On-farm trials identify diverse adaptive management options for rainfed production in semi-arid West Africa

Abstract

Rainfed crop production is the primary means of food security and income generation for rural households in semi-arid West Africa, which contains a high level of agro-ecological and socio-economic heterogeneity. Official management recommendations focus on the use of purchased certified seed and inorganic fertilizers, but are based primarily on highly controlled on-station trials that do not capture the heterogeneity and complexity of on-farm conditions. This study established hundreds of on-farm field trials across Senegal and The Gambia that tested integrated practices related to seeds, inorganic fertilizers, and organic amendments. All treatments were found to reliably increase yield and many had a greater effect than the recommended practice, which was not highly valued by farmers. These findings suggest that recommendations should focus on multiple "better" options rather than singular "best" practices, and should encourage farmers to adapt based on their individual circumstances and preferences.

Author Bio

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Introduction

Agriculture is the deliberate manipulation of complex ecological systems to meet social needs and interests, a goal-driven effort that is highly constrained by economic and agronomic circumstances (Shennan 2008). These managed ecosystems are under increasing stress throughout the world due to a diverse range of interacting factors, such as population growth, competing land uses, and climate change (Foley et al 2011). The management decisions of independent farmers are a critical fulcrum for adapting to these stressors, and improved practices have the potential to meet broad social and environmental goals while also providing immediate economic benefit through more efficient production (Thompson and Scoones 2009). Accordingly, a key function of agricultural research is to inform adaptive decision-making by testing alternative management practices (Vanlauwe et al 2016).

However, the role of research in influencing alternative management decisions is often prescriptive, with farmer-driven adaptation presumed to be analogous to the adoption of official recommendations regarding "best" practices, "improved" varieties, "proven" technologies, and "right" fertilization strategies (Chambers and Jiggins 1987a, Le Gal et al 2011). These recommendations are developed primarily from replicated small plot experiments conducted on research stations, where alternative management practices are compared under highly controlled conditions (Vanlauwe et al 2016). The design, management, analysis, and interpretation of these trials are typically performed by researchers, often with a focus on maximizing yield per unit area. Farmer involvement in these steps is often limited or negligible. The resulting recommendations are then extended beyond the tested locations and conditions, under the dual assumptions that the research trials have effectively captured the complexity and heterogeneity of the targeted production system and that the adoption of the resulting recommendations will be reliably adaptive (Hounkonnou et al 2012).

The practice of relying on highly controlled on-station trials to generate management recommendations is increasingly being called into question, particularly when adoption proves to be maladaptive for a significant subset of the targeted farmers (Vanlauwe et al 2016). This breakdown may often result from avoidable issues, such as inadequate research investment, misinterpretation of trial results, and competing social, political, or economic forces influencing the final recommendations (Evenson and Gollin 2003). However, there are additional methodological concerns, including potential confounding effects resulting from the small scale of most on-station plots (Kravchenko et al 2017), unique or non-representative agro-ecological conditions at research stations (Vanlauwe et al 2016), and deliberate release from constraints that are often unavoidable in production systems, such as weed pressures and input limitations (Giller et al 2011). The emerging understanding of complex systems also undermines the notion that multivariate interactions can be effectively reduced to and then predicted from investigations of select composite interactions under highly controlled conditions (Liu et al 2007). While such trials remain appropriate for assessing possible causal mechanisms within homogeneous and well-studied systems, they may often be inappropriate for predicting probable complex system behavior and exploring heterogeneous and under-studied systems (Scoones et al 2007).

An increasingly popular alternative is to conduct collaborative on-farm experiments that embed alternative management practices within the complex production system of interest (Vanlauwe et al 2016). Such on-farm trials have a long history in agronomy as a demonstrative method, but only more recently, with the development of new statistical methods and advanced modeling capabilities, have they become appreciated for their research potential (Knapp 1909, Johnson et al 1994, Krupnik et al 2015). With sufficient replication at the field level and adequate representation of relevant social and spatial heterogeneity, on-farm trials can effectively capture the complexity of the targeted production system and be used to inductively generate management recommendations (Krupnik et al 2015). This aspect makes them highly complimentary to highly controlled trials investigating associated causal mechanisms, and an increasing number of studies directly integrate the two approaches within a single study, such as through a "mother-baby" design (Snapp 2002).

On-farm research trials may be particularly appropriate within developing countries, where the production systems are often more heterogeneous and understudied than the industrialized high-input systems that have been the primary focus of agricultural research in the last century (Vanlauwe et al 2016, de Roo et al 2017). In addition, these countries often have fewer resources to allocate to agricultural research, which can result in less prior knowledge of the system to inform the experimental design, greater reliance on reductionist assumptions during the interpretation of results, and an increase in the likelihood of over-extension of recommendations into untested and inappropriate conditions (Chambers and Jiggins 1987a, Scoones et al 2007). While the use of on-farm research trials in developing countries is increasing, they remain an unconventional approach and are rarely incorporated into national and international research programs (Snapp et al 2003).

Study Location

Agricultural recommendations for smallholder farmers in sub-Saharan Africa often focus on 1) improved germplasm, 2) purchased inorganic fertilizers, and 3) local organic materials (Evenson and Gollin 2003, Vanlauwe et al 2014). These entry-points for alternative management are increasing recommended in combination, such as through the Integrated Soil Fertility Management (ISFM) paradigm, which encourages the pursuit of all three adaptive pathways to maximize yield per unit input (Vanlauwe et al 2010). However, such general directives are not sufficient to directly inform adaptive decision-making by farmers, as each pathway can be pursued through a wide range of specific management practices that vary widely in costs, benefits, risks, and constraints (Place et al 2003). Conventional highly-controlled research trials can provide valuable information about specific practices or combinations, such as maximum attainable yield, but alone are not sufficient to prioritize among alternative options and to investigate the relative influence of variable socio-economic and agro-ecological conditions on alternative practices.

The countries of Senegal and The Gambia span the semi-arid Sahel and Savannah zones along the West Africa coast, and rainfed crop production is the primary means of both subsistence and income generation for the majority of rural households (Nyong et al 2007). However, short rainy seasons with low annual rainfall and high spatial and temporal variability make these production systems prone to significant climate-induced crop loss or failure (Sivakumar et al 2005, Eldon and Rapaport 2017). This problem is exacerbated by naturally sandy and low organic matter soils, limited market access, and changes in population density and land tenure practices that restrict historical crop rotation and annual migration strategies (Raynaut 2001, Baro and Deubel 2006). Accordingly, there has been significant national and international investment in agricultural research to support farmer-driven adaptation, with Senegal becoming a regional leader in semi-arid cropping systems research (Fall and Thiongane 2005).

