	0.005	43	0.43
HC312	1.625	0.096	0.976	0.004	156	0.29
HC313	1.280	0.076	0.974	0.004	177	0.24
HC323	1.429	0.094	0.970	0.005	158	0.21
HC324	1.136	0.079	0.961	0.007	155	0.19
Achefer, ET	2.279	0.196	0.972	0.006	24	0.53
Bougouni, ML	1.859	0.106	0.973	0.004	98	0.39
Farako-ba, BF	1.802	0.105	0.973	0.004	104	0.36
Kapchorwa, UG	1.094	0.149	0.959	0.015	38	0.20
Mlingano, TZ	0.987	0.092	0.975	0.006	106	0.19
Mwanza, MW	2.135	0.200	0.972	0.007	25	0.47
Nyakunguru, TZ	1.246	0.090	0.967	0.006	80	0.30
Siaya, KE	1.473	0.098	0.965	0.006	78	0.34
Wenchi, GH	1.144	0.084	0.975	0.005	141	0.22

[†] *GYGA-RD* Global Yield Gap Atlas recommendation domains, *HC-AEZ* Harvest Choice agroecological zones. OFRA-IT OFRA Inference Tool

queries were 1.86, 0.99, 1.25, and 1.14 Mg ha^{-1}. Similarly, Mwanza, Nyakunguru, and Siaya were in GYGA-RD 7501 which had a b value of 1.60 Mg ha^{-1} while the respective values determined from the OFRA-IT queries were 2.14, 1.25, and 1.47 Mg ha^{-1}. The overall coefficient c value was 0.970. The c value was relatively low for the GYGA-RD 6701, HC-AEZ 324, and Kapchorwa inference domains. The GYGA-RD had greater differentiation compared with HG-AEZ, both for response at low and at high N rates (Fig. 2a). GYGA-RD 6701 and GYGA-RD 10301 had similarly steep yield response at low N rates. Kapchorwa, Nyakunguru and Siaya which were within 1.5 degrees of the equator had low c values but only intermediate b values for N response compared with higher latitude query points. This indicated more yield response, N uptake and N recovery efficiency at low N rates for low latitudes with bimodal rainfall distribution compared with higher latitudes. However, high latitude Achefer and Mwanza with high b values, also had large responses to low N rates (Fig. 2b). The mean R^2 values were 31, 23, and 33% for GYGA-RD, HC-AEZ, and OFRA-IT inference domains, respectively. The mean standard deviation for b was 1.00, 1.09, and 0.96 and the mean standard deviation of c was 0.056, 0.063, and 0.051 for the GYGA-RD, HC-AEZ, and OFRA-IT inference domains, respectively. The maximum differences in b values were 8.6, 5.7 and 10.4 times the mean associated SE for GYGA-RD, HC-AEZ, and OFRA-IT inference domains, respectively.

The overall potential yield response to applied P (coefficient b) was 0.65 Mg ha^{-1} but values ranged from 0.29 to 1.85 Mg ha^{-1} for HC312 and Achefer, respectively (Table 5). Bougouni, Mlingano, Nyakunguru and Wenchi had b values of 0.32, 0.59, 1.10, and 0.67 Mg ha^{-1}, respectively, although all were in HC313 which had a b value of 0.61 Mg ha^{-1}. Similarly, Mwanza, Nyakunguru, and Siaya were in GYGA7501 which had a b value of 0.52 Mg ha^{-1} while the respective OFRA-IT values were 0.50, 1.10, and 1.14 Mg ha^{-1}, respectively. The overall coefficient c value was 0.90. The c value was relatively low for GYGA7501 but within the SE of the mean. The GYGA-RD had less differentiation compared with HG-AEZ inference domains for responses at both low and high P rates (Fig. 3a). The differences in response were much greater for the OFRA-IT compared with GYGA and HC domains ranging from 0.32 to 1.52 Mg ha^{-1} with 30 kg ha^{-1} P applied. With the exception of GYGA6701, HC324, and HC312, responses to P were very similar for GYGA-RD and HC-AEZ. As with N, the Achefer query resulted in a great response to P (Fig. 3b). The three low latitude

