Better than best practices: Using farmer field trials to identify adaptive management options within complex agricultural systems

Eldon, J.[1,2,*], Shennan, C.[1], Rapaport, P.[3], Jansen, T.[2], Sidibeh, S.[2]

[1]*University of California - Santa Cruz, California, USA*
[2]*Concern Universal, Senegal/The Gambia/Guinea Bissau regional office*
[3]*Africa Geodata, The Gambia*

* *jeldon@ucsc.edu*

Abstract:

Agricultural systems are widely recognized as being complex, dynamic, and diverse, and containing of many uncertain or unknown components and interactions. However, management recommendations are often derived from highly controlled experiments that reduce the complex working of the system to artificially simple relationships that are typically investigated in isolation under the assumption of "all else being equal." Such reductionist experiments are appropriate for investigating certain aspects of agricultural systems, but do not estimate the reliability or robustness of the effect of specific manipulations, which is what is implied by "best management practice" recommendations. These limitations are illustrated here through the preliminary results of an ongoing project in Senegal and The Gambia, where a network of farmer field trials tests and largely rejects current recommendations for rain-fed crop production, while suggesting potentially more reliable alternatives. These results also demonstrate the research value of experiments that are embedded within a complex system, both as a stand-alone method and as a part of a more integrated approach to the study of complex agricultural systems. While this approach may lead to general recommendations, it can also identify a range of potentially adaptive practices, thereby encouraging multiple adaptive pathways, a result that makes this approach particularly valuable in diverse and understudied systems.

Keywords: complex systems, soil fertility, farmer field trials, best management practices, Senegal, The Gambia

Introduction

The concept of "best management practices" in agriculture refers to attempts by researchers to develop and prescribe broadly appropriate and reliable management recommendations to farmers. This approach is a deliberately integrated alternative to one-dimensional interpretations, and might balance productivity with input efficiency, cost-benefit analysis, and environmental externalities (Ryan et al 2012). However, the specifics and appropriateness of these recommendations are strongly dependent on the breadth, quality, and relative inclusion of the researchers' knowledge, as well as their personal bias towards certain issues, such as production over externalities or vice versa (Roberts 2007). More critically, the output of this approach is often a specific plan that is assumed to be broadly suitable for adoption, such as an integrated fertilizer use protocol. While there might be a "right source, right place, right timing and right application method" to achieve maximum effect size or input efficiency under certain conditions, it cannot always or even often be assumed that there is also a single management plan that is “right” or “best” for a broad group of farmers (Giller et al 2011, Ryan et al 2012). The wide variation found in agricultural systems results in such diverse conditions and constraints that adopting a specific “best management practice” might be adaptive for one farmer but maladaptive for a neighbor (Giller et al 2009). While these integrated interpretations of agricultural systems may be improvements over one-dimensional analyses, the underlying prescriptive approach remains problematic.

The more that is known about an agricultural system, the better that recommendations can be tailored to the known system diversity and behavior, thereby reducing the possibility of “best” recommendations being unreliably adaptive or, worse, reliably maladaptive (Giller et al 2011). However, the less that is known, the greater the risk of inappropriate interpretations, making these recommendations potentially dangerous in relatively understudied or particularly diverse or complex systems. In some cases, the best available information may simply not be good enough to justify “best” recommendations, particularly if there is no measure of the reliability of a practice across the relevant diversity of the target system. Despite this risk, it is still common to develop and prescribe recommendations that are based on simplistic assumptions rather than sufficient knowledge of relevant system behavior (Vanlauwe & Giller, 2006).

An alternative approach in understudied situations is to embed agricultural research within working agricultural systems to implicitly capturing the relevant complexity, uncertainty, and variability of the target system (Shennan 2008). This approach considers farmers and researchers as complimentary specialists, and is in direct contrast to the more conventional top-down model of research and extension, where farmers are not explicitly included in the former and are passive recipients of the latter. While farmer-researcher consultation is a critical component of any agricultural research, the use of farmer field trials is emerging as a rigorous experimental method and legitimate tool for investigating complex systems, rather than simply an extension strategy to demonstrate recommended practices (Snapp 2002).

This embedded strategy is currently being applied on a large scale in Senegal and The Gambia through coordination among an American university, a UK-based international non-government organization, regional cooperative farmer organizations, and hundreds of individual farmers (Table 1). This paper is a preliminary report on this project and is divided into two parts. The first is a discussion of the theoretical issues underlying this approach, with a focus on the concept of a “(complex) system perspective” as a deliberate epistemological position with implications for research design. The second part describes the project, the methods, and some of the initial results. While preliminary and incomplete, these early results show the benefits of this strategy for testing prescriptive hypotheses, and reveal some trends that suggest relevant interactions and alternative options that are not well researched or recognized in the literature.