This agricultural research in Senegal and The Gambia has primarily consisted of highly controlled small-plot studies, the majority of which have been located on research stations within the “peanut basin” of central Senegal (Ba et al 2005, Ndiaye et al 2005). The resulting official recommendations are focused predominantly on the use of certified seed of newly developed cultivars and on the application of inorganic fertilizers. Many of the recommended cultivars were developed locally through the Senegalese Institute of Agricultural Research (ISRA) and related organizations, and locally produced and certified seed stock is now commercially available throughout Senegal (Fall and Thiongane 2005). Recommended rates of inorganic fertilization vary by crop, region, and recommending organization, but are typically a pre-plant rate of 150-200 kg/ha compound NPK, with an additional top-dress of 150-200 kg/ha urea for cereals (Posner and Crawford 1991, Khouma et al 2005). Organic amendments, particularly animal manures and crop residues, have been tested and often found beneficial to crop production, but are not commonly part of official management recommendations.

Despite decades of promotion, these “best practice” management recommendations are not common in production fields (Khouma et al 2005). The majority of farmers in these two countries instead rely on seed that is privately saved from the previous season, obtained from neighboring farmers, or purchased at local uncertified markets (Niangado 2010). Inorganic fertilizers are widely available throughout both countries, but are primarily applied only to high-value commercial crops such as vegetables (Khouma et al 2005). The average application rate of inorganic fertilizer on arable land in 2014 was only 6.7 kg/ha in Senegal and 5.6 kg/ha in The Gambia (FAOSTAT 2014). Widespread economic constraints on the use of purchased inputs suggests that the recommended rates may be financially impossible for many farmers, and limited on-farm trials have found adoption of these practices to have mixed results (Posner and Crawford 1991, Khouma et al 2005). The current recommendations may therefore by largely impractical for this region, and performance under highly controlled conditions a poor indicator of the adaptive potential of adoption.

This study provides a large-scale on-farm compliment to the existing on-station research through the establishment of a network of field trials that compare current farmer practices for rainfed crop production against seventeen integrated treatments related to improved germplasm, inorganic fertilization, and use of local organic materials. This applied research is a direct test of the existing management recommendations and has the potential to inductively identify alternative "recommendation domains" tailored to specific crops, conditions, and constraints (Hildebrand 1984). These on-farm field trials also demonstrate alternative management options to surrounding farmers, thereby complimenting conventional extension efforts in the region, and encourage farmer learning and adaptation through supervised experimentation (Chambers and Jiggins 1987a).

Methods

Nearly 600 field trials targeting five common rainfed crops were established in 2015 and 2016 in seven regions that span the environmental heterogeneity of Senegal and The Gambia (Table 1, Figure 1). The trial design consisted of overlapping strip plots of 1) cultivar (new, local), 2) inorganic fertilization (high, low, zero), and 3) organic amendment (manure, crop residue, none), resulting in 18 non-replicated 5m X 10m treatment plots per trial (Table 2). Trials were managed by participating lead farmers, who were identified through partner rural organizations in each region and split evenly among 4-6 community clusters per region. Each lead farmer provided the seed for the "local" cultivar of their trial, and a single "new" cultivar for each crop was selected jointly by the participating organizations from among the nationally certified and commercially available options. The inorganic fertilizers used in all trials were 15-15-15 NPK, the most widely available compound fertilizer, and urea (46-0-0). The organic amendments were air-dried cattle manure and millet husks, the crop residue from threshing (Table 2). The "new" cultivar seeds and inorganic fertilizers was purchased through nationally licensed dealers in Senegal and distributed to participating lead farmers, who collected the organic materials locally and hand-pulverized the manure. The NPK and organic amendments were broadcast immediately prior to planting and lightly incorporated through the use of horse or donkey drawn seeders. Urea was applied as a top-dressing to the cereal crops approximately 3 weeks after emergence. Regional field officers supervised the site selection, establishment, amendment and fertilization, and harvest of the trials, while the lead farmers provided the necessary labor and made all planting and in-season management decisions. Harvest was assessed within each plot as 1) yield, as dry cleaned seed weight per area, and 2) maturation success, as number of harvested plants per area. These were used to calculate 3) plant vigor, as dry seed weight per harvested plant. Relative treatment effect was calculated for each plot within each trial as the percentage difference from the adjacent no-input local cultivar control plot.

Surveys were conducted of participating households in 2016 prior to planting for socio-economic conditions and post-harvest for perspectives on the alternative management practices. An equal number of neighboring households conducting cultivar-only trials (data not shown) were also surveyed in each regional cluster, as they had attended all training and discussion meetings associated with this project and the majority had conducted the described cultivar-fertility trials in 2015. All interviews were conducted by the regional field officer with the male or female member of the household who oversaw management of the target crop.

Rainy season characteristics were estimated from the daily 10km resolution African Rainfall Estimation Algorithm 2.0 (RFE2) dataset using a single pixel centered within the regional community clusters or individually within each cluster when they were more widely dispersed (Xie and Arkin, 1996). Select rainy season characteristics were calculated for 2015, 2016, and the average of 2001-2016, using the period between the first and last days of a year with a minimum of 10 mm/day, with correction for isolated offseason storms. Regional cropland soil characteristics were estimated from an overlay of the European Space Agency Climate Change Initiative (ESACCI) land use map and the Africa Soil Information System (AFSIS) spatial model (Bontempts et al 2013, Hengl et al 2015). Political insecurity was calculated as the number of conflict events and resulting fatalities within each region from 1997-2016, as reported in the Armed Conflict Location and Event Data (ACLED) database (Raleigh et al 2010).

Soil was sampled in August 2016 from each active trial to a depth of 15 cm and bulked from four representative locations. Analysis was conducted at a laboratory established through an agricultural cooperative in central Senegal. Soil pH was measured from 15g of air-dried soil in 1:1 ratio with distilled water. Percent soil organic matter was calculated from weight loss on ignition of 5g of oven-dried soil (100C) after four hours at 500C. Percent sand was calculated from the weight loss of

100g of oven-dried soil following a 12-hour soak in distilled water, wet sieving by hand through a 0.53mm sieve, and re-drying at 100C.

Trials were analyzed within a Bayesian generalized linear model (GLM) framework using the above measures as predictor variables and yield and maturation success as outcome variables. Selection between competing model variations of additive predictors was performed using the Watanabe-Akaike information criterion (WAIC), which balances the explanatory value of each additional variable against a penalty for over-inclusion (Watanabe 2010). Direct effects of all treatment variables (cultivar, inorganic, organic) and biologically critical variables (crop type, cultivar-crop nested effect) were fixed in all compared models. All other measured variables, selected interaction effects, and multilevel structures by study region and individual trial were iteratively assessed using WAIC.

