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REVIEW ARTICLE

Nutrient management in African sorghum cropping systems: applying meta-analysis to assess yield and profitability

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Abstract Declining soil fertility and limited farmer access to inorganic fertilizer frequently cause sub-optimal grain yields throughout sub-Saharan Africa. Farm productivity is also at risk from extreme weather and future climate change. Significant uncertainty remains in predicting climate in Africa, increasing the challenge of planning for climate change adaptation. Sorghum is adapted to African climate patterns and is predicted to maintain widespread suitability across different African climatic zones under climate change. Sorghum's drought tolerance and ability to withstand water logging make it an important crop for maintaining productive agroecosystems under a changing climate. Due to its status as a staple grain, improved sorghum management can provide smallholder farmers with stability in their household nutritional needs. We reviewed sorghum (*Sorghum bicolor*) yield trends across nutrient management scenarios using meta-analysis. We compared yield across eight nutrient management practices: (i) N-only, (ii) P-only, (iii) N and P, (iv) N and P microdose, (v) legume management, (vi) manure addition, (vii) organic matter (OM) amendment, and (viii) mixed amendment. Our review demonstrated (1) yield improvement considering all scenarios averaged 66 % relative to no nutrient inputs, (2) yield under chemical fertilizer amendment increased by 47–98 % of control yield, (3) yield under organic nutrient amendment increased by 43–87 % of control yield, and (4) the profitability of a management scenario was not solely determined by the magnitude of yield increase. For example, due to the high cost of fertilizer, addition of nitrogen (N) and phosphorus (P) generated the largest yield increase, but the lowest profit, in two of three countries analyzed. In contrast, an edible legume in rotation averaged 43 % yield improvement relative to no nutrient inputs and a net profit of US $146 to $263 per hectare. Facilitating access to both fertilizer inputs and diversified rotations has the greatest potential to increase grain yield in Africa.

Keywords Africa · *Sorghum bicolor* · Sorghum yield · Nutrient amendment · Meta-analysis · Cropping system profitability · Sustainable livelihoods

Abbreviations

CI	Confidence intervals
FAO	Food and Agriculture Organization
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
MAP	Mean annual precipitation
N	Nitrogen
OM	Organic matter
P	Phosphorus
WUE	Water use efficiency

Contents

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1 Introduction

Improving crop yield and food self-sufficiency under increasing population pressure is a primary goal for attaining food security in Africa (Bremner 2012). At the same time, declining soil fertility is a dominant constraint toward achieving improved yield across Africa (Bosede 2010; Chianu et al. 2012; Mafongoya et al. 2006; Waddington et al. 2010). In addition, many farmers are unable to access inorganic fertilizer due to lack of credit, fertilizer's high cost, and general lack of policy and institutional support for fertilizer use (Chianu et al. 2012; Croppenstedt et al. 2003; Holloway et al. 2005). Therefore, African grain agroecosystems are commonly managed as low-input systems. Limited access of smallholder farmers to inorganic fertilizer or manure amendments is compounded by increased continuous cropping in response to food demand and population growth. Numerous African governments responded to the perception of low inorganic fertilizer use through a commitment to re-invest in agriculture. The resulting Abuja Declaration in 2006 called for an increase in inorganic fertilizer use by smallholder farmers in Africa. While there is evidence to suggest that inorganic fertilizer use has increased in recent years, low grain to fertilizer response rates caused by low soil fertility remains a challenge (Jayne and Rashid 2013; Sheahan and Barrett 2014).

Typical crop management planning which addresses soil fertility, pests, and water management, is further complicated by climate change. In the coming decades, climate change will build uncertainty into crop yield potential across Africa. A recent interdisciplinary workshop discussed how Saharan temperatures have increased at three times the global average over the past three decades, leading to the potential for famine and resource conflicts in Northern Africa and the Sahel (Claussen et al. 2015). Preparing for climate change is complicated by poor climate predictive capacity across Africa (Boko et al. 2007; Ramirez-Villegas and Challinor 2012), though climate researchers remain optimistic about potential for improvement of Africa climate modeling in the near term (Hansen et al. 2011; Ndiaye et al. 2011). Current predictions for crop yield response to climate change are varied, with yield decline predicted in some cases (Knox et al. 2012; Schlenker and Lobell 2010; Zinyengere et al. 2013), and yield improvement or maintenance predicted in other scenarios (Liu et al. 2008; Roudier et al. 2011).

Sorghum is a broadly suitable grain for African agroecosystems. Due to its evolutionary origin as an East African tropical cereal grass, sorghum is adapted to African climate patterns. In particular, sorghum is tolerant to both drought as well as extensive periods of water logging, conditions which are common in semi-arid and sub-tropical climate regions of African arable landscapes (Edmonds et al. 2009). Ramirez-Villegas et al. (2011) mapped the current widespread suitability of sorghum in sub-Saharan Africa using data compiled by the Food and Agriculture Organization (FAO) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). They projected that sorghum will continue to be suitable throughout much of its current range under climate change. While traditional sorghum-growing regions of East Africa have increasingly grown maize over the last half century, promoting successful sorghum management strategies is an important component of food security. Multiple studies of maize and sorghum under medium to severe water stress conditions demonstrated that sorghum yield can be higher than maize yield under drought stress as well as more profitable (Farré and Faci 2006; Schittenhelm and Schroetter 2014; Staggenborg et al. 2008). Sorghum's tolerance to variable weather patterns was also observed in a recent assessment of crop growth in response to decadal variation in temperature and rainfall in Mali, which indicated that sorghum yield variation was not correlated to weather patterns, while maize yield was positively correlated with rainfall (Traore et al. 2013). While a recent field experiment found maize to produce higher yields than sorghum and millet following variable seasonal rainfall distribution conditions in Zimbabwe (Rurinda et al. 2014), field studies in Mali indicated maize sensitivity to erratic rainfall conditions (Traore et al. 2014). Figure 1a illustrates that well-managed sorghum can be a high-yielding crop and Fig. 1b illustrates sorghum in a diversified smallholder cropping system. In addition to suitability to African climate, sorghum has a higher level of nutritional carbohydrates content, lower fat content, and higher iron content than maize (Rurinda et al. 2014, p. 38). Sorghum is also a staple in a variety of nutritious traditional foods in many parts of Africa (Dicko et al. 2006; Elkhalifa 2012). Nutritional benefits combined with tolerance to adverse weather conditions make efforts to improve sorghum productivity an essential component for increasing African agricultural productivity and household food security in the twenty-first century.

With these considerations in mind, we conducted a meta-analysis of sorghum yield in Africa to quantify the effect of various nutrient management strategies on improving crop yield. We subsequently addressed the economic feasibility of these nutrient amendment scenarios in three representative

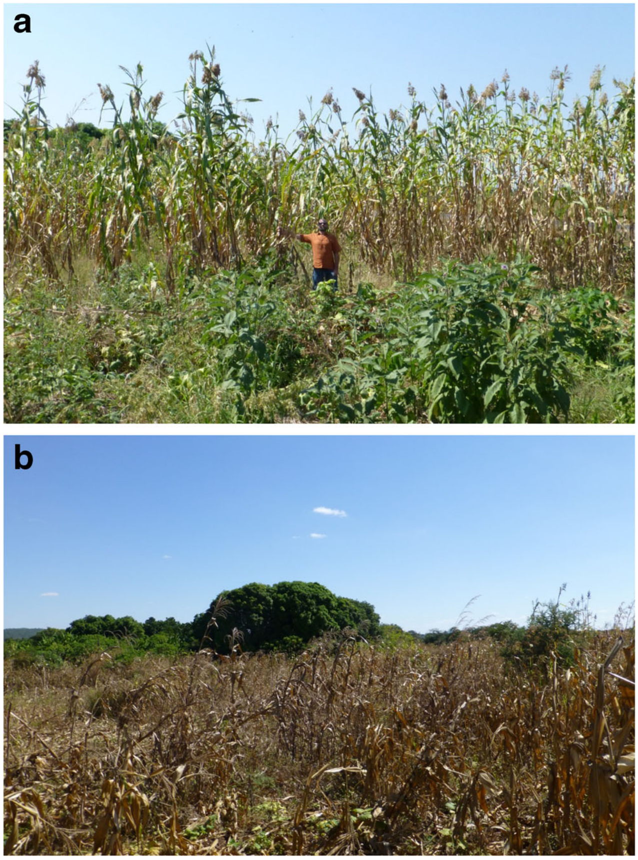

Fig. 1 Sorghum cropping systems in eastern province of Zambia. **a** Sorghum growing under favorable conditions. **b** A diversified smallholder farm growing, sorghum along with maize, groundnuts, squash, okra, and cotton. (Photo courtesy of Noel Gurwick, USAID)

countries: Burkina Faso, Ethiopia, and Zimbabwe (discussed in section 2.3). We expect that all nutrient amendment strategies will improve yield relative to the common occurrence of no nutrient amendment. We applied meta-analysis to test whether the conventional Green Revolution strategy of agronomic optimal fertilizer application leads to the highest yields, as well as the extent to which alternatives to inorganic fertilizer application improve yield. Our combined agronomic and economic analysis outlines when farmers will benefit most from convention strategies versus alternative nutrient management such as Integrated Soil Fertility Management (ISFM) promoted by the Alliance for a Green Revolution in Africa (AGRA) (Vanlauwe et al. 2012; Vanlauwe 2013). We conclude with a discussion of these quantitative outcomes in the context of agroecosystem management for mitigation of pests, environmental uncertainty, and climate change. Meta-analysis techniques differ from a more general literature review in that meta-analysis requires a strict comparison of paired control and treatment data points. Recent literature has identified meta-analysis as a tool that fundamentally changed how scientists synthesize data trends, allowing researchers to compare consistencies and inconsistencies across individual experiments, assess how well data fit theory, and identify research gaps (Koricheva and Gurevitch 2014; Nakagawa and Santos 2012). The findings in this study provide important insights into appropriate agronomic and economic nutrient management practices that can help farmers profitably manage sorghum production in response to declining soil fertility.