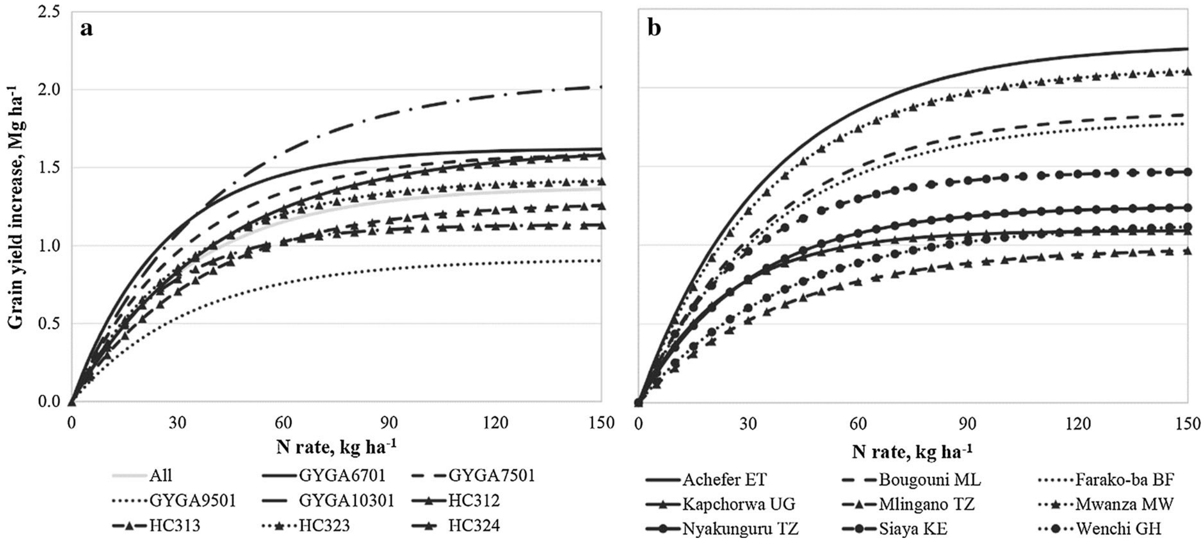

Fig. 2 Maize response to N by inference domains in Sub-Saharan Africa

Table 5 Maize P response function results for selected Harvest Choice (HC) AEZs, Global Yield Gap Atlas (GYGA) recommendation domains and OFRA Inference Tool domains in Sub-Saharan Africa

Domain	b	b_se	c	c_se	Function (n)	Pseudo R^2
All	0.650	0.042	0.898	0.017	519	0.10
GYGA6701[†]	1.050	0.192	0.900	0.046	37	0.17
GYGA7501	0.519	0.091	0.840	0.068	51	0.10
GYGA9501	0.699	0.131	0.919	0.033	11	0.18
GYGA10301	0.698	0.125	0.920	0.034	59	0.18
HC312	0.290	0.078	0.852	0.098	77	0.03
HC313	0.609	0.065	0.892	0.029	118	0.15
HC323	0.705	0.129	0.911	0.040	97	0.09
HC324	0.994	0.094	0.901	0.024	144	0.17
Achefer, ET	1.847	0.418	0.922	0.041	22	0.28
Bougouni, ML	0.323	0.114	0.869	0.116	54	0.03
Farako-ba, BF	0.340	0.102	0.867	0.099	62	0.03
Kapchorwa, UG	0.720	0.158	0.900	0.057	34	0.11
Mlingano, TZ	0.590	0.092	0.918	0.030	73	0.18
Mwanza, MW	0.500	0.184	0.913	0.077	13	0.17
Nyakunguru, TZ	1.098	0.204	0.911	0.040	55	0.15
Siaya, KE	1.143	0.187	0.912	0.035	60	0.17
Wenchi, GH	0.670	0.097	0.918	0.028	94	0.17

[†] GYGA-RD Global Yield Gap Atlas recommendation domains. HC-AEZ Harvest Choice agroecological zones. OFRA-IT OFRA Inference Tool

OFRA-IT sites had the next greatest responses to P. The mean R^2 values for P compared with N response were less and were 16, 11, and 14% for GYGA-RD, HC-AEZ, and OFRA-IT inference domains, respectively. The mean standard deviation for b was 0.80, 0.95, and 1.10 and the mean standard deviation of c was 0.28, 0.46, and 0.39 for GYGA-RD, HC-AEZ, and OFRA-IT inference domains, respectively. The maximum differences in b values were 3.9, 7.7 and 8.81 times the mean associated SE for GYGA-RD, HC-AEZ, and OFRA-IT inference domains, respectively.