The primary models estimated absolute harvest measures and relative treatment effect directly from a multivariate normal additive model, i.e.

$$[yield\_i,\ matsuc\_i] \sim MVN\ ([u\_yield\_i,\ u\_matsuc\_i],\ \Sigma)$$

where u_yield_i and u_matsuc_i are the respective means of plot i and are log-linked additive functions of predictor variables for plot i, and Σ is the standard variance-covariance matrix of the multivariate normal distribution. Relative magnitude and variability was assessed for the coefficients of all modeled variables, absolute yield and maturation success was estimated for all eighteen management treatments, and relative treatment effect was estimated for all seventeen alternative treatments. Due to the limited sample size and crop/region imbalance, these models were not used to estimate absolute yield for specific crops, treatments, or regions.

Additional secondary models transformed yield and maturation success into treatment difference variables by subtracting the corresponding control plot harvest measures from the observed outcomes in all treatment plots,

$$yield\_diff\_i = yield\_i - yield\_control\_j$$

$$matsuc\_diff\_i = matsuc\_i - matsuc\_control\_j$$

where *control_j* is the control plot corresponding to plot *i*. These new outcome variables were modeled with the same equations as the primary models, with the addition of the control plot yield/maturation success included both as a solitary additive effect and as an interaction effect with the treatment variables. This allowed for the relative treatment effect to be compared against the control plot harvest measures, which are used as a proxy for underlying field productivity.

Results:

Regional baseline analysis:

Average rainy season characteristics from 2001-2016 within targeted regions varied from 313 mm over 78 days in Louga to 855 mm over 100 days in Ziguinchor, with a corresponding north-south gradient in the regularity and intensity of rainfall events (Table 3). Rainfall at the specific trial locations during 2015 and 2016 varied from a low of 254 mm over 71 days in Matam to a high of 748 mm over 102 days in Ziguinchor. Modeled and in-field soil analysis identified strong corresponding latitudinal gradients, with percentage sand and pH higher in the north and soil organic matter higher in the south (Table 4). Population density, percentage of land under cultivation, and population density relative to area under cultivation were highest in the central and otherwise intermediary regions of Thies and Kaolack (Table 5). Political insecurity was highest in the Ziguinchor region, where nearly 1000 fatalities have been reported since 1997 as the result of over 300 distinct events. Select spatial patterns are shown in figure 2 and more detail in Eldon and Rapaport (2017). The socio-economic resources of participating farmers were found to be highly variable within and among all regions (Table 6).

Farmer Field Trials

Harvest was assessed for approximately 44% of the trials due to issues that are common to production fields and on-farm trials, including drought, erosion, pest damage, and insufficient labor, supervision, or cooperation (Table 1). These factors could not be adequately distinguished from each other, or from crop failure related to the experimental treatments. Descriptive analysis of the harvested trials across all crops, regions, and years found all seventeen treatments to have positive effects on yield in the majority of the trials (Table 7). The least effective treatment was adoption of the new variety alone, which increased yield in 69% of the trials with an overall median increase of 28% over the corresponding control plot. The most effective treatment was the combination of the new variety with manure and high inorganic fertilization, which increased yield in 90% of the trials with an overall median increase in 168%. The general trends observed in yield are reflected in both maturation success and plant vigor (Table 7).

Analysis of the coefficients of the primary GLMs for yield found all five individual management options—adopting a new variety, amending with crop residue or animal manure, and applying high or low levels of inorganic fertilizers—had strong positive treatment effects across all studied conditions (Figure 3). The organic and inorganic soil amendment treatments had low variability, while the effect of adopting a new cultivar, which averaged across the six crops and a wide range in quality and variety of the local comparison, was more variable. The coefficients of the treatment interactions were zero or slightly negative, indicating that these five alternative practices had additive or slightly less than additive effect when used in combination. Political insecurity and total annual rainfall were both found to have a positive interactive effect with cultivar, while season length had a negative interactive effect. Other measured variables had little or no explanatory value.

Analysis of the coefficients for maturation success found similar overall patterns with some notable differences (Figure 3). The effectiveness of the soil amendment treatments were considerably lower for maturation success than for yield, with crop residue having no effect, while the cultivar coefficient was slightly higher but also more variable. Positive treatment interactions were seen for crop residue and cultivar, for manure and high inorganic, and for crop residue and low inorganic. The interactive effects of insecurity and total annual rainfall on cultivar were lower than for yield but remained positive. The differences between the coefficients of yield and maturation success indicate a variable treatment effect on plant vigor, which was not modeled independently as it was not measured directly.

Probability density functions of treatment effect allows for more nuanced comparisons among the individual and integrated soil fertility treatments, all of which led to positive increases in yield over the control no-input treatment when assessed for the local cultivar (Figure 4a). High inorganic fertilization had the greatest effect of any single practice in isolation, with a mean increase of +105%, which was nearly identical to the effect of low inorganic with crop residue. High inorganic in combination with crop residue increased the mean effect to +155% of the control and in combination with manure to +200%. Probability density functions of resulting absolute yield showed the same rank order as the relative treatment effect, but much greater overlap among the treatments and the no-input control (Figure 4b).

Linear regression analysis of the secondary models found an increase in the treatment effect of both manure and high inorganic fertilization with increasing field productivity, as measured by the yield of the corresponding control plot. However, the data contained limited representation and high variability among the higher yielding fields, leading to large confidence intervals. No clear interaction was seen between underlying productivity and low inorganic fertilization or crop residue (Figure 5).

Farmer surveys

Surveys of participating farmers identified high variability in the initial valuation of alternative practices both within and among regions (Tables 8-9). Burning in-field crop residue was the most highly valued soil fertility management practice prior to participation, and saving seed for replanting was the most highly valued seed management practice. Perceptions changed dramatically with participation, which resulted in an increase in perceived value for nearly all management practices related to the experimental treatments. The exception was field burning, which decreased in perceived value from a combined average of 2.1 to 0.8, where 0 is no value and 3 is high value. The perceived value of the organic amendments changed the most in Ziguinchor, where the regional average increased from 0 to 2.5 for manure amendment and 0 to 2.4 for crop residue amendment. The perceived value of inorganic fertilizer following participation was lowest in this southern region (0.6) and highest in the more arid north (Louga = 2.6, Matam = 2.4).

Saving seed for replanting remained the most highly valued means of seed management, but the perceived value of purchasing new certified seed stock increased dramatically in all regions. Of the three adaptive pathways, farmers on average prioritized improved germplasm and organic amendments over inorganic fertilizers in all regions.