2 Methods

2.1 Systems compared, data sources, and compiled information

The application of meta-analysis techniques requires that each study compares a control to an experimental treatment and that these control and treatment scenarios can be consistently defined across studies. In order to compare the response of sorghum yield to a range of amendment techniques, we defined the control treatment as the common practice of no nutrient inputs. We contrasted this control system to sorghum systems with nutrient amendments conducting our main categorical analysis to look at the impact of nutrient amendment strategies grouped into eight categories: (1) N addition, (2) P addition, (3) N and P addition, (4) microdose of N and P, (5) legume management, (6) manure addition, (7) organic matter (OM) amendment, and (8) mixed amendment.

We compiled data from the peer-reviewed literature using field studies that compared sorghum yields from fields without nutrient inputs to yields under various nutrient amendment strategies for field observations from Sahelian, Sudano-Sahelilan, Sudanian, and Eastern Africa. We searched the Web of Science database using the search terms (“sorghum” and “yield” and “Africa”) as well as (“sorghum” and “productivity” and “Africa”) to locate field outcomes reporting yield across management techniques; the search resulted in 296 and 86 articles, respectively. To be included in this analysis studies had to have a field without nutrient amendment (the control) compared to at least one nutrient amendment scenario (inorganic fertilizer, legume, manure, or OM amendment). We extracted sorghum yield outcomes from articles meeting these criteria. A total of 29 publications met the criteria for inclusion in this study, these data represent 33 study sites and 165 paired yield outcomes. Multiple data pairs from a single publication qualified for inclusion in our meta-analysis because individual publications generally reported outcomes from multiple sites and for multiple treatment scenarios. Each data pair is from a different field and represents an outcome experiencing unique environmental conditions. The majority of the experiments were conducted as on-farm trials (45 %) and represent yield outcomes averaged over multiple fields. The remaining field trials were conducted at experimental stations (30 %) and on lands representative of regional agricultural landscapes (25 %). Because study fields represent unique locations and the data are from a broad distribution of environmental conditions, the potential for data non-independence to drive yield trends is minimal. When studies reported the *Sorghum bicolor* variety used, it was indicated that locally relevant varieties were planted. Many studies were from farmer fields. In cases where experiments were conducted on research farms, we expect that common regional varieties were studied such that results would reflect farmer experience. While sorghum variety can greatly influence maximum potential yield, the change in yield between control and treatment fields (the metric of our analysis) remains a useful tool to compare relative impact of nutrient amendment across studies. Because different sites use different regional varieties we do not have sufficient data to consider variety for a categorical analysis. Table 1 lists the studies used in this meta-analysis. Section 3.1 describes the characteristics of the data used in this study.

As part of our data compilation and analysis, we categorized the following factors in our database: mean annual precipitation (MAP), soil texture, and N or P rate. In addition to our main comparison of nutrient amendment sub-groups, we contrast change in yield across soil texture sub-groups categorized as heavy (clay + clay loam), medium (loam + silt loam + sandy clay), or light (sand + loamy sand + sandy loam + sandy clay loam). Because many studies did not report the form of fertilizer used, we had insufficient data to conduct a sub-group analysis of the impact of fertilizer type.

2.2 Meta-analysis

Meta-analysis is a tool for quantifying trends across systems characterized by different summary statistics. This property of meta-analysis allowed us to compare sorghum yield across broad climate, soil types, and amendment protocols. To conduct a meta-analysis, an effect size estimator is calculated as an index for comparing the experimental treatment mean to the control treatment mean (Gurevitch and Hedges 1999; Philibert et al. 2012; Koricheva and Gurevitch 2014). Ultimately, the effect size estimator allows us to quantify the magnitude of a treatment effect. We calculated our effect size using the response ratio ($r=\overline{Xe}/\overline{Xc}$), which is the relative impact of nutrient amendment (the experimental treatment Xe) compared to a cropping system with no nutrient inputs (the control treatment Xc). The response ratio is a typical effect size applied in ecological studies focused on the change in productivity across treatments (e.g., Johnson and Curtis 2001; Koricheva and Gurevitch 2014). In order to perform the meta-analysis on normally distributed data, we used a log transformation of the response ratio, $R=\ln(r)=\ln(\overline{Xe})-\ln(\overline{Xc})$. For analyses where $\overline{Xc}$ is constrained to non-negative values and where $\overline{Xe}$ and $\overline{Xc}$ are normally distributed, such as the application presented here, R should be approximately normally distributed with a mean approximately equal to the true response ratio (Johnson and Curtis 2001). To facilitate the interpretation of the change in yield across treatments, meta-analysis results are graphically presented using back-transformed response ratios such that the change in yield is reported in percent deviation from the control yield (e.g., Johnson and Curtis 2001); this is calculated as change in yield (%) $=100\times((Xe/Xc)-1)$. We conducted our meta-analysis using MetaWin version 2.1 software (Rosenberg et al. 2000).

Because nearly all of the studies we used did not report a measure of variance, we conducted an unweighted meta-analysis using a fixed-effects model. The statistical significance of our unweighted meta-analysis was enhanced by the calculation of confidence intervals (CI). After a mean effect size was calculated, a bias-corrected 95 % confidence interval was generated by a bootstrapping procedure (5000 iterations) using the MetaWin software (Rosenberg et al. 2000). Using meta-analysis, we explored the mean response ratio using soil texture as a categorical variable. Means were considered to be significantly different from one another if their bias-corrected 95 % CIs were non-overlapping and were considered significantly different from zero if the bias-corrected 95 % CI did not overlap zero (Gurevitch and Hedges 1999; Johnson and Curtis 2001).

We assessed publication bias by comparing how effect size varied across increasing replication in experimental design. Effect sizes measured using the log response ratio ranged from $-1<R<2$, indicating that experiments with negative results are included in the peer-reviewed literature. As replication increased, effect size narrowed with the majority of values ranging from $0<R<1$. The data indicate that non-significant experimental results were published and that increasing replication reduced the influence of outlier results on aggregate outcomes. We did not find evidence of publication bias in the data used in this analysis for two main reasons. First, most outcomes cluster around moderate yield improvement following nutrient inputs, and second, data included negative yield outcomes and exhibited outlier outcomes only for low-replication studies.

2.3 Economic analysis

We recognize that nutrient amendment is a significant expense for African smallholder farmers. Therefore, we compared the net profit of applying the nutrient management techniques studied in our meta-analysis to outline circumstances under which a given amendment strategy is possible and favorable. We calculated economic profitability of different management scenarios based on sorghum output prices and fertilizer costs using price data for Burkina Faso, Ethiopia, and Zimbabwe. These countries cover west, east, and southern Africa, respectively. We chose these example countries for our economic analysis because (1) Burkina Faso and Zimbabwe are the most represented countries in