Complex Systems Theory and Experimental Methods

A system is a set of independent components that interact to produce some shared emergent properties. A complex system is one where the processes within the system and the patterns that emerge are not linear, straightforward, or otherwise easily predictable (Zeigler et al 2000). Used in this sense, a complex system is distinct from a complicated system, which might simply have a large number of moving parts. A complex system might be ontologically complex, due to having some probabilistic or stochastic interactions, or it might be epistemologically complex, due to incomplete knowledge of the components, interactions, and emergent processes of the system. Any system that requires investigation falls into the latter category and should accordingly be described and investigated as a complex system.

The concept of a "system perspective" can be found in many of the disciplines that are highly relevant to agricultural sciences. For example, ecology is explicitly focused on the interactions among organisms rather than isolated observations, and the associated concept of an ecosystem is now used throughout the biological sciences (Odum 1977). "Agro-ecosystem" has been used for decades to describe ecosystems that are managed to produce food and fiber, and current system perspectives on agriculture often draw from the literature on "socio-economic" and "socio-ecological" systems. (Conway 1987, Young et al 2006, Giller 2013). This emerging perspective is a point of coalescence of multiple paradigms, including those that make explicit mention of systems, such as farming systems research, as well as those that do not, such as agroecology and sustainable rural livelihoods (Chambers and Conway 1992, Wezel et al 2011). However, this approach has a much longer history and the term "farming system," for example, was used in the early 1800's to argue that the interaction of topography, climate, infrastructure, and labor force made Scotland's Orkney islands more suited for smallholder production than large-scale industrialized agriculture (Shireff 1814).

The adoption of a system perspective is often closely associated with an attempt to rigorously describe the system of interest, which can be referred to more specifically as *system analysis*. This analysis might focus on the *system structure,* the equivalent of a schematic diagram identifying components and potential or common interactive pathways, or the *system behavior*, which would be a more pragmatic description of how the system responds to various stimuli without necessarily describing the internal mechanisms (Zeigler et al 2000, Giller 2013). This system analysis is primarily a descriptive activity, but the resulting explicit understanding can be used to design experiments to further investigate that system.

A common approach to experimental design is to conduct manipulative studies that investigate a small number of interactions under highly controlled conditions and the assumption of "all else being equal." This method is to deny complexity as such, as from a system perspective this "all else" can never be assumed *a priori* to be irrelevant from the interactions of interest. This approach is therefore *reductionistic* as it presumes to reduce complexity to a series of simple interactions that can be investigated in piecemeal fashion, as if a single complex three-way interaction was analogous to three simple two-way interactions.

An alternative is to design *composite* investigations that manipulate or measure many of the diverse components and complex interactions that have been recognized as potentially relevant to the processes of interest. These composite experiments, also known as "integrated system experiments," are growing in popularity and improve on some of the shortcomings of the reductionist approach, but are not without their own serious drawbacks (Shennan 2008). Being more complicated by design, these experiments are also more complicated to implement and interpret, and often require significantly higher research investment in terms of time, funding, and expertise. In addition, only recognized complexity can be incorporated into a composite experiment, making them, like reductionist investigations, susceptible to being undermined by unforeseen or unappreciated components and interactions. Therefore, while composite investigations are an example of applying a system perspective to experimental design, it is still accurate to describe them as an “outside looking in” perspective on complex systems.

An alternative means of applying a system perspective to agricultural experiments is through an “inside-out” or “in-situ” approach where the experiment is embedded within the known and unknown complexity of the system of interest. Unlike composite studies, these *embedded investigations* might focus on manipulating and/or measuring a single variable rather than multiple related variables, but unlike reductionist methods, such experiments are perturbations of a relatively intact complex system rather than manipulations of an artificially simple one. This experimental approach to complex systems is widely used in ecology to study ecosystem responses to changes in specific variables, such as with enclosure or exclusion field trials and large-scale free-air CO2 enrichment experiments (Tilman 1989, Ainsworth and Long 2005).