Discussion

This network of on-farm trials identified diverse alternative management practices that reliably increased rainfed crop production across Senegal and The Gambia despite high underlying social and spatial heterogeneity. The relative benefits of adopting certified seed stock of new cultivars, applying high or low rates of inorganic fertilizers, and amending the soil with crop residue or animal manure each on average far outweighed the potentially mitigating influence of variability in rainfall, soil characteristics, crop management practices, field history, and other variables. The relative increase in yield was comparable among these alternative practices when they were applied in isolation, differing by a factor of 2.6, and they were found to have largely additive effects when practiced in combination. Despite the reliability of the relative increase with adoption, these management practices were not good predictors of resulting yield due to the high underlying variability.

These results suggest that there is not sufficient justification for the current official management recommendation to be considered the general "best practice" in this region. The use of certified seed of new cultivars and a high rate of inorganic fertilization on average resulted in nearly twice the yield than the current practices, so it is certainly not a useless practice. However, it is unlikely to be the most efficient or widely appropriate option, as this effect could also be achieved though multiple alternative practices, such as by using current seed stock and one-third of the recommended inorganic fertilization in combination with manure. It was also not the most productive option, as the additional amendment of 3000 kg/ha of manure nearly doubled the effectiveness of the recommended management strategy. The current recommendations may be suitable for farmers with high cash flow and poor access to organic materials, but the prioritization by participating farmers for organic materials and high-quality seeds over inorganic fertilizers suggests that this is not a widespread situation. The current recommendations are therefore likely a reflection of the biases and limitations of relying solely on highly controlled trials to generate predictions within a complex production system.

Rather than select a new "best" practice for this complex and heterogeneous production system, official management recommendations in this region should focus instead on the range of reliably "better" alternative practices and leave it to farmers to individual select among them. This conclusion of suggestions rather than prescriptions might be problematic if it were not evident that participating farmers were actively interpreting the field trials and drawing personalized conclusions. Such interpretation is clear in the dramatic shift in perspective following participation, which included related practices that were not directly tested, such as tethering livestock and refraining from burning in-field crop residue. The follow-up surveys also revealed high variability in valuation among neighboring individuals, which indicates that farmers are already making individual calculations without any statistical analysis or direction from researchers. This information also provides a feedback opportunity whereby farmer input might drive organizations seeking to encourage farmer adaptation. In the conflict zone of Ziguinchor, for example, the perceived value of the organic amendments was negligible before the trials but high after participation, which suggests that this might be a particularly appropriate adaptive pathway in this region and worth targeted promotion by relevant organizations.

This conclusion that farmers in Senegal and The Gambia have diverse adaptive management options demands a critical reassessment of some common assumptions regarding farmer adaptation in sub-Saharan Africa. For example, these smallholder systems are often discussed as if alternative management practices can have little relative influence on crop production, which is instead primarily driven by environmental conditions that are beyond the control of farmers (Knox et al 2012). Alternatively, it is also often assumed that increasing productivity requires capital-intensive practices, such as heavy reliance on chemical inputs and mechanization, or that high-yielding fields are nearing a production ceiling and require radically new technologies, such as genetically modified cultivars (Evenson and Gollin 2003). Finally, it is not uncommon to hear that low-yielding fields are unresponsive to alternative management practices and therefore not worth further investment (Paarlberg 2012). The failure of these scenarios to effectively describe semi-arid West Africa suggests that such conclusions may be overstated in other locations and production systems.

Advocates of farmer-led adaptation in sub-Saharan Africa are increasingly aligning behind the Integrated Soil Fertility Management (ISFM) paradigm (Vanlauwe et al 2010). However, this study of the three management pathways that make up ISFM—improved germplasm, inorganic fertilization, and organic soil amendment—emphasizes the need for a nuanced application of these underlying ideas. First, it is often stated by IFSM proponents that the integration of these three adaptive pathways will result in an interactive effect, with the combination of practices increasing yield by more than the sum of each in isolation. While there is theoretical support for this expectation, such as increased soil organic matter resulting in higher nutrient use efficiency of inorganic inputs, this study found the combined effects to be additive or slightly less than additive. Second, these proponents often emphasis “complete IFSM,” where farmers simultaneously pursue all three adaptive pathways (Vanlauwe et al 2010). While the corresponding treatment in this study (new seed/high inorganic fertilization/manure) did result in the greatest treatment effect across these trials, it was also the most intensive practice and possibly the least applicable across the region, given the high variability in input access, financial capital, labor availability, and other relevant factors. Given comparable benefits and no interactive effect among the alternative pathways, it would be more appropriate to encourage farmers to prioritize among these pathways based on personal cost and risk assessment. Third, IFSM emphasizes the importance of tailoring management practices to local environmental conditions, such as distinguishing between “responsive” versus “unresponsive” soils. While this is again a theoretically well-supported concept, the results of this study caution against making deductive assumptions regarding the importance of specific variables. For example, soil characteristics and rainfall patterns, though both clearly relevant to crop production, were in fact poor predictors of the effectiveness of the alternative management practices. These results also suggest that the threshold for unresponsive conditions may in some circumstances be far lower than is often assumed, and in such cases the use of untested demarcations could hinder rather than promote adaptation. The findings of this study therefore support ISFM as a general framework for empowering farmer adaptation, but caution against the underlying principles being used to generate recommendations in lieu of ground-truthing research.

While these embedded on-farm experiments are best suited for identifying general patterns of response to alternative management options, these results do suggest relevant underexplored causal processes. For example, millet husks have largely been overlooked as a potential soil amendment, both by farmers in Senegal and The Gambia, who often burn the piles, and by researchers, who have instead focused primarily on their potential value as a biochar substrate (Raveendran 1995). Although these fibrous husks have low immediate nutrient value, they have been found to be particularly effective for reducing soil bulk density and increasing water holding capacity and crop water use efficiency (Tarafdar 2003, Anguria et al 2017). This function could be highly beneficial in sandy soils and semi-arid climates, and might account for why amendment with 3000 kg/ha millet husk had roughly the same effect on crop yield as low rates of inorganic fertilization. This equivalence is a strong indication of the complexity of soil processes relating to crop growth and the variety of ways in which soil ecosystems can be manipulated to increase production.