Table 1 Data sources reviewed in the meta-analysis

Author	Year	Journal	Country	# sites	MAP	Soil texture	Years	Amendments	Sorghum variety
Aune and Ousman	2011	Experimental Agriculture 47 (3):419–430	Sudan	1	430	Sand	3	N + P microdose	Yarwashsa
Aune et al.	2007	Outlook on Agriculture 36 (3):199–203	Mali	13	621		2	N + P, N + P microdose	Bafaloubé
Aune and Ousman	2011	Experimental Agriculture 47 (3):419–430	Sudan	53	430	Sand	3	N + P microdose	
Bado et al.	2007	Advances in Integrated Soil Fertility Management in Sub-Sahara Africa: Challenges and Opportunities. 171–177	Burkina Faso	4	887	Loamy sand	3	N + P, P + K, N + P + manure	Gnofing
Bagayoko et al.	2000	Plant and Soil 218:103–116	Burkina Faso	2	850		2	Legume	
Bationo et al.	1997	Nutrient Cycling in Agroecosystems 48:179–189	Mali	30	800		4	N + P	
Bostick et al.	2007	Soil & Tillage Research 93:138–151	Burkina Faso	4	1100	Loamy sand	11	N + P + K, P + K	
Carsky et al.	1995	Agricultural Water Management 28:1–8	Cameroon	4	750	Clay	1	N, N + P	SAFRARI-40, SAFRARI-7, BOURGOURI-28
Hagedorn et al.	1997	Plant and Soil 195:365–375	Uganda	4	1150		3	Legume, manure	Ikinyaruka
Haile and Hofsvang	2001	International Journal of Pest Management 47 (4):259–264	Eritrea	4	550	Silt loam	2	N + P	Amal
Kaizzi	2007	Agronomy Journal 99:847–853	Uganda	5–17	1000; 1150	Loamy sand	1	Legume, N, N + P	Sekedo, Epurpur
Khan et al.	2007	Crop Science 47:730–736	Kenya	4	900		1	Legume	Gadam Hamam
Knewtson et al.	2007	Communications in Soil Science and Plant Analysis 39 (1–2):217–230	Mali	5	619	Clay	8	Legume, legume GM	CSM 219E
Kouyat et al.	2000	Plant and Soil 225:141–151	Mali	5	619	Loam, loamy sand	8	Legume	CSM 219, CSM 219-E
MacCarthy et al.	2010	Field Crops Research 118:251–258	Ghana	1	731	Eutric, Gleyic, Regosol	1	N + P	
Mando et al.	2005	Soil Use and Management 21:25–31	Burkina Faso	3	800	Sandy loam	11	N + P, N + P + manure, manure, OM, N + P + OM	ICSV 1049
Maranville et al.	2002	Communications in Soil Science and Plant Analysis 33 (9–10):1519–1536	Niger	1	422	Loamy sand	3	N + P	NAD-1, Sepan82, IRAT 204
Nyakatawa et al.	2001	Journal of Sustainable Agriculture 17 (2–3):53–65	Zimbabwe	3	500	Sand, sandy clay	2	Manure	SV2
Ouédraogo et al.	2007	Soil & Tillage Research 94:64–74	Burkina Faso	3	773	Silty loam	2	N + P, OM	Zuguils
Ouédraogo et al.	2005	Biology and Fertility of Soils 41:458–465	Burkina Faso	4	935	Loamy	1	Compost + P	Sariasso-14
Ouédraogo et al.	2001	Agriculture Ecosystems and Environment 84:259–266	Burkina Faso	4	924	Loamy sand	1	Compost	Sariasso-14
Pandey et al.	2001	Communications in Soil Science and Plant Analysis 32:(9–10):1465–1482	Niger	4	587	Loamy sand, sandy loam	1	N + P	Sepon-82
Reda et al.	2005	Journal of Agronomy & Crop Science 191:20–26	Ethiopia	3	570, 1000		3	Legume	Ganseber, Kutbie
Sauerborn et al.	2000	Journal of Agronomy and Crop Science 184:67–72	Ghana	6	1043	Sandy clay loam	1	Legume	Kadaga
Tilander and Bonzi	1997	Plant and Soil 197:219–232	Burkina Faso	1	985		3	OM	ICSV 1049
Twomlow et al.	2010	Nutrient Cycling in Agroecosystems 88:3–15	Zimbabwe	323	599	Sand, clay loam, sandy loam	2	N microdose	Macia
Wortmann	2001	Nutrient Cycling in Agroecosystems 61:267–272	Uganda	6	1070	Clay	3	Legume, legume GM	Shokani
Zaongo et al.	1997	Plant and Soil 197:119–126	Niger	6	559	Sandy loam	1	N	Mota Maradi
Zougmoré et al.	2003	Soil Use and Management 19:257–264	Burkina Faso	2	800	Sandy loam	3	N, compost	Sariasso-14

the yield database used for our meta-analysis, (2) sorghum provides greater than one third of total caloric intake in Burkina Faso (Aguado-Santacruz et al. 2012), (3) sorghum is believed to have evolved in Ethiopia (Aguado-Santacruz et al. 2012; Dicko et al. 2006), and (4) there are a number of traditional sorghum-based foods in Ethiopia (Dicko et al. 2006; Elkhalifa 2012).

We calculated sorghum profitability under four different management treatments: (1) N addition, (2) N and P addition, (3) microdose of N and P, and (4) legume management; these four treatments are the most common treatments applied in our meta-analysis, accounting for 72 % of our database. We calculated the profitability of different sorghum nutrient amendment treatments as a net return per hectare. For the three countries assessed, we calculated the (1) increase in grain revenue, (2) cost of fertilizer management, (3) cost of legume management, and (4) net return for a field in country (i) managed under each of the four treatments (j) as:

1. Grain revenue$_{i,i}$ (ha) = (price sorghum$_i$) × (yield differential$_{i,j}$ (ha))
2. Cost of nutrient management treatment$_{i,j}$ (ha) = cost of fertilizer applied$_{i,j}$ (ha)
3. Cost of legume management treatment$_{i,j}$ (ha) = cost of cowpea (0.5 ha)
4. Net return$_{i,j}$ (ha) = grain revenue$_{i,j}$(ha) − cost$_{i,j}$ (ha)

To calculate grain revenue, we use the meta-analysis outcomes to derive the yield differential relative to the control resulting from treatment j. We derived yield differentials by taking the country-specific mean yield for the control treatment and varying this yield by the percent improvement under a specific management treatment quantified in the meta-analysis. We then multiplied yield differential values derived from the meta-analysis with country-specific sorghum and cowpea price data from the Food and Agricultural Organization Statistics (FAOSTAT 2012) and household surveys (Ethiopian Rural Household Survey 2009 for Ethiopia, ICRISAT Sorghum Macia Impact Assessment Survey 2013 for Zimbabwe). To assess the cost of nutrient amendment treatment, the cost of treatment j in country i was calculated as the cost per hectare of the median fertilizer treatment rate applied in the meta-analysis database. In our cost calculations, we used fertilizer price data from AfricaFertilizer.org (Africa Fertilizer 2012) for Burkina Faso (monthly price data from 2010–2012) and household survey data for Ethiopia (sampled in 2009) and Zimbabwe (sampled in 2013). For legume management, we considered two scenarios. Under legume intercropping, the primary crop is sorghum; while cowpea is planted with the sorghum, we do not consider cowpea sales in this scenario, using this scenario to represent cowpea used for animal fodder or soil amendment. The second scenario was addition of legumes in a rotation, in which we assumed a farmer sowed 0.5 ha to sorghum and 0.5 ha to cowpea in a given growing season; the per hectare net return for this rotation was conducted using grain revenue and management costs for a hectare equally split between sorghum and cowpea management. Management under legume intercropping or legume rotation does not include fertilizer application. We included the cost of cowpea seed in our assessment of legume management. We assume the upper seeding rate recommended in Dugje et al. (2009) of 25 kg ha^{-1} would apply for a hectare of pure cowpea and, therefore, use a conservative estimate of 12.5 kg ha^{-1} for the intercropping and rotation cost analysis. We use a cowpea seed cost of \$1 kg^{-1} based on the conventional cowpea seed price of \$0.80 (Burkina Faso), \$1 (Niger), and \$0.60 (Nigeria) per kilogram reported in Coulibaly (2008).

We conducted a sensitivity analysis of profitability to changes in fertilizer cost. We establish the *break-even* cost of fertilizer across inorganic fertilizer treatments as the fertilizer cost when profit equals zero. Therefore, for profit = revenue − cost, at the break-even point revenue = cost. For scenarios with a single fertilizer type applied, the break-even price = revenue/(fertilizer application rate). For the N and P treatment, we hold the N fertilizer price constant and establish the *break-even* price for a combined N and P fertilizer source (NPK, DAP, or Compound D).

The economic scenarios presented in this analysis are simplifications that do not consider all costs (both direct and opportunity costs) and benefits of different treatments. We do not price sorghum seed as we assume that the cost of sorghum seed would be the same regardless of amendment strategy. We also do not assess labor costs or issues surrounding farmer access to markets. Though our economic analysis does not examine all constraints placed on the farmer, this aggregate comparison of regional differences in grain revenues and management costs illustrates that potential yield increase per hectare is not sufficient information for selecting the most profitable sorghum nutrient management strategy.

3 Results and discussion

3.1 Characterization of the published studies

Our analysis included data from 33 study sites representing 11 countries across Sahelian, Sudano-Sahelilan, Sudanian, and Eastern Africa. The mean annual precipitation (MAP) gradient ranged from 430 mm to 1150 mm; rainfall occurred in a single season for MAP < 900 mm and in two seasons for MAP ≥ 900 mm. No studies applied irrigation. Loamy sand was the dominant soil texture, characterizing 45 % of the study sites. Overall, light soil texture characterized 69 % of the sites, medium textured soils characterized 26 % of sites, and heavy textured soils characterized 10 % of the sites. Studies using N and P amendment comprised the largest category of data fitting our constraints, legume management was the second most common amendment strategy, N-only amendment the third largest, N and P microdosing the fourth largest, amendment with manure or OM tied for fifth, and P-only amendment was the smallest category. Urea was the most commonly applied synthetic fertilizer, used at 30 % of sites where fertilizer was applied; ammonium nitrate was the next most common fertilizer type, applied at 10 % of fertilized sites. Total N applied in fertilizer was reported in all studies, but 23 % of sites did not report fertilizer type. Fertilizer application rate varied over a narrow range in N-only and microdose studies, but there was a wider range of N applied across treatments with N and P. We include the full range of experimental nutrient application rate in our analysis as the literature does not indicate regional optimal application rate and the highest application rates are within the range recommended for grain sorghum grown in temperate climates. Furthermore, yield improvement was not fully explained by nutrient application rates, with high relative yield improvements achieved under intermediate nutrient application rates (discussed below). The majority of yield trials were conducted as short-term studies (47 % 1 year, 15 % 2 years, 22 % 3 years); trials greater than 8 years in duration constitute 10 % of the data. Many studies report aggregate yield data from multiple on-farm trials; 62 % of data pairs extracted from the reviewed literature are aggregate results of mean observations across 4–10 field sites. The largest on-farm study was conducted in Zimbabwe and included over 300 field trials (Twomlow et al. 2010).