Response information for K was available for just seven of the query locations (Table 3). The overall potential yield response to applied K (coefficient b) was only 0.22 Mg ha^{-1} with a range of

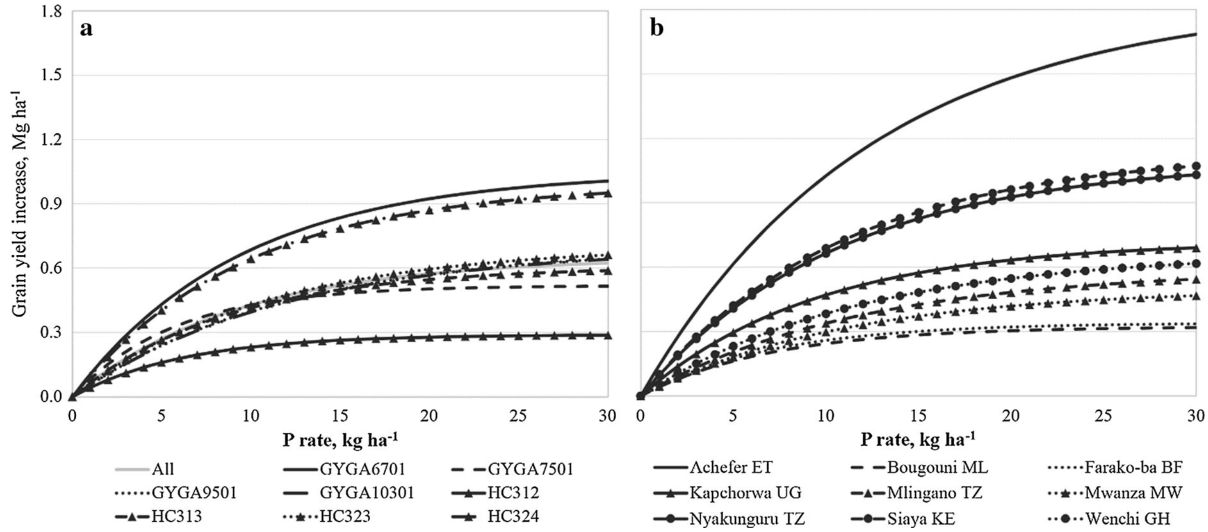

Fig. 3 Maize response to P by inference domains in Sub-Saharan Africa

0.00–0.36 Mg ha^{-1} for GYGA6701 and Wenchi, respectively (Table 6). Bougouni, Mlingano, Nyakunguru and Wenchi had b values of 0.15, 0.34, 0.36, and 0.36 Mg ha^{-1}, respectively, although all were in HC313 which had a b value of 0.26 Mg ha^{-1}. Similarly, Nyakunguru and Siaya were in GYGA7501 which had a b value of 0.25 Mg ha^{-1} while the respective values determined from the OFRA-IT queries were 0.36 and 0.33 Mg ha^{-1}, respectively. The overall coefficient c value for queries with a response was 0.86. GYGA6701 and GYGA10301 had too little response to K to estimate c. HC324 had an exceptionally high c value which is reflected in the near linear effect of K on yield response up to 60 kg ha^{-1} K (Fig. 4a). With the exceptions of HC324 and GYGA9501, the overall response to K represented the HC-AEZ and GYGA-RD based estimates well. The OFRA-IT query results however split into two groups with yield increases due to K application of <0.16 and >0.33 Mg ha^{-1} with the overall response

Table 6 Maize K response function results for selected Harvest Choice (HC) AEZs, Global Yield Gap Atlas (GYGA) recommendation domains and OFRA Inference Tool domains in Sub-Saharan Africa