To conclude with multiple adaptive options rather than prescriptive “best” practices is not to admit investigative defeat in the face of complexity and heterogeneity, but to provide immediately practical results until more explicit conclusions are possible. Increased trial numbers and higher resolution measurement of relevant social and environmental factors might allow for future recommendations to be fine tuned to specific agro-ecological and socio-economic conditions, such as for farmers in drier regions with little available labor or those in wetter regions with high access to organic amendments but little purchasing power. In the meantime this interpretation encourages farmers to make individualized decisions based on their own understanding of their circumstances. This conclusion does not diminish the role of agricultural research in driving farmer adaptation, but rather embraces a complimentary role for farmer knowledge as a replacement for problematic simplifying assumptions and the methodological removal of relevant complexity and heterogeneity from the research design. This approach, which relies on farmer field trials as a primary research method, has the potential open new avenues of agricultural research and empower farmer adaptation in new ways, and is particularly well suited to the complex and heterogeneous agricultural systems found in sub-Saharan Africa.

Tables:

Table 1) Total number of community clusters, trials established, and trials harvested per year and region, and crops targeted within each region in 2016.

Region	# Clusters 2015/2016	# Trials Established 2015/2016	# Trials Harvested 2015/2016	2016 Crops					
				Groundnut	Cowpea	Millet	Maize	Rice	Sorghum
Louga	4/4	30/48	16/33	X	X	X			X
Matam	4/6	30/48	3/11	X	X	X			X
Thies	4/4	30/48	8/22	X	X	X			X
Kaolack	4/4	30/60	7/15	X	X	X	X		X
The Gambia	4/4	30/48	23/31	X	X	X	X		
Tambacounda	4/4	30/60	12/25	X	X		X	X	X
Casamance	4/6	30/72	15/41	X	X	X	X	X	X
Total	**28/32**	**210/384**	**84/178**						

Table 2) Descriptions of the individual treatments for seeds/cultivars, inorganic fertilization, and organic amendments.

Pathway	Treatment	Description
Seeds / cultivars	Local	Farmer standard (highly variable among farmers and regions)
	New	Groundnut – 55-437; Cowpea – Yacine; Millet – Souna 3; Maize – Early Thai; Sorghum – Faourou (621B); Rice – Nerica 4
Inorganic fertilizer	Zero	No inorganic fertilization
	Low	50 kg/ha of 15-15-15 NPK preplant for all crops 50 kg/ha of 46-0-0 NPK (urea) topdressing for cereals only
	High	150 kg/ha of 15-15-15 NPK preplant for all crops 150 kg/ha of 46-0-0 NPK (urea) topdressing for cereals only
Organic amendment	None	No organic amendment
	Crop Residue	Millet husk @ 3000 dry kg/ha
	Manure	Cattle manure @ 3000 dry kg/ha

Table 3) Estimated rainfall (mm) and season length (days) in 2015 and 2016 at the study sites, based on the 10km resolution RFE2 spatial dataset and 10 mm/day cutoffs for the beginning and end of the rainy season.

	Average 2001-2016					2015		2016	
Region	**Total Annual (mm)**	**Season Length (days)**	**Regularity (% days w/ >0mm)**	**Intensity (mm/day when >0)**	**Community**	**mm**	**Days**	**mm**	**Days**
Louga (S)	313	78	50%	7.93	Bandegne	290	77	261	70
					Ndanda	309	78	303	70
					Kelle Gueye	291	77	262	70
					Mbendiene	300	77	261	69
Matam (S)	361	87	53%	7.79	Matam	299	79	401	77
					Dabia	269	76	394	91
					Agnam Thiodaye	254	71	355	91
					Seno Palel	336	88	404	75
					Sintithiou Bambe	---	---	411	75
					Orkadiere	---	---	430	75
Thies (S)	384	82	52%	9.01	Kuer Balla Lo	395	83	360	66
					Takhoum	408	81	303	70
					Notto	389	82	374	66
					Pambal	353	81	349	61
Central River (G)	490	95	63%	8.21	Kaur	469	91	326	67
					Fass	450	94	367	102
Kaolack (S)	498	94	62%	8.64	Sibissor	487	92	455	67
					Dya	487	93	464	67
					Ndiebel	458	93	463	70
					Thiomby	480	94	484	70
Tambacounda (S)	517	98	63%	8.26	All communities	618	103	683	102
North Bank (G)	568	95	65%	9.17	Njawara	525	95	404	78
					Kerr Omar Sene	518	93	407	78
Ziguinchor (S)	855	100	71%	11.92	All communities	748	102	655	91

Table 4) Average soil characteristics from 0-15cm as A) estimated by spatial models and summarized as the regional mean for the "intensive cultivation" land use category (ESACCI), and B) sampled within fields adjacent to trials and summarized as median (bold/black) and standard deviation (gray)

	A) Spatial Estimates			B) Field Sampling		
Region	**pH**	**% Sand**	**% SOC**	**pH**	**% Sand**	**% SOM**
Louga (S)	6.9	81.2	0.32	**6.40**	**90.4**	**0.54**
n=88-89				0.81	9.2	0.30
Matam (S)	6.7	57.9	0.62	**5.91**	**82.0**	**0.88**
n=82-88				0.92	16.8	0.83
Thies (S)	6.4	76.2	0.50	**6.17**	**77.9**	**1.13**
n=63-72				0.74	12.2	0.79
Central River (G)	5.9	63.3	0.95	**5.94**	**77.2**	**1.03**
n=33-43				0.76	11.5	0.60
Kaolack (S)	5.7	78.0	0.54	**5.16**	**82.3**	**0.83**
n=71-87				0.68	6.4	0.37
North Bank (G)	6.1	60.7	0.84	**5.45**	**85.8**	**0.93**
n=46-47				0.48	4.0	0.40
Tambacounda (S)	5.6	66.8	0.85	**5.79**	**71.5**	**1.56**
n=92-93				0.84	11.7	0.85
Casamance (S)	5.5	47.7	1.59	**5.72**	**83.9**	**1.16**
n=77-123				0.62	13.5	0.59

Table 5) Social characteristics of the study regions, as estimated from census and remote sensing data. "Pop" is the number of inhabitants, "Ag" is a combination of intensive, mosaic, and irrigated land use categories (ESACCI), and "P.I." is reported instances of political insecurity since 1997 (ACLED). The regions are ranked from lowest to highest total rainfall and noted as part of Senegal (S) or The Gambia (G).

	Social				
Region	**Pop / total km2**	**% Land in Ag**	**Pop / Ag km2**	**P.I. Events**	**P.I. Fatalities**
Louga (S)	35	47	75	11	4
Matam (S)	20	15	134	7	0
Thies (S)	280	94	297	28	1
Central River (G)	79	79	100	5	14
Kaolack (S)	188	93	202	13	3
Tambacounda (S)	17	16	103	17	11
North Bank (G)	104	66	156	6	0
Ziguinchor (S)	78	61	128	305	976

Table 6) Distribution of socio-economic resources among households within each region, as percentage of the regional total.