3.2 Crop yield trends

For control fields (fields with no nutrient amendment), the mean and range of sorghum yield was similar across the MAP gradient (Fig. 2). Under nutrient amendment, there was a significant overlap in the range of sorghum yield across the MAP gradient, with the mean yield showing considerable increase under the highest MAP category corresponding to agroecosystems with two rainy seasons (Fig. 2). Amendment with N and P resulted in a significant yield improvement for all levels of nutrient inputs—from the low application rates observed in microdosing studies through studies applying excess fertilizer (Fig. 3a). Linear regression was conducted to assess the suitability of nutrient application rate for determining the change in yield on coarse textured soils; studies on medium and fine-textured soils tested a narrow range of nutrient application rate and were not suitable for regression analysis. Simple linear re gression indicated N input rate was a good indicator of change in yield in systems with a single rainy season (Fig. 3b); the relationship between P added and change in yield was inconsistent, in part due to limited variation in P application rate in systems with moderate or high annual rainfall (Fig. 3c).

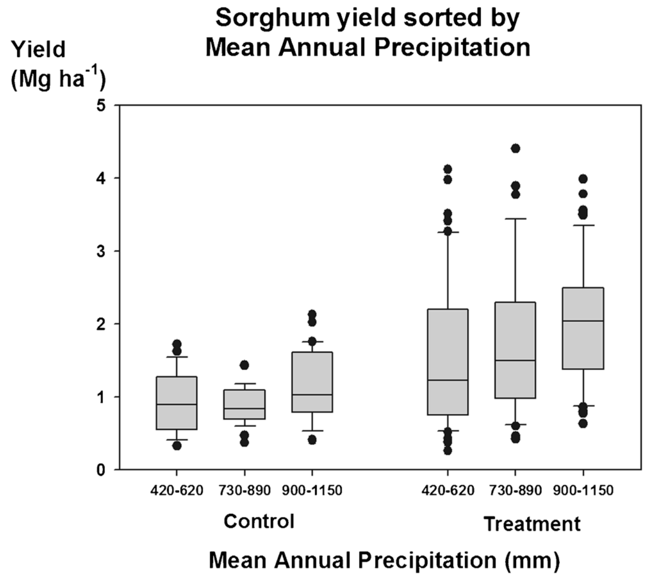

Fig. 2 Distribution of sorghum yield across a mean annual precipitation (MAP) gradient for control and treatment fields

Our quantitative review of the peer-reviewed literature using meta-analysis concluded that nutrient management techniques averaged a 66 % yield improvement relative to no nutrient inputs (Fig. 4). Amendment with N and P fertilizer resulted in the highest yield improvement, averaging 98 % improvement relative to the control scenario. Relative to the control, amendment with N-only, P-only, or manure improved yield by 72, 72, and 87 %, respectively, with the 95 % confidence intervals showing a significant overlap with the highest yielding N and P amendment category. On average, including legumes in a rotation improved yield by 43 %, OM amendment improved yield by 47 %, and microdose application improved yield by 47 % relative to management with no nutrient inputs. Amendment using both synthetic fertilizer and an organic N source averaged an 80 % yield improvement, with this mixed treatment category exhibiting a large range in outcomes. Figure 5 illustrates the distribution of observed change in yield as a result of nutrient management. Approximately 12 % of observations showed a small yield response to nutrient management, with 6 % of observations exhibiting a yield decrease ranging from −15 to 0 % change and 6 % of observations exhibiting a yield increase ranging from 0 to 15 % change relative to control yield. In most studies, a substantial yield increase was observed under nutrient management treatments, with a range of 15–30 % increase occurring in 12 % of observations, a 30–50 % increase documented in 16 % of observations, a 50–75 % increase documented in 13 % of observations, a 75–100 % increase documented in 11 % of observations, and >100 % increase documented in almost 32 % of observations.

We assessed heterogeneity of the compiled dataset using the meta-analysis statistic Q; this analysis yielded non-significant *p* values within nutrient treatment sub-groups. A non-

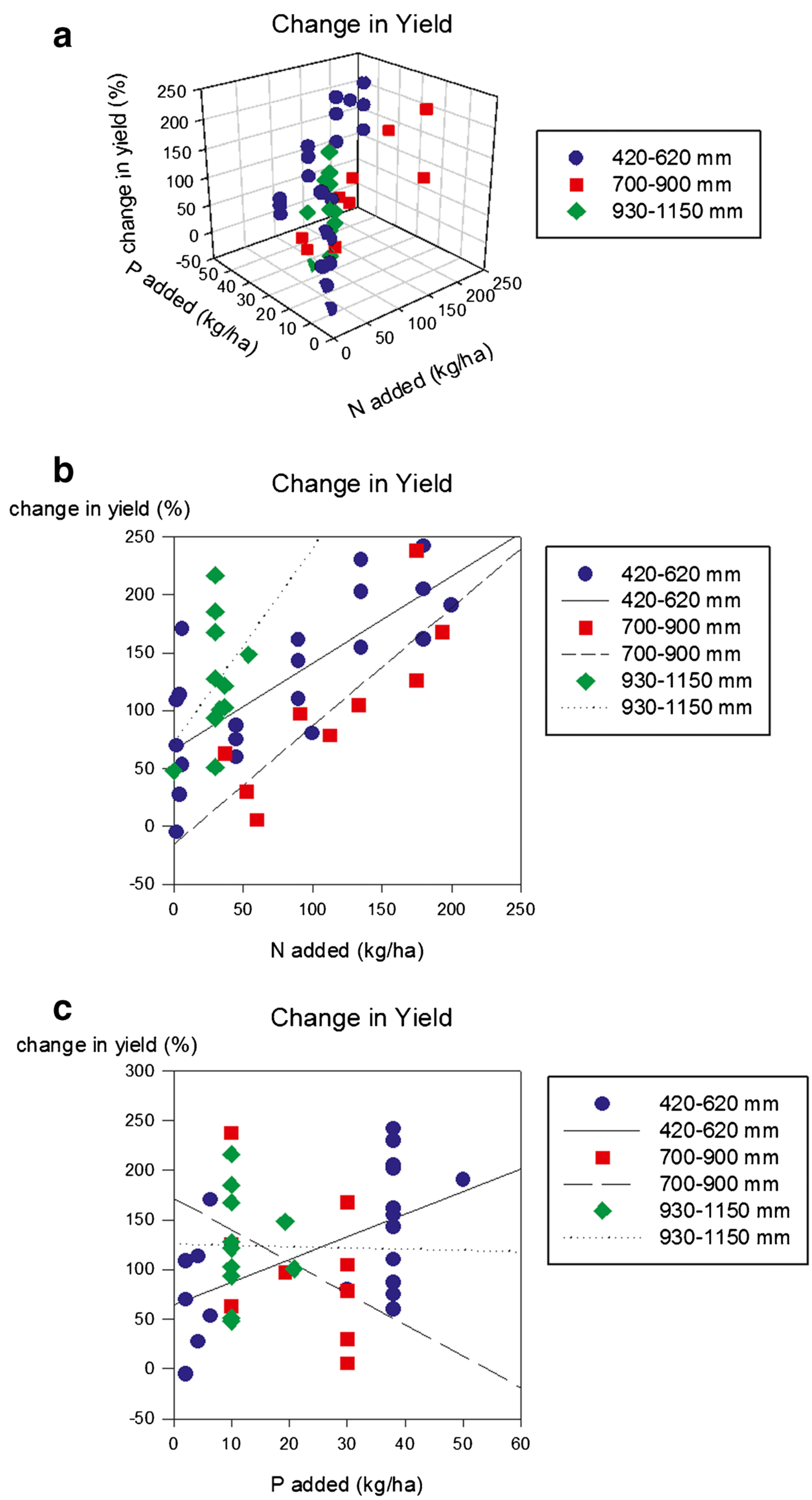

Fig. 3 Change in yield across the range of N and P amendment applied. **a** Change in yield as a function of N and P input. **b** A regression analysis of N amendment on change in yield, which was significant for MAP of 420–620 mm ($R^2 = 0.59$) and MAP of 700–900 ($R^2 = 0.71$). **c** A regression analysis of P amendment on change in yield, which was not significant. All observations are for coarse-textured soils

significant Q statistic indicates that we cannot refute the hypothesis that the effect size is representative of the respective nutrient treatment effect; the Q statistic cannot be used to prove the effect size is the true treatment effect size. The between treatment group Q statistic was also non-significant, concurring with the significant overlap in the confidence intervals across treatment sub-categories (Fig. 4). Because many of the studies we surveyed did not indicate experimental variance, we conducted an unweighted meta-analysis; as a result, further heterogeneity analysis using the τ statistic was not