Domain	b	b_se	c	c_se	Function (n)	Pseudo R^2
All	0.220	0.042	0.859	0.075	174	0.03
GYGA6701†	0.000	0.000			6	0.00
GYGA7501	0.246	0.055	0.906	0.053	21	0.15
GYGA9501	0.330	0.164	0.882	0.153	16	0.04
GYGA10301	0.063	0.083			27	0.00
HC312	0.190	0.063	0.824	0.192	53	0.03
HC313	0.263	0.100	0.932	0.067	37	0.04
HC323	0.210	0.189	0.848	0.401	14	0.02
HC324	0.561	0.760	0.976	0.060	20	0.05
Bougouni, ML	0.154	0.065	0.864	0.159	50	0.02
Farako-ba, BF	0.130	0.064	0.854	0.204	54	0.01
Kapchorwa, UG	0.086	0.090	0.913	0.232	7	0.02
Mlingano, TZ	0.337	0.104	0.892	0.086	25	0.07
Nyakunguru, TZ	0.355	0.105	0.862	0.113	22	0.08
Siaya, KE	0.335	0.079	0.902	0.059	28	0.10
Wenchi, GH	0.364	0.085	0.905	0.057	37	0.08

† GYGA-RD Global Yield Gap Atlas recommendation domains. HC-AEZ Harvest Choice agroecological zones, *OFRA-IT* OFRA Inference Tool

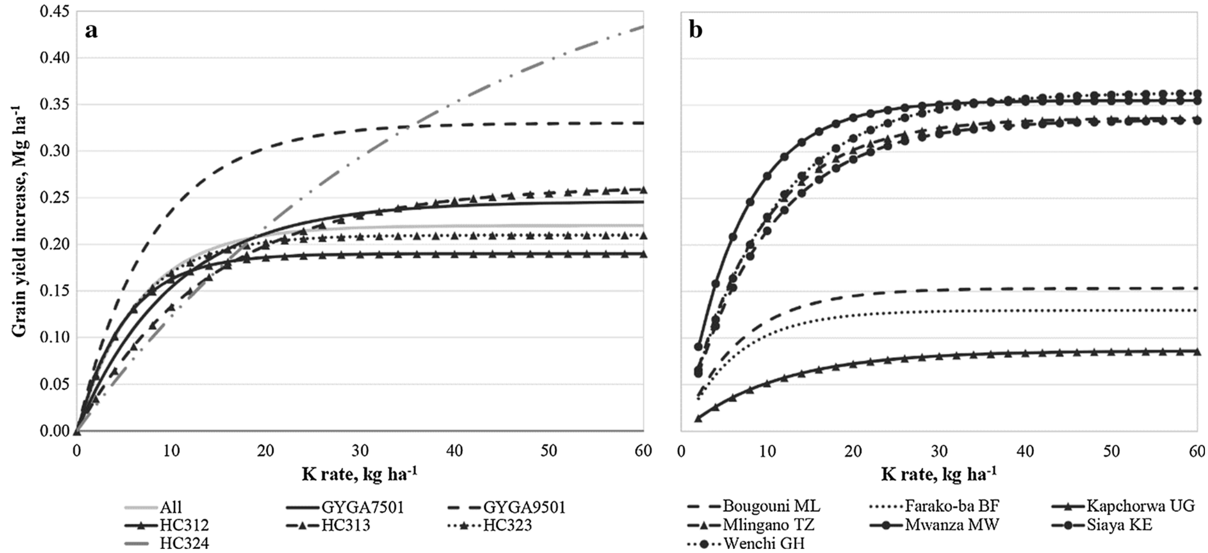

Fig. 4 Maize response to K by inference domains in Sub-Saharan Africa

function poorly representing all sites (Fig. 4b). Latitude was not a determinant of response to K. The mean R^2 values for maize yield response to applied K were just 4.8, 3.1 and 5.6% for GYGA-RD, HC-AEZ, and OFRA-IT inference domains, respectively. The maximum differences in b values were 3.3, 1.3 and 3.3 times the mean associated SE for GYGA-RD, HC-AEZ, and OFRA-IT inference domains, respectively.

Interpretation of the S and Zn results need caution as trial distribution was narrow with trials often conducted in response to suspected deficiencies. The S trials were conducted primarily in Malawi, Nigeria and southern Tanzania, and most Zn trials were conducted in Nigeria. Maize S response coefficients for b ranged by location from 0.142 to 0.947 Mg ha^{-1} (Table 7). The lower b values are associated with low c values implying that much of the response is achieved at low S rates. The two locations with low response were in one GYGA-RD and the two locations with high response to S were in another GYGA-RD. Two of the high response and one of the low response locations were in HC313 while the other two locations were in HC 312. Maize Zn response functions were determined for only three locations due to limited data availability. There was too little maize response to Zn for the Wenchi query to estimate the c value. The Zn response functions determined from the Mali and Burkina Faso queries had b values >0.57 Mg ha^{-1}.