Human resources	**Very Low (1-2)**	**Low (3-4)**	**Medium (5-6)**	**High (7-8)**	**Very High (9+)**
Louga (n=85)	6	36	33	12	13
Matam (n=57)	54	25	5	2	14
Thies (n=64)	3	30	39	9	19
Kaolack (n=86)	19	36	27	9	9
Gambia (n=82)	1	24	57	7	10
Tambacounda (n=89)	8	42	39	7	4
Ziguinchor (n=125)	4	12	36	22	26
Draft Animals	**None (0)**	**Minimal (1)**	**Low (2)**	**Medium (3)**	**High (4+)**
Louga (n=87)	3	2	24	17	53
Matam (n=58)	40	28	10	10	12
Thies (n=65)	12	18	29	20	20
Kaolack (n=93)	28	18	22	11	22
Gambia (n=86)	1	15	24	21	38
Tambacounda (n=91)	19	42	29	11	0
Ziguinchor (n=130)	34	14	13	9	30
Mechanical Equipment	**Very Low (1-2)**	**Low (3-4)**	**Medium (5-6)**	**High (7-8)**	**Very High (9+)**
Louga (n=85)	6	36	33	12	13
Matam (n=57)	54	25	5	2	14
Thies (n=64)	3	30	39	9	19
Kaolack (n=86)	19	36	27	9	9
Gambia (n=82)	1	24	57	7	10
Tambacounda (n=89)	8	42	39	7	4
Ziguinchor (n=125)	4	12	36	22	26

Table 7) Descriptive statistics of all harvested trials as A) percentage of trials with a positive treatment effect on yield and B) median observed treatment effect for yield (harvest weight/area), maturation success (harvested plants/area), and plant vigor (harvest weight/plant). Results are displayed in the 18-plot orientation of the field trials and relative to the Local Cultivar / Zero Inorganic / No Organic control treatment (dark gray).

Treatment Effect		Organic Amendments						Inorganic Fertilizer
		No Organic		**Crop Residue**		**Manure**		
A) % Positive	**Yield**	86	88	90	91	89	90	**High**
		79	84	85	86	85	86	**Low**
			71	72	77	78	86	**Zero**
B) Median % Treatment Effect	**Yield**	66	99	99	136	117	168	**High**
		33	67	60	98	95	130	**Low**
			31	29	58	52	87	**Zero**
	Mat. Success	25	30	38	51	50	65	**High**
		11	26	26	35	40	51	**Low**
			11	10	24	23	39	**Zero**
	Plant Vigor	32	44	39	57	38	62	**High**
		18	29	25	35	30	43	**Low**
			11	15	16	14	30	**Zero**
		Local	**New**	**Local**	**New**	**Local**	**New**	
		Cultivar						

Table 8) Average perceived value of alternative management practices relating to soil fertility and seeds/varieties prior to participation in the trials, where 0 = no value and 3 = high value. The mean of each region is shown in bold/black and the standard deviation is shown in italic.

Soil Fertility Management											
		Manure				**Crop Residue**				**Inorganic**	
		Tether		**Collect**		**Burn**		**Collect**		**Purchase**	
Region		**Mean**	*SD*	**Mean**	*SD*	**Mean**	*SD*	**Mean**	*SD*	**Mean**	SD
Louga n=91-92	Before	0.8	*1.0*	2.7	*0.8*	1.8	*1.1*	1.3	*1.3*	1.2	*1.0*
	After	1.0	*1.2*	2.8	*0.6*	1.2	*1.0*	2.2	*1.3*	2.6	*0.9*
	Difference	**+0.3**	*0.7*	**+0.2**	*0.6*	**-0.6**	*0.9*	**+0.8**	*1.1*	**+1.3**	*1.7*
Matam n=59-61	Before	0.5	*1.0*	1.8	*1.2*	0.5	*0.8*	0.1	*0.5*	0.6	*1.0*
	After	0.7	*1.1*	2.6	*0.7*	0.5	*0.9*	2.0	*1.1*	2.4	*0.8*
	Difference	**+0.2**	*0.8*	**+0.8**	*1.0*	**0.0**	*0.8*	**+1.8**	*1.1*	**+1.8**	*1.1*
Thies n=66	Before	0.5	*0.8*	0.9	*1.0*	2.5	*0.7*	0.4	*0.9*	1.1	*1.0*
	After	1.8	*0.9*	2.5	*0.5*	0.4	*0.8*	1.6	*1.3*	1.7	*0.6*
	Difference	**+1.3**	*0.9*	**+1.7**	*0.9*	**-2.1**	*1.0*	**+1.2**	*1.3*	**+0.6**	*1.5*
The Gambia n=50-53	Before	0.4	*0.7*	1.8	*0.7*	2.1	*0.6*	1.8	*0.7*	1.4	*2.4*
	After	1.1	*1.1*	2.5	*0.6*	1.5	*0.9*	2.5	*0.6*	1.2	*0.8*
	Difference	**+0.7**	*0.8*	**+0.6**	*1.0*	**-0.6**	*1.0*	**+0.6**	*0.9*	**-0.2**	*0.8*
Tambacounda n=93-101	Before	0.1	*0.5*	0.1	*0.4*	2.8	*0.4*	0.2	*0.4*	1.3	*0.6*
	After	0.2	*0.6*	1.2	*0.5*	0.0	*0.1*	1.7	*0.5*	1.3	*0.5*
	Difference	**0.0**	*0.3*	**+1.1**	*0.5*	**-2.8**	*0.4*	**+1.5**	*0.5*	**+0.1**	*0.4*
Ziguinchor n=139-144	Before	0.6	*0.2*	0.0	*0.1*	2.5	*1.1*	0.0	*0.1*	0.2	*0.5*
	After	2.5	*0.5*	2.7	*0.5*	1.0	*0.3*	2.4	*0.6*	0.6	*0.8*
	Difference	**+2.5**	*0.6*	**+2.6**	*0.5*	**-1.4**	*1.2*	**+2.4**	*0.6*	**+0.4**	*0.7*
Total n=514-500	Before	0.3	*0.7*	1.0	*1.3*	2.1	*1.1*	0.5	*1.0*	0.9	*0.9*
	After	1.4	*1.2*	2.4	*0.8*	0.8	*0.9*	2.1	*1.0*	1.6	*1.1*
	Difference	**+1.0**	*1.2*	**+1.4**	*1.1*	**-1.4**	*1.3*	**+1.6**	*1.1*	**+0.7**	*1.1*