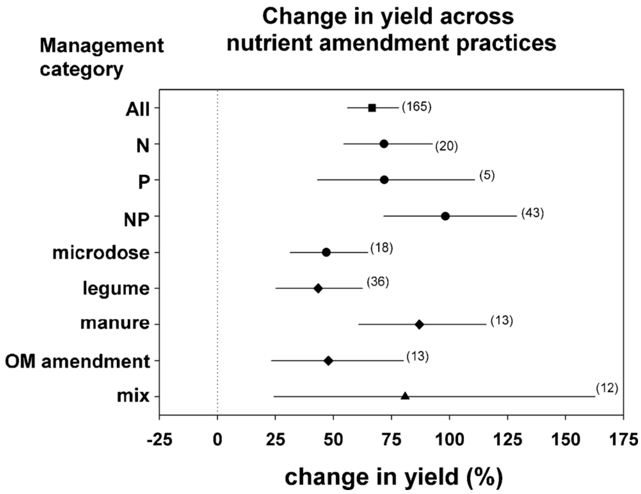

Fig. 4 Percent change in yield across nutrient amendment scenarios. Effect of nutrient amendment on sorghum yield in units of percent change from the control (no nutrient inputs) grouped by amendment category. Mean values and 95 % confidence intervals of the back-transformed response ratios are shown (number of comparisons in parentheses). *Square icon* represents data from all practices, *circles* are inorganic fertilizer, *diamonds* are organic nutrient amendments, and the *triangle* represents mixed amendment

warranted. Rather, the variance in the data analysis is best illustrated by the meta-analysis confidence intervals (Fig. 4).

Light-textured soils represented 69 % of the data pairs and resulted in significantly larger yield improvements relative to medium- or heavy-textured soils (Fig. 6). Light-textured soils are fast draining and therefore subject to greater soil moisture stress. Due to this physical soil property, light-textured soils extract greater benefit from organic matter amendment with regard to water retention. The light-textured soil category includes observations of significant yield gains from legume, manure, and OM amendment, which likely demonstrates the co-benefit of these management practices with respect to increasing plant access to both macro- and micronutrients, as well as water. Similar to heterogeneity analysis of the nutrient treatment sub-group categorization, the Q statistic was non-significant within a texture sub-group. However, the between-group Q statistic was significant, indicating effect size was significantly different across soil texture sub-groupings. Because light-textured soil is the dominant field condition across studies in our database, the overall treatment effect size is weighted toward the outcomes for light-textured soils.

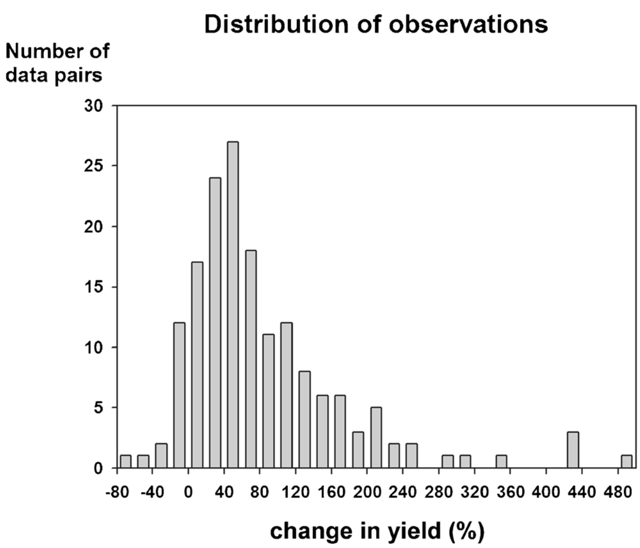

Fig. 5 Distribution of observed change in yield as a result of nutrient management. Histogram shows the frequency of percent change in yield resulting across all management treatments for bins in 20 percentile increments

3.3 Meta-analysis limitations

The ability to extract a mechanistic understanding of trends observed in meta-analysis is limited by data quality and comparability. In this example, all studies indicated nutrient amendment type, allowing us to quantify how different amendment practices impacted yield. However, other crop management details that we know impact yield were not described in the literature, preventing us from exploring additional mechanistic drivers of yield. Even in cases where the literature includes information about mechanistic drivers, the experimental design may not lend to comparison. For instance, we did not have sufficient data to compare the impact of inorganic fertilizer form or sorghum variety on yield trends. Meta-analysis relies on extracting data from experiments that are conducted with different hypotheses. While studies that are focused on yield outcomes generally have similar fundamentals in their design, the studies will all have slight differences in methods.

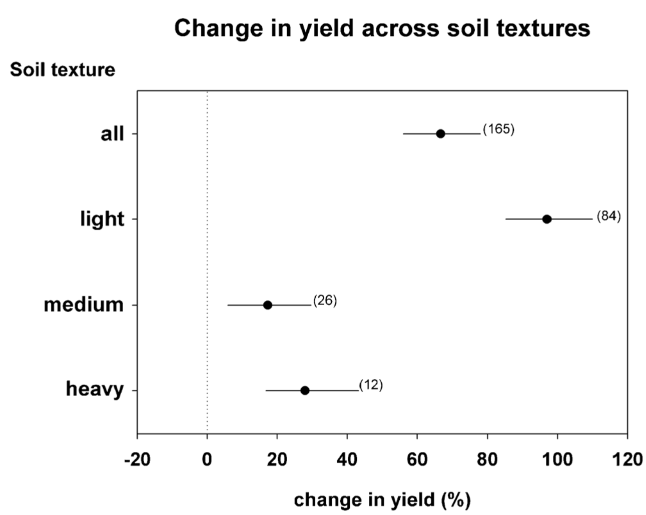

Fig. 6 Percent change in yield across nutrient amendment scenarios sorted by soil texture. Effect of nutrient amendment on sorghum yield in units of percent change from the control (no nutrient inputs) grouped by soil texture. Mean values and 95 % confidence intervals of the back-transformed response ratios are shown (number of comparisons in parentheses)

Additionally, for ecological studies, one is comparing outcomes across a broad gradient of environmental conditions.

Another limitation of meta-analysis is whether the data set is indicative of true population dynamics. We followed a standard meta-analysis practice of deriving data from peer-reviewed journal literature. As mentioned in section 2.2, this may result in some data sets being excluded from the analysis. However, an analysis of publication bias can illuminate whether the data are skewed, for instance, due to the absence of negative outcomes in the peer-reviewed literature. In this study, publication bias analysis suggested that negative data were published and that studies with greater replicates converged on the observed mean. Furthermore, once a critical mass of data is compiled, meta-analysis results are a good indication of population mean dynamics. Additional data points can narrow the confidence interval range of the analysis, but are not expected to significantly alter the mean effect size.

3.4 Economic feasibility of management alternatives

Access to N inputs is a serious limitation to cereal yield improvement in Africa. Edmonds et al. (2009) found that fertilizer use in sub-Saharan Africa has been declining in the beginning of the twenty-first century while population continues to increase. Increasing population and declining yields may lead to smaller per capita farm sizes and lower per capita incomes. This in turn may make it difficult for many African farmers to purchase inorganic fertilizer. Therefore, it is important to consider the benefits and costs of non-chemical input treatments such as legume rotation and OM amendments as possible alternatives to chemical fertilizer. Management using organic nutrient inputs is potentially more affordable to farmers and provides ecological services of improved soil fertility, increased soil water-holding capacity, and reduced soil compaction.

Our meta-analysis is a comprehensive analysis of field observations and provides a quantitative metric for how nutrient management techniques affect sorghum yield. After completing the meta-analysis, we applied the results of how sorghum yield responds to nutrient management with input and output prices to assess the profitability of these practices. Results from the profitability scenarios are presented in Tables 2, 3, 4, and 5. Table 2 presents the yield and revenue increase for six different nutrient amendment scenarios applied to three focus countries across Africa. In order to better understand the distribution of the returns to various treatments, we assess country-specific yield response rates using the meta-analysis outcomes for (i) the mean, (ii) the lower 95 % confidence interval, and (iii) the upper 95 % confidence interval. Yields across treatments were highest in Burkina Faso, followed by Zimbabwe and Ethiopia. This order is generally reflective of relative agronomic conditions in these countries. Yield gain from a nutrient treatment follows the results from the meta-analysis (Fig. 4, Table 2), sorghum amended with N and P had the highest additional yield gain at the mean response, followed by manure amendment, then treatment with N only, followed by N and P microdosing, and finally sorghum under legume management. However, when considering the additional and net revenue of amendment treatments, the benefit of each treatment does not strictly follow the yield outcomes. Below we outline how combining an economic analysis to the ecological outcomes provides a different recommendation for farmers to maximize profitability.