Table 7 Maize S and Zn response function results for selected OFRA Inference Tool domains

Domain	b	b_se	c	c_se	Function (n)	Pseudo R^2
S						
Bougouni, ML	0.142	0.047	0.655	0.255	13	0.11
Farako-ba, BF	0.166	0.053	0.736	0.192	12	0.13
Mlingano, TZ	0.947	0.200	0.899	0.043	6	0.77
Mwanza, MW	0.374	0.116	0.819	0.135	9	0.21
Wenchi, GH	0.863	0.134	0.817	0.069	13	0.42
Zn						
Bougouni, ML	0.593	0.107	0.332	0.175	12	0.40
Farako-ba, BF	0.577	0.137	0.295	0.230	12	0.25
Wenchi, GH	0.091	0.048			8	0.00

Sensitivity of the OFRA Inference Tool

Mean coefficient b values were similar for OFRA-IT queries with the default criteria and with the criteria ranges expanded by 20–25% for N and P responses but less than for the queries with the narrow criteria ranges (Table 8). This difference however was much affected by the Achefer results, 83% of which were from several locations of research conducted in 2013 by one research team where yields and responses were unusually great. The mean b coefficient value for K response was higher for the default compared with the wide query but similar compared with the narrow query. The mean coefficient c values were similar for the three sets of query criteria for N and P, but relatively high for K with the default compared with other criteria.

The mean b coefficient standard errors for response to N, P, and K was much higher using the narrow compared with the intermediate (default) and wide range of criteria in the OFRA-IT query. The mean coefficient C standard errors were similar for N for the three sets of query criteria but highest and least for P and K response using the wide and narrow ranges of search criteria, respectively.

The mean R^2 values were highest for N and least for K. The R^2 values for N response were on average similar for the three query criteria. The mean R^2 value for P response was greater for the narrow compared with the other queries, but if the unusually high R^2 for P at Achefer was omitted, the three query ranges had similar R^2. Responses to K were small and R^2 values were low for all queries.

The standard error for coefficient b for N and P response, and the R^2 value for P response decreased as observations for P response increased. The R^2 for N response and the standard errors for the c coefficients did not vary with number of observations.

Discussion

Maize responses to applied nutrient were highly varied across site-seasons as expected given the high variability in maize yield (http://www.yieldgap.org) and the many biotic and abiotic constraints that affect maize growth, yield and response in Sub-Saharan Africa. The findings of this research support the expectation that results from areas of similar conditions can be applied to decision making at a location of interest (Aiken et al. 2001), but with more confidence for maize response to applied N and little confidence for maize response to applied K as indicated by R^2 values. The R^2 values were lowest for HC-AEZ for which each AEZ represented relatively more area and research findings compared with the GYGA-RD and the locations used for the OFRA-IT queries (Tables 4, 5, 6). The OFRA-IT queries resulted in higher R^2 values for N, P, and K compared with HC-AEZ and GYGA-RD which generally had more and fewer response functions per inference domain, respectively, compared with the OFRA-IT queries (Tables 4, 5, 6). The OFRA-IT queries resulted in greater separation of response functions compared with HC-AEZ and GYGA-RD (Figs. 2, 3, 4). While the query methods often did not differ with statistical significance, the differences in response functions imply much difference in yield increase and profit potential due to nutrient application. For example, if the cost of using N is \$1 kg^{-1} and maize value to farmer is \$0.2 kg^{-1}, the projected N rate to maximize returns to N use is 64 kg ha^{-1} with \$94 ha^{-1} net return to N and a yield increase of 0.79 Mg ha^{-1} for Mlingano. In contrast for Achefer, the projected N rate to maximize returns to N use is 90 kg ha^{-1} with \$330 ha^{-1} net return to N and a yield increase of 2.10 Mg ha^{-1}. A similar comparison for the constrained farmer whose available finance allows application of just \$40 ha^{-1} of N with a projected mean profit of 269 and 86 \$ ha^{-1} for Achefer and Mlingano, respectively, with mean projected yield increases of 1.55 and 0.63 Mg ha^{-1}.

Results indicate that use of the OFRA-IT is superior to use of the HC-AEZ and GYGA-RD inference domains for finding maize-nutrient response results that are applicable to a point of interest. The HC-AEZ and GYGA-RD are climate based while the OFRA-IT considers soil and climate related variables, including distance from the equator which accounts for variation in rainfall modality and therefore monthly distribution of rainfall.