Seed Management									
		Save		Neighbors		Local Market		Certified	
Region		**Mean**	*SD*	**Mean**	*SD*	**Mean**	*SD*	**Mean**	*SD*
Louga n=91-92	Before	2.5	*0.9*	1.3	*1.0*	1.5	*1.3*	1.4	*1.2*
	After	2.4	*1.0*	1.0	*1.0*	0.9	*0.9*	2.9	*0.5*
	Difference	**-0.1**	*0.8*	**-0.2**	*0.7*	**-0.7**	*1.0*	**+1.5**	*1.2*
Matam n=59-61	Before	2.4	*0.9*	0.6	*0.9*	1.0	*1.1*	0.5	*1.0*
	After	2.8	*0.5*	0.4	*0.7*	0.3	*0.8*	2.5	*0.8*
	Difference	**+0.4**	*0.8*	**-0.2**	*0.8*	**-0.7**	*1.1*	**+2.0**	*1.1*
Thies n=66	Before	2.8	*0.5*	0.9	*1.0*	1.0	*1.1*	0.3	*0.8*
	After	1.9	*1.3*	0.2	*0.5*	0.1	*0.3*	1.8	*1.4*
	Difference	**-0.9**	*1.4*	**-0.8**	*0.9*	**-0.9**	*1.1*	**+1.5**	*1.7*
The Gambia n=50-53	Before	2.4	*0.7*	0.7	*0.8*	0.6	*0.8*	0.7	*0.6*
	After	2.7	*0.5*	0.7	*0.8*	0.7	*0.7*	1.3	*0.8*
	Difference	**+0.3**	*0.7*	**+0.1**	*0.9*	**+0.1**	*0.9*	**+0.5**	*1.1*
Tambacounda n=93-101	Before	2.6	*0.5*	0.2	*0.4*	1.6	*0.5*	0.2	*0.4*
	After	1.9	*0.6*	0.2	*0.4*	1.0	*0.3*	0.3	*0.6*
	Difference	**-0.6**	*0.6*	**0.0**	*0.2*	**-0.5**	*0.6*	**+0.1**	*0.6*
Ziguinchor n=139-144	Before	2.3	*0.7*	0.8	*0.5*	0.3	*0.5*	0.2	*0.5*
	After	2.3	*0.5*	1.1	*0.5*	0.2	*0.5*	2.0	*0.6*
	Difference	**0.0**	*0.9*	**+0.2**	*0.6*	**-0.1**	*0.5*	**+1.7**	*0.1*
Total n=514-500	Before	2.5	*0.7*	0.8	*0.8*	1.0	*1.0*	0.5	*0.9*
	After	2.3	*0.8*	0.7	*0.7*	0.5	*0.7*	1.8	*1.1*
	Difference	**-0.2**	*1.0*	**-0.1**	*0.7*	**-0.4**	*0.9*	**+1.3**	*1.3*

Table 9) Survey results of participating households' prioritization of the three adaptive pathways tested in the farmer field trials (organic, inorganic, cultivar). Each household representative ranked the pathways as first (1), second (2), and third (3) priority, which are summarized as regional means.

Region	Organic	Inorganic	Seeds
Louga (n=92)	2.1	2.6	1.3
Matam (n=59)	1.3	2.7	2.0
Thies (n=66)	2.1	2.8	1.2
The Gambia (n=49)	1.0	2.9	2.1
Tambacounda (n=93)	1.5	2.5	1.9
Casamance (n=139)	1.9	2.9	1.3

Figures:

Figure 1) Approximate locations of regional clusters of farmer field trials over a map of average annual rainfall from 2001-2016 for Senegal, The Gambia, and Guinea Bissau. The rainfall legend is included in Figure 2.

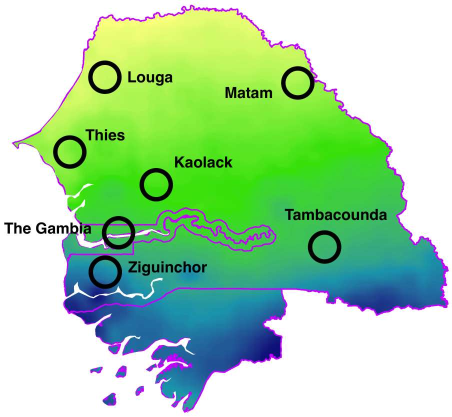
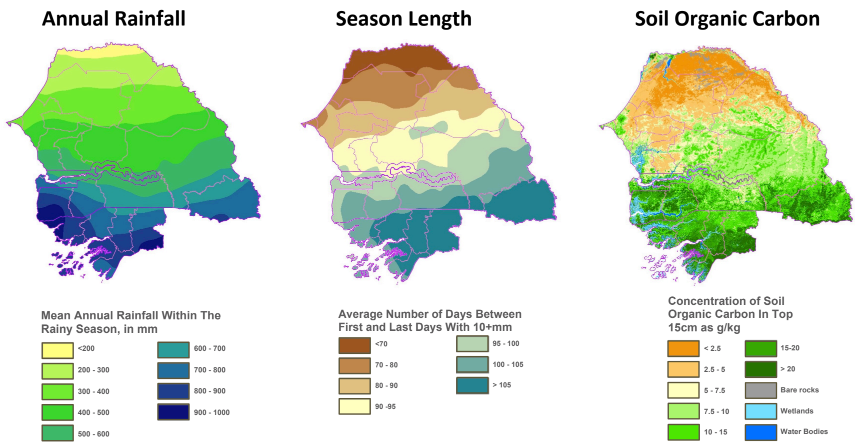


Figure 2) Spatial patterns of select variables across Senegal, The Gambia, and Guinea-Bissau that may influence rural livelihoods, agricultural constraints and opportunities, and the effectiveness of alternative practices. Maps are from Eldon and Rapaport (2017) and original data sources are identified in the Methods.



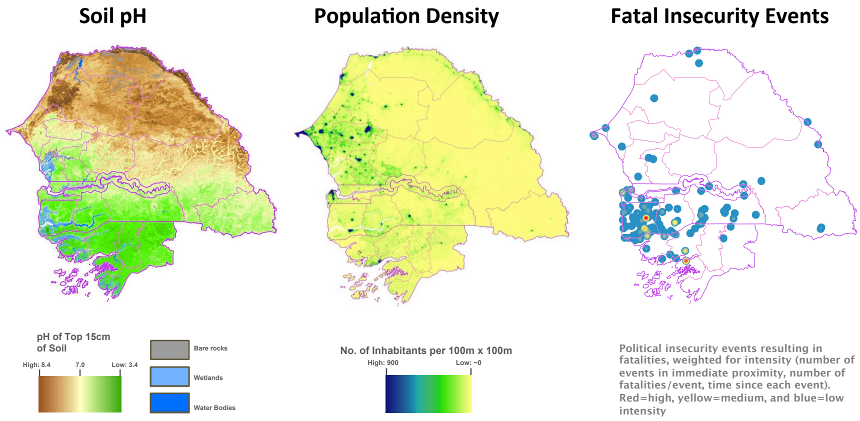


Figure 3) Magnitude and variability of coefficients of select factors in the final GLM for yield and maturation success, presented as relative effect.