Different findings emerge when examining the additional revenue from various management strategies. In Burkina Faso, N and P amendment generated the highest revenue when assuming a mean yield response; revenue from other treatments followed the ordering manure, legume rotation, N amendment, N and P microdose, and legume intercropping, in descending order (Table 2). In contrast, in Ethiopia and Zimbabwe, sorghum rotated with cowpea generated the highest revenue assuming a mean yield response, followed by N and P amendment, manure, N amendment, N and P microdose, and legume intercropping (Table 2). This is an important finding because cowpea is not widely grown in these countries. However, the value added from cowpea in terms of revenue and household nutritional benefits raises the potential for promoting sorghum and cowpea in rotation.

Table 3 presents median fertilizer application rate and cost for four nutrient amendment practices across the three focus countries in Africa; in addition, the cost of cowpea seed is considered under legume management. Fertilizer costs were calculated for the median N and P amendment rates derived from the meta-analysis. We focus on fertilizer costs because fertilizer is usually the limiting factor for many farmers in Africa. Additionally, the cost of sorghum seed would remain the same across the different nutrient amendment treatments, the only management difference compared is the nutrient amendment practice.

Labor is also a cost of production in these systems. Legume intercropping is generally regarded as having a higher labor cost associated with it than mono-cropping a single cereal (Kanyama-Phiri et al. 2000; Snapp et al. 2002). However, because farm labor in sub-Saharan Africa typically comes from the household directly, there is no standardization for quantifying labor costs. Even if we consider an additional per hectare labor cost of US $40 for applying nutrient amendments compared to the control of no amendments, most of the amendments would still be profitable. Therefore, we find it more accurate to focus our cost assessment on purchased inputs.

Based on nutrient application rates and relevant prices, Table 3 shows N and P amendment had the highest cost per hectare across the three countries at the median application rate. This was not surprising given the relatively large quantity of N and P applied (Table 3) to achieve the mean yield increase observed in the meta-analysis (Table 2, Fig. 4).

Table 2 Yield and revenue increase by country across nutrient amendment treatments

	Mean yield increase			Yield increase at lower 95 % CI*			Yield increase at upper 95 % CI		
	Burkina Faso	Ethiopia	Zimbabwe	Burkina Faso	Ethiopia	Zimbabwe	Burkina Faso	Ethiopia	Zimbabwe
Yield[a] increase in kg ha^{-1} (treatment–control)									
Nitrogen only	720	390	580	550	300	440	930	510	740
Nitrogen and Phosphorus	990	540	790	720	390	580	1300	710	1030
NPK microdose	470	260	380	320	170	250	650	350	520
Sorghum-cowpea intercropping (1 ha sorghum)	440	240	350	250	140	200	630	340	500
Sorghum-cowpea rotation[b] (0.5 ha sorghum)	220	120	175	125	70	100	315	170	250
Sorghum-cowpea rotation[c] (0.5 ha cowpea)	410	410	410	410	410	410	410	410	410
Manure	880	480	700	610	330	490	1170	640	930
Grain price (US $ kg^{-1})									
Sorghum[d]	$0.20	$0.30	$0.19	$0.20	$0.30	$0.19	$0.20	$0.30	$0.19
Cowpea[e]	$0.28	$0.54	$0.59	$0.28	$0.54	$0.59	$0.28	$0.54	$0.59
Additional revenue[f] per hectare from treatment (yield increase * price)									
Nitrogen only	$144	$117	$110	$110	$90	$84	$186	$153	$141
Nitrogen and phosphorus	$198	$162	$150	$144	$117	$110	$260	$213	$196
NPK microdose	$94	$78	$72	$64	$51	$48	$130	$105	$99
Sorghum-cowpea intercropping	$88	$72	$67	$50	$42	$38	$126	$102	$95
Sorghum-cowpea rotation	$159	$257	$275	$140	$242	$261	$178	$272	$289
Manure	$176	$144	$133	$122	$99	$93	$234	$192	$177

**CI* Confidence Interval

[a] Yield values are from the meta-analysis and are rounded to nearest 10 kg

[b] The sorghum-cowpea rotation assumes 0.5 ha planted to sorghum, 0.5 ha planted to cowpea

[c] Cowpea rotations are unfertilized and cowpea yields are assigned as 820 kg ha^{-1} based on Kaizzi et al. (2007)

[d] Sorghum prices are 5-year average from FAOSTAT

[e] Cowpea prices are five year average from FAOSTAT, (due to availability cowpea prices for Zimbabwe come from Malawi)

[f] Additional Revenue numbers rounded to the nearest US $1.00

Nitrogen-only amendment generated the second highest cost per hectare, while NPK microdose amendment generated a smaller cost per hectare than applying only N, due to the targeted nature of the fertilizer application. Because we calculated costs using the median field application rate of fertilizer, these costs are a realistic estimate of farmer costs. Given the high variation in experimental application rates under the N and P treatment, our revenue and costs analysis is an optimistic assessment of farmer costs to achieve the doubling of yield observed in the N and P treatment in this meta-analysis. Nutrient amendment through management of legume intercropping or legume in rotation with sorghum had a fertilizer cost per hectare of zero because fertilizer was not used, with all N added to the system coming from N fixation during the cowpea growing season. The cost of legume seeds was similar to that of microdosing inputs.

Table 4 presents the net return per hectare of the four amendments based on median fertilizer application rates. These results make the assumption that households have access to different types of fertilizer and the resources to purchase them. While this assumption may not necessarily be realistic for many farmers in Africa, the results illustrate the economic potential of sorghum using different amendments if the constraints to fertilizer use can be overcome.

Table 4 demonstrates that N amendment through management of cowpea in rotation with sorghum generated the highest return for all countries studied. This was clearly due to the high revenue generated from planting half a hectare to cowpea and the zero cost of fertilizer. Legume intercropping also generated favorable revenue, though significantly less than the sorghum-cowpea rotation because cowpea is not sold in this scenario. The potential for legume intercropping to significantly increase agroecosystem profitability was similarly concluded in a local assessment of conventional maize compared with maize-pigeonpea intercropping in Malawi (Ngwira et al. 2012). In this system, the net return of the maize-pigeonpea system was double than that of the conventional maize system. These results point to the value of including a legume in the rotation with sorghum.

Table 3 Management costs

	Burkina Faso	Ethiopia	Zimbabwe
Median fertilizer application rate[a] (kg ha^{-1})			
Nitrogen only (urea or NH_4NO_3)	64	64	86
Nitrogen and phosphorus (NPK or DAP)[b]	54 urea + 133 NPK	58 urea + 85 DAP	100 NH_4NO_3 + 143 NPK
NPK microdose	23	16	5 NH_4NO_3 + 23 NPK
Cowpea (intercropping or rotation)	0	0	0
Fertilizer price[c] (US $ kg¯1)			
Nitrogen only (urea or NH_4NO_3)	$0.76	$0.69	$0.84
Nitrogen and phosphorus (NPK or DAP)	$0.58	$0.86	$0.75
Fertilizer cost per hectare (US $)			
Nitrogen only (urea or NH_4NO_3)	$48.64	$44.16	$72.24
Nitrogen and phosphorus (NPK or DAP)	$118.18	$113.12	$191.25
NPK microdose	$13.34	$13.76	$21.45
Cowpea (intercropping or rotation)	$0.00	$0.00	$0.00
Legume seed cost[d] (US $ kg)			
Cowpea	$1.00	$1.00	$1.00
Legume management cost per hectare[e] (US $)			
Cowpea (intercropping or rotation)	$12.50	$12.50	$12.50

The median fertilizer application rate and cost by country across amendment treatments and the cost of legume management are presented. Manure amendment was not included in this table because reliable application rates and cost information are not available

[a] Application rates are derived from the meta-analysis

[b] NPK combination is 15-15-15 in Burkina Faso, DAP in Ethiopia, and Compound D 7-14-7 in Zimbabwe

[c] Fertilizer price data are from AfricaFertilizer.org and household surveys, calculated as median price per kilogram

[d] Cost of seeds derived from Coulibaly (2008)

[e] Legume management derived from Dugje et al. (2009)

There are several key points to consider with this finding. First, legumes such as cowpea can often be used as a cash crop to provide income for households. Second, legumes provide nutritional benefits as an important source of protein when consumed by households. Third, legumes return nitrogen to the soil, which over time can lessen the need to apply inorganic N fertilizers. Fourth, sorghum-cowpea intercropping is a traditional rotation in many regions of East Africa and can reduce *Striga* pest pressure (Carsky et al. 2010). Additionally, adding a legume to a rotation is the only management technique that adds N to the system using solar energy rather than fossil fuel energy. Fertilizer production is an energy intensive process and even in highly mechanized agricultural systems of the US Corn Belt, energy resulting from fertilizer production is >30 % of farm energy use in rain-fed maize systems (Kim et al. 2009). Assuming a cowpea seed yield of 820 kg ha^{-1} (Kaizzi et al. 2007) and seed N content of 4 % (Tagoe et al. 2010), sale of cowpea seed removes 16.4 kg N ha^{-1} of the N fixed during the