The OFRA-IT inference domain results were sometimes affected by expanding or decreasing criteria ranges but often not and not greatly. The default values which were determined from agronomic judgement worked similarly well as for wider and narrower query criteria. The results suggest that query criteria should be widen for crop-nutrient responses that are

Table 8 Comparison of query results with wide, intermediate and narrow ranges of search criteria†

	Wide				Intermediate				Narrow			
	b	c	n	R^2	b	c	n	R^2	b	c	n	R^2
Achefer												
N	2.142 (0.182)	0.973 (0.006)	28	0.49	2.279 (0.196)	0.972 (0.006)	24	0.53	2.907 (0.573)	0.972 (0.014)	6	0.48
P	1.849 (0.347)	0.920 (0.035)	27	0.30	1.847 (0.418)	0.922 (0.040	22	0.28	2.923 (0.629)	0.923 (0.039)	9	0.53
Farako-ba												
N	1.773 (0.101)	0.974 (0.004)	214	0.36	1.802 (0.105)	0.973 (0.004)	104	0.36	1.773 (0.111)	0.974 (0.005)	79	0.37
P	0.703 (0.186)	0.915 (0.054)	69	0.07	0.340 (0.102)	0.867 (0.010)	62	0.03	0.310 (0.128)	0.857 (0.145)	46	0.02
Kapchorwa												
N	1.281 (0.133)	0.973 (0.007)	65	0.22	1.094 (0.143)	0.959 (0.015)	38	0.2	1.095 (0.154)	0.955 (0.017)	34	0.2
P	0.654 (0.104)	0.879 (0.049)	59	0.12	0.720 (0.158)	0.900 (0.057)	34	0.11	0.691 (0.170)	0.887 (0.071)	28	0.12
K	0.068 (0.076)	0.836 (0.570)	7	0.02	0.086 (0.090)	0.913 (0.232)	7	0.02	0		6	
Siaya												
N	1.422 (0.181)	0.968 (0.0370)	101	0.32	1.473 (0.098)	0.965 (0.006)	78	0.34	1.000 (0.104)	0.960 (0.011)	38	0.30
P	0.654 (0.087)	0.879 (0.005)	58	0.12	1.143 (0.187)	0.912 (0.035)	60	0.17	1.592 (0.294)	0.915 (0.038)	31	0.24
K	0.358 (0.078)	0.886 (0.065)	32	0.10	0.335 (0.079)	0.902 (0.059)	28	0.10	0.343 (0.176)	0.853 (0.215)	10	0.06
Wenchi												
N	1.333 (0.071)	0.974 (0.004)	209	0.26	1.144 (0.084)	0.975 (0.005)	141	0.22	1.392 (0.171)	0.980 (0.006)	66	0.22
P	0.548 (0.103)	0.919 (0.036)	133	0.08	0.670 (0.097)	0.918 (0.028)	94	0.17	0.848 (0.175)	0.922 (0.038)	30	0.17
K	0.170 (0.059)	0.869 (0.124)	62	0.02	0.364 (0.085)	0.905 (0.057)	37	0.08	0.342 (0.092)	0.915 (0.059)	20	0.08

† The query criteria ranges were approximately 20% wider and 20% narrower for the wide and narrow queries, respectively, compared with the ranges for the intermediate or standard query. The numbers in parenthesis are the standard error of the means

relatively data scarce. A risk of narrowing the query criteria is that the results may be unduly affected by a small set of research results, even for the data abundant maize N and P responses.

Conclusions

Estimates of crop response functions lack exactness globally but especially with SSA smallholder agriculture where crops inconsistently encounter numerous uncontrolled biotic and abiotic constraints. In consideration of crop nutrient response function differentiation, standard errors, standard deviations, and R^2 values, selecting relevant maize nutrient response functions for estimating an inference, maize nutrient response function overall appeared to be best estimated using OFRA-IT (http://agronomy.unl.edu/OFRA) and less ecologically specific with HC-AEZ compared with other query options. The OFRA-IT was tolerant of differing query criteria ranges and the default criteria worked well for maize response to applied N, P, and K. Queries for crop-nutrient responses that are relatively data scarce may be improved by widening the criteria ranges.

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