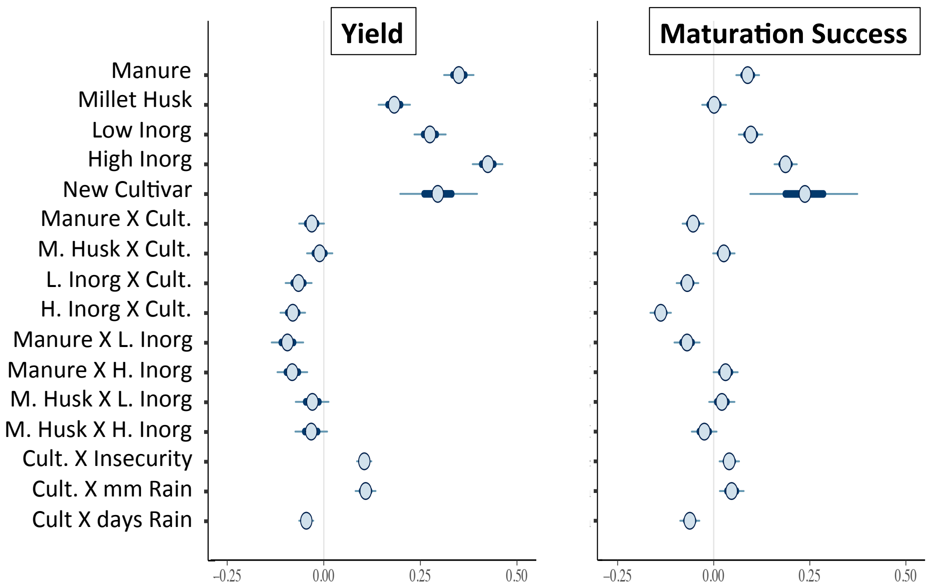
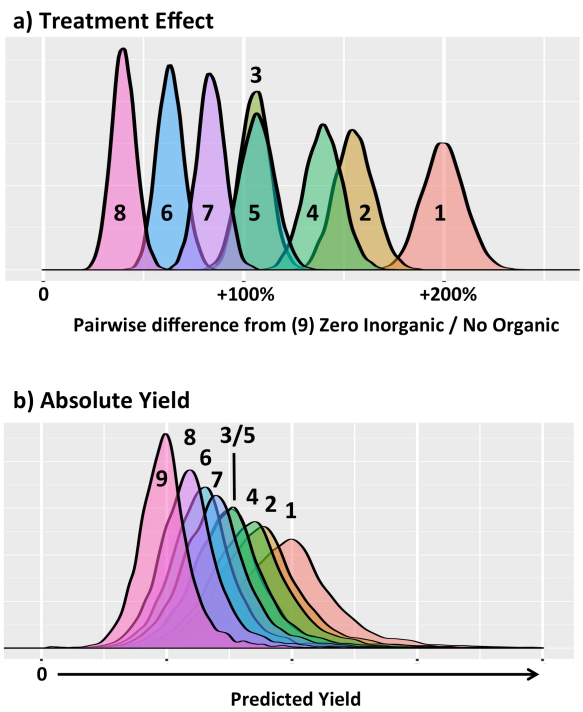


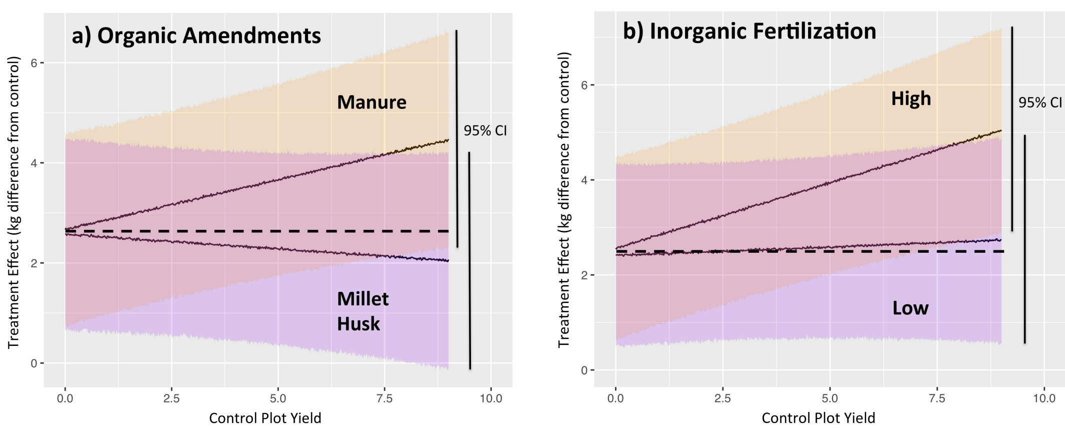
Figure 4) Probability density functions of a) treatment effect as relative increase in yield over the control (L-0-No) plot and b) resulting absolute yield, for combinations of organic and inorganic fertility treatments using local cultivars and generalized for all crops, regions, and years. The Y-axis in both figures is the probability density, which is the continuous equivalent of count frequencies in categorical histograms and is not intuitive or necessary for visual interpretation. The X-axis for (b) is a crop-generic yield measurement.



	Inorganic	Organic
1	High	Manure
2	High	Millet Husk
3	High	None
4	Low	Manure
5	Low	Millet Husk
6	Low	None
7	Zero	Manure
8	Zero	Millet Husk

	Inorganic	Organic
1	High	Manure
2	High	Millet Husk
3	High	None
4	Low	Manure
5	Low	Millet Husk
6	Low	None
7	Zero	Manure
8	Zero	Millet Husk
9	Zero	None

Figure 5) Modeled linear regressions comparing treatment effect and underlying field productivity, as control plot yield, for a) organic soil amendments and b) inorganic fertilization rates. Shaded regions represent the 95% confidence interval and the dashed line indicates the zero-slope line that would indicate no change in effect with underlying yield. The axis units are a crop-generic yield measure from the nested model and cannot be applied directly to any crops.



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