Table 4 Net return per ha (revenue − amendment cost) at median fertilizer application rate

Treatment	With mean yield improvement			With yield improvement at lower 95 % CI			With yield improvement at upper 95 % CI		
	Burkina Faso	Ethiopia	Zimbabwe	Burkina Faso	Ethiopia	Zimbabwe	Burkina Faso	Ethiopia	Zimbabwe
Nitrogen only (urea or NH_4NO_3)	$95	$73	$38	$61	$46	$11	$137	$109	$68
Nitrogen and phosphorus (NPK or DAP)	$80	$49	*−$41*	$26	$4	*−$81*	$142	$100	$4
NPK microdose	$81	$64	$51	$51	$37	$26	$117	$91	$77
Legume intercropping	$76	$60	$54	$38	$30	$26	$114	$90	$83
Legume rotation (sorghum and cowpea)	$146	$245	$263	$127	$230	$248	$165	$260	$277

Net revenue numbers are rounded to the nearest US $1.00. *Italics* indicate management incurs a net loss

CI Confidence Interval

Table 5 Sensitivity analysis: break-even cost of fertilizer based on estimated yield improvements and grain prices from Tables 2, 3, and 4

Treatment	With mean yield improvement			With yield improvement at lower 95 % CI			With yield improvement at upper 95 % CI		
	Burkina Faso	Ethiopia	Zimbabwe	Burkina Faso	Ethiopia	Zimbabwe	Burkina Faso	Ethiopia	Zimbabwe
Nitrogen only (urea or NH_4NO_3)	$2.25	$1.83	$1.28	$1.72	$1.41	$0.97	$2.91	$2.39	$1.63
Nitrogen and phosphorus (NPK or DAP)	$1.18	$1.44	*$0.46*	$0.77	$0.91	*$0.18*	$1.65	$2.04	$0.78
NPK microdose	$4.09	$4.88	$2.96	$2.78	$3.19	$1.88	$5.65	$6.56	$4.11

Italics indicate break even price occurs following a reduction in current fertilizer price

CI Confidence Interval

legume growing season (given our legume management scenarios which assume 0.5 ha of legume per growing season). Based on observed N fixation in African cowpea varieties ranging from 48–182 kg N ha^{-1} (Belane et al. 2014), the remaining root and shoot biomass would provide on the order of 7–75 kg N ha^{-1} to the field or for use as animal fodder.

The benefits of legumes in rotation need to be qualified; however, because they assume that farmers have access to cowpea seeds, can generate a significant return when planting cowpea, and have a place to market cowpea; this may be a large assumption for many farmers in Africa. Kerr et al. (2007) discussed uncertain market access, unstable legume prices, limited access to improved seeds, and insufficient research attention to multi-functional benefits of legumes as barriers to legume adoption. In their participatory research study of legume adoption in Malawi, Kerr et al. (2007) identified addressing soil nutrient deficiencies using more cost-effective technologies than fertilizer as a high priority for farmers. Kerr et al. (2007) documented increased farmer interest in legumes with farmer participation increasing from 183 individuals to over 3000 individuals in 4 years. Additionally, many farmers indicated that they successfully substituted legumes as an alternative to fertilizer application. Though farmers face challenges to incorporating legumes in a rotation, our results illustrate the potential benefits to including a legume such as cowpea in rotation with sorghum.

Across the inorganic nutrient amendment scenarios at a mean yield response, N-only amendment had the highest net return in Burkina Faso and Ethiopia, while NPK microdose amendment was most profitable in Zimbabwe. The returns to microdosing and N-only amendment are positive across all countries. The relatively high return to NPK microdose comes from the low level of fertilizer that needs to be applied in order to achieve the observed mean yields. The fact that microdosing targets fertilizer close to the root system of the plant cuts down on the amount that needs to be applied. This can be useful for farmers who are only able to purchase fertilizer in small quantities, due to income or credit constraints. The drawback to microdosing is that it is labor intensive compared to other forms of application, so may not be realistic for households who have limited family labor available and are unable to hire in labor from outside. Regardless, it is worth training farmers on the potential of microdosing, particularly in areas where fertilizer access and use is limited.

Amendment with N and P produced the lowest return among the four amendment scenarios for Ethiopia and Zimbabwe, and there was a net loss in Zimbabwe. In contrast, in high-yielding Burkina Faso, the N and P amendment had a favorable net return. Given the relatively high application rate of both urea and NPK that is needed to generate the mean yield increase in Table 2, the returns to N and P amendment were not favorable in regions with moderate to low sorghum yield. While fertilizer application is often the focus of discussion surrounding increasing grain yield in Africa (e.g., Mueller et al. 2012), this analysis of field data coupled to an economic assessment suggest that fertilizer application is not always a profitable scenario for smallholder farmers. Rather, optimal management will depend on regional environmental and market conditions.

Manure amendment showed great potential to increase yields and generate revenue for farmers across the three focus countries in this study. The costs and net profitability of manure were not calculated in Tables 3 and 4 because reliable application rates and cost information were not available and an agronomic and economic survey of manure use in households is beyond the scope of this research. Nevertheless, the positive returns in Table 2 suggest that it is worth considering wider promotion of animal manure. This is particularly the case in places like Ethiopia and Zimbabwe where livestock agriculture is widespread and farmers have access to animal manure. In places where livestock is less common programs that promote livestock rearing can have the double benefit of increasing incomes through livestock meat and products and increasing efficient use of nutrients through manure application to cropping systems. Increased use of manure also offers farmers a sustainable solution when credit constraints inhibit them from purchasing inorganic fertilizer on the commercial market. In addition, manure can be sourced locally compared to inorganic fertilizer which must be imported into much of sub-Saharan Africa at a high cost.

Part of the challenge in pricing manure management is that designing optimal manure management is complex and dependent on site properties. In a study of manure application in Zimbabwe, Zingore et al. (2008) demonstrated that the benefits of fertilizer or manure application depend on soil texture and nutrient management history. Compared to clayey soils, sandy soils accrued greater benefit from manure application as manure increased micronutrient availability and reduced nutrient leaching, both more prominent problems in sandy soils. Zingore et al. (2008) also discussed that simply adding inorganic fertilizer in African systems with poor fertility, especially low SOC, was not a long-term successful management strategy due to reduction in soil pH and insufficient focus on managing micronutrients, especially calcium. However, it is important to note that adding manure to soil can complement inorganic fertilizer, making it more effective at increasing yields through build up of soil organic matter (SOM) and resulting increase in cation exchange capacity (CEC), nutrient retention, and pH (Zingore et al. 2008). After 9 years of manure application in this Zimbabwe system, Rusinamhodzi et al. (2013) reported long-term manure application resulted in improved soil fertility by increasing SOC content in both clayey and sandy soils. Increased SOC benefits crop productivity by improving moisture retention (especially in sandy soils), nutrient retention, and soil structure. Manure addition also improved yields by increasing water infiltration on clayey soils.

Though manure amendment has many benefits, manure application is not always readily practiced. Rusinamhodzi et al. (2013) assessed that farmer access to manure was only sufficient to supply a fraction of their landbase; therefore, farmers strategically use manure on home fields to reap the best yields. In a survey of smallholder manure usage in South Africa, Materechera (2010) identified lack of labor and transportation as limitations to manure management. Adoption of manure application practices was also limited due to reduced manure quality (resulting from poor storage facilities and technical knowledge), as well as farmer concern that manure application led to higher infestation with weeds, insects, and worms. While manure has many long-term soil improvement benefits, especially increased SOC, depending on storage prior to application, much of the manure N content can be lost through leaching or volatilization, making manure application insufficient for supplying total crop N needs.

Table 5 provides a sensitivity analysis for the fertilizer price that allows farmers to break-even in Burkina Faso, Ethiopia, and Zimbabwe for each nutrient amendment. Since the price of inorganic fertilizer fluctuates across countries and over time, it is important to estimate a range of how much the price per kilogram of each nutrient amendment can increase (or decrease in a few scenarios) and still allow farmers to break-even (make zero profits). In order to give a realistic range and provide useful site specific information, we run the sensitivity analysis for the mean yield improvement along with the lower 95 % confidence interval yield improvement and the upper 95 % confidence interval yield improvement. The sensitivity analysis presented in Table 5 is itself a simplification because it assumes that farmers do not adjust input use as input prices change. Nevertheless, the results of Table 5 demonstrate that given the yield increases from different amendment strategies found in this meta-analysis, many of the amendments will remain profitable with fairly substantial increases in fertilizer prices, and no change in input use.

3.5 Contextual agricultural development

Our analysis focused on the role of nutrient amendment in supporting crop yield and farmer profit. In addition to promoting access to nutrient amendments, agricultural development must consider ecological needs regarding pest management and uncertainty from climate change, as well as farmer socio-economic and cultural needs.