These three experimental approaches to complex systems—reductionist, composite, and embedded—are not in direct competition but rather are each well suited for different questions or interests. Reductionist investigations are appropriate for identifying if a specific interaction or effect is possible or estimating what the effect size might be under certain highly specific conditions. However, unless the system is known to be relatively simple, constant, homogeneous, and well-understood, this approach cannot be trusted to estimate the overall robustness of an specific interaction or the reliability of a specific effect size across diverse conditions. The ability to more effectively do so is one of strengths of embedded investigations, which in turn are not appropriate to estimating a maximum effect size of a specific process and not well suited for investigating potential mechanisms. Of the three, composite investigations are most apt for clarifying complex interactions and identifying the specific circumstances under which the benefits of a practice might outweigh the costs and risks associated with adoption, but they require extensive and accurate knowledge of the system to do so. These respective strengths and weaknesses are recognized by research programs that apply multiple approaches to a targeted system or specific studies that augment a reductionist or composite experiment with an embedded component, an approach that is sometimes referred to as a “mother-baby” design (Snapp 2002). Even when this integration is not possible within a single study, embedded experiments alone can be used to test specific hypotheses, such as “best management practices” and can identify robust ways to manage system behavior even when the mechanisms of the complexity are not well understood.

Rainfed Farming Systems in West Africa

Rainfed agriculture is the primary means of both subsistence food production and income generation in rural parts of Senegal and The Gambia, with most of it occurring on sandy and semi-arid upland soils with low soil organic matter. Uncultivated fields are routinely found to have less than 1% soil organic carbon (SOC), even within only the top 5cm, while the percentage in cultivated fields is much less and can be can be as low as 0.15% (Tiessen et al 1998, Peters 2000, Elberling et al 2003). As 0.5% SOC is globally used as a rough threshold to identify severely degraded soils that are not well suited for agriculture, it is likely that soil fertility is a common constraint in this region. In addition, there has been limited development and distribution of newly developed crop varieties, and most farmers do not have access to seed stores that might offer high quality seed stock. While traditional methods of seed preservation and exchange are still common in many areas, it is likely that some proportion of farmers in this region, perhaps especially the poorest ones, are working with low quality seed stocks or poorly adapted varieties.

The use of organic amendments, inorganic fertilizers, and high quality and locally-adapted seed stocks are therefore likely variables that can be manipulated to increase crop production, and through that, the production-dependent aspects of food security in rural Senegal and The Gambia (Vanlauwe & Giller, 2006). While these three variables are often key components of agricultural recommendations, the interaction is not necessarily part of standard "best practice recommendations." For example, while all three might be considered "good," this doesn't address how adopting a new crop variety might compare with increasing the fertilization of the current variety. In addition, of course, the effect of any specific practice can be highly variable due to local variation in availability, soil conditions, application logistics, and other characteristics of diverse agricultural systems that influence farmer practices, treatment effects, and cost-benefit interpretations (Vanlauwe & Giller 2006, Smith et al 2011).

The current official recommendations for fertility management of upland crops in Senegal and The Gambia range from 150-200 kg NPK per hectare annually with the same rate of urea application for non-legume crops (Posner & Crawford 1992, ISRA 2005). Specialized NPK mixes such as 6-20-10 or 8-18-27 are recommended but widely unavailable, and so often replaced by the more ubiquitous 15-15-15. These general recommendations come with no further clarification given for the relative influence of other variables that are known to be relevant to production, such as field history, socioeconomic conditions, or variation in rainfall and associated ecological characteristics. The recommendation of inorganic fertilizer is not, for example, described in associated with the use of local organic amendments, despite the common cultural use of these inputs and the increasing scientific evidence of effective integration of the two (Place et al 2003). In addition, it is not stated whether the recommended rates reflect the productive ceiling, which is the common target of agronomists, or some unstated cost/benefit calculation, such as any farmer must make.

New crop varieties are a major part of many agricultural recommendations in sub-Saharan Africa, and are often presumed to be well adapted, to the extent that they are often referred to as "improved" rather than "new" varieties. This presumption, however, is based primarily on highly controlled reductionistic studies and is rarely tested across the spatial or social variation that occurs within the scale at which they are recommended. The Gambia has limited capacity to develop or test new varieties, and while Senegal does, the rainfed crop trials occur primarily at research stations in the central Thies region (ISRA 2005, Figure 1). The local development and testing of new varieties often selectively excludes many of the stresses that are expected in farmer's fields, such as weed pressure, intermittent drought, and low soil nutrient levels, as well as relevant social and economic constraints, such as labor and adoption cost.

Farmer Field Trials in Senegal and The Gambia

This ongoing project is a large-scale embedded investigation of alternative management practices for rain-fed crop production in Senegal and The Gambia, with a focus on 1) locally available organic amendments, 2) widely available inorganic fertilizers, and 3) nationally-certified seeds, which may or may not be distinct varieties from what farmers are currently planting. Instead of attempting to control for all of the known, unknown, and unappreciated complexity found in this region, this two-year project establishes trials of fixed design in hundreds of independent farmer fields across the region, which are then managed by participating farmers under the supervision of project staff. These farmer-led trials are not controlled and replicated in the traditional sense that reduces and thereby denies complexity. Instead, the complexity of the system is constrained by the standardized design, training, and supervision of the participants, and the trials are repeated broadly across the diversity of conditions found within the system to document the robustness of any effects.

Over 400 farmer-led trials were established in 2015 within 6 focal regions in Senegal and 1 in The Gambia (Figure 1). Four community clusters were selected within each region, with each cluster representing up to three immediately adjacent communities and the clusters spaced no less than 15 kilometers from each other and all within 50 kilometers of the primary regional population center. The primary emphasis during 2015 was on millet, groundnut and cowpea, with secondary emphasis on upland rice, sorghum, and maize.

Two trial designs were used in this project, both using a non-replicated split-plot factorial design. "Step 1" trials tested a single "new" certified variety of each crop alongside the participating farmer's "local" seed stock and across a combination of two organic and two inorganic fertility treatments, resulting in 18 treatment plots per trial. Each treatment was 5m x 10m, for a total of 30m x 30m for each Step 1 trial. The organic treatments were millet husks, the waste of the threshing process, and locally gathered cattle manure, which is often applied to fields through annual or seasonal livestock rotations. Both organic amendments were applied at 3000 kg/ha (1.34 US tons/acre), which was agreed upon by participating farmers as a rate that might reasonably be locally collected and applied by most farmers. Inorganic fertilizer was applied at the recommendation level of 150 kg/ha ("high") and 50 kg/ha ("low") 15-15-15 NPK, with the same level of urea also added for non-legumes. These Step 1 trials were designed to target farmers who were producing primarily for personal consumption and had limited experience investing in their production. These are more likely to be relatively resource-poor households, who might be limited by insecure or insufficient access to land, labor, and financial investments. Those farmers who might already be producing on a commercial level and experienced with investing in their production were targeted by "Step 2" trials, which compared the farmer-standard seed stock against four certified varieties that are currently available for purchase in Senegal. These trials ranged from 0.25 to 1 hectare in size depending on the crop, and both groundnut and millet were 1 hectare in total with each varietal plot 0.2 ha in size.

All trial areas were demarcated by project field officers working alongside the participating farmers. The farmers were given the appropriate seeds for each trial and trained in the design and constraints of the trial, particularly the importance of managing each trial as a unit so that, for example, all plots are planted and weeded at the same time. The timing of the planting was determined by the farmer, but usually after the second or third significant rain in the region. Animal traction was used for all plantings, and hired locally as necessary. The organic amendments for Step 1 trials were collected by each participating farmer and applied under supervision just after the first rain. Inorganic fertilizer was applied by project field officers soon after emergence for the NPK and a few weeks later during rapid vegetative growth for the urea. Harvest was again supervised by field officers using local labor and consisted of all Step 1 treatment plots (5m X 10m each) and a representative 5m X 10m plot within each Step 2 varietal planting. Field measurements consisted of 1) number of productive plants or tillers, 2) fresh weight of harvest, and 3) dry plucked or threshed weight, all measured per plot.

Results are reported for millet and groundnut trials and presented here in three ways, 1) as dry harvest per hectare, 2) as # productive plants/tillers per hectare, and 3) as dry harvest per plant. In the few cases where the fresh weight was available but the final dry weight was not, the latter was estimated using the mean percent weight loss with drying across all trials for that crop. The results are shown here primarily as the median percent change from the control plot, which is the "local/no organic/no inorganic" plot for Step 1 and "local" for Step 2. The Step 2 trials (varietal) are of a simpler design and the results thereby presented before the Step 1 trial (variety X organic X inorganic) results and also include the median, max, and min of the harvest measurements.

Preliminary Results

Only a subset of the farmer field trials that were established were successfully measured during harvest (Table 2). When averaged across all Step 2 trials, the new groundnut resulted in increased yield per hectare and productivity per plant, while the new millet varieties showed the former for three out of the four varieties (Table 3). However, all three yield measurements varied by orders of magnitude for both crops. The only strong trend of the median effect size, calculated as the percent difference from the control within each trial, was an increase in yield per hectare of new groundnut varieties, and again there was dramatic variation among the trials for all measures (Table 4). The same analysis of the Step 1 trials appears to show