Pests such as *Striga* and stem borers can have devastating consequences for grain yield throughout Africa. In addition to herbicide application (Carsky et al. 1994; Tuinstra et al. 2009) and the use of fungal spores (Marley and Shebayan 2005; Venne et al. 2009), crop rotation has been demonstrated to control *Striga* and improve yield. Carsky et al. (2010) demonstrated maize-soybean rotations reduced the *Striga*-derived yield decline in maize relative to a continuous grain rotation; the authors suggest the control mechanism is soybean reduction of the *Striga* viable seedbank by exuding a germination stimulant. De Groote et al. (2010) and Khan et al. (2008) compared yield and profit across maize monoculture and push-pull rotations for *Striga* and stem borer control, including rotations with green manures. Cropping system complexity was demonstrated to improve grain yield and cropping system profitability. Kfir et al. (2002) identified intercropping, crop residue management, and manipulation of sowing dates and densities as successful measures against stem borer infestation. Nutrient amendment which diversifies crop rotation or promotes incorporation of plant residues has the potential for co-benefits with regard to pest management. A 20-year study of *Striga* control (Ayongwa et al. 2010) showed infestation increased across sorghum and maize crops. However, the study also showed that the level of *Striga* infestation did not strongly correlate to yield decline. Instead, the impact of *Striga* infestation appeared to be compounded by poor soil fertility. Over the study period, pressure to increase yields reduced fallow periods and increased cereal mono-cropping, both of which facilitate *Striga* infestation. These studies demonstrate that management strategies must consider the multi-dimensional challenges to sorghum yield improvement.

A systems approach to managing agricultural landscapes aims to improve field conditions for multiple environmental drivers of crop growth and is often focused on improving crop yield by supporting biological processes in the rhizosphere. Integrated Soil Fertility Management (ISFM) embraces a systems approach and is widely adopted as a driving philosophy in the African Green Revolution (Vanlauwe et al. 2012; Vanlauwe 2013). Crop residue management and diversified rotations are two main techniques for promoting rhizosphere processes. For example, crop residue management improved cereal growth in Sahel regions by increasing P availability, increasing root growth, decreasing soil erosion, and improving OM retention (Buerkert et al. 2000). Use of cereal-legume rotations changed soil biological and chemical properties relative to soils in continuous grain rotations, in particular, promoting increased mycorrhizal infection rates and increased P access (Alvey et al. 2001). Strategic use of N-fixing tree species can also improve plant nutrient access and crop yield (e.g., Payne et al. 1998; Wilson et al. 1998). A recent review by Bayala et al. (2012) quantified the yield impact of various conservation agriculture techniques, demonstrating a significant sorghum yield improvement under management including green manure, diversified rotations, and mulching. Strategic crop diversification and residue management can improve biological, chemical, and physical rhizosphere properties resulting in improved plant access to nutrients.

Adoption of innovations against vulnerability is a key strategy for climate resilience in drought-susceptible Sahelian regions and the need for water management is magnified by soil degradation (Barbier et al. 2009; Stroosnijder 2009). A review of crop models by Kang et al. (2009) emphasized that crop yield can decline due to water stress from reduced precipitation as well as increased evapotranspiration resulting from increased temperature. A variety of water management strategies are available to African farmers. Improved plant available moisture was observed under OM amendment, hedgerow, and stone row management (Stroosnijder 2009), as well as under intercropping (Oluwasemire et al. 2002). Conservation agriculture techniques—including residue management, diversified rotations, and reduce tillage—have demonstrated the potential to improve soil nutrient and moisture availability, and ultimately improve crop growth when management is appropriately designed for field environmental conditions (e.g., Rusinamhodzi et al. 2011; Siddique et al. 2012; Thierfelder et al. 2012, 2013; Thierfelder and Wall 2009). Recent work by Traore et al. (2014) identified how grain crop varieties and planting dates can be selected to optimize yield under variable rainfall patterns and access to fertilizer. These studies demonstrate that nutrient management and improved water use efficiency are complementary goals to buffer agricultural productivity against climate and population pressure on the agricultural land base.

Work by Jones and Thornton (2009) emphasized that enhancing food security will include livelihood transitions in addition to improved crop productivity. Their analysis of downscaled climate predictions for sub-Saharan Africa identified regions where increased likelihood of cropping failures should be buffered by increasing the dependence on livestock farming. Using farmer surveys to analyze farmer response to climate variables, Seo (2010) similarly concluded that higher diversity in farm management is a likely response to mitigating climate change risk. Multiple studies suggest that increased farm diversity is an important component of reducing farmer risk to environmental variation and resource constraints (e.g., Rufino et al. 2006; Valbuena et al. 2012), implying that opportunities for farmers to include diverse rotations and manure management as nutrient amendment strategies are important components of sustainable agricultural management.

This meta-analysis suggests adding legumes to a sorghum rotation can be profitable and ecologically beneficial for farmers; however, this recommendation needs to be viewed in light of farmer interests outlined in participatory research. For instance, Snapp et al. (2002) found farmers in Malawi identified maize-legume rotations as having advantages including less labor and land for two crops, easier weed control, increased food security, fuelwood production, improved soil fertility, and cash sales potential. However, farmers also experienced challenges implementing these diversified rotations including seed availability, slow legume growth or late harvest, livestock damage, low grain legume price, and limited market access. In a national-scale study of the potential of diversified systems in Malawi, Snapp et al. (2010) highlighted the need to choose appropriate legumes when developing diversified cropping systems, in particular, legumes that perform well on degraded soils and have economic or livelihood value for the farmer. In this Malawi study, farmers preferred legume systems to maize monoculture, including short-duration grain legumes (peanut or soybean), intercropping (maize-pigeonpea), and semi-perennial systems of maize—*Mucuna pruriens*, with the strongest preference for the *M. pruriens* system (despite its less palatable biomass, *M. pruriens* growth form has minimal interference with maize crop growth and produces abundant biomass). This participatory research demonstrated that developing cropping systems that are ecologically beneficial as well as socio-economically useful requires a significant engagement with stakeholder communities to assess farmers' cultural and economic needs.

4 Conclusions

We conducted a comprehensive review of sorghum response to different nutrient amendment scenarios in sub-Saharan Africa using meta-analysis (a robust quantitative tool for synthesizing compiled experiments to summarize aggregate trends). Our study synthesizes data representing a range of environmental conditions as well as a range of management options available to farmers. In addition, we combined these ecological outcomes with economic examples of how management costs, revenues, and net profits differ given recent prices for farm inputs and grain sales. We demonstrated that nutrient amendments generate significant yield improvements for sorghum cropping systems across sub-Saharan Africa, with yield improvements ranging from a 45 to 100 % increase in yield relative to no nutrient inputs.

Our analysis demonstrated increased sorghum yields when farmers apply inorganic fertilizer. Furthermore, inorganic fertilizer inputs using microdosing management techniques were demonstrated to have a significant financial advantage in an environment where sufficient labor is available. These results are in general agreement with the rationale for the 2006 Abuja Declaration, where many African governments committed to helping smallholder farmers increase the use of inorganic fertilizer, mainly through subsidizing the price of the input. As a result, fertilizer use has increased among smallholders in a number of African countries over the past few years, particularly for maize cultivation (Sheahan and Barrett 2014). However, while fertilizer use has increased, yields and response rates among African smallholders remain low, raising questions about the cost-effectiveness of providing subsidies for inputs (Jayne and Rashid 2013).

Various studies suggest that limiting agricultural management to focus only on inorganic fertilizer is insufficient to improve long-term yields on degraded soils (e.g., Jayne and Rashid 2013; Rusinamhodzi et al. 2013; Zingore et al. 2008). Our results highlighted that yields can also be improved by adding manure to soil or adding legumes in rotation, and for some cases, legume management was a particularly profitable scenario. Legume rotation also provides a source of protein-rich grain, improves soil nutrients reducing the need for inorganic N fertilizer over time, and has been demonstrated to control *Striga* infestation. The benefits of including a legume in rotation—which extend beyond improvement in grain yield—suggest the need for a systemic evaluation of how agricultural management strategies can improve farmer livelihoods. Our results and the systemic agricultural intensification concept of management support the ISFM strategy for improving yield and farmer livelihoods that is currently being promoted by The Alliance for a Green Revolution in Africa (AGRA).

While we demonstrated in this study that multiple nutrient amendment tools significantly improve sorghum yield, the appropriate nutrient strategy depends on (1) farmers' access to fertilizer, manure, seeds, labor, and credit; (2) the need for households to produce nutritionally balanced foods on-farm; (3) the extent of soil degradation: (4) the need to coordinate nutrient amendment with pest management strategies; and (5) farmers' increasing need to manage for climate change and other environmental risks. Due to its adaptation to African climatic patterns, especially tolerance of climatic extremes including drought and water-logged soils, sorghum is an important grain to consider for reducing risk under climatic uncertainty. This interdisciplinary analysis indicates potential benefits of supporting research and extension outreach to farmers that includes a broad range of sorghum management practices to simultaneously promote farm productivity and profitability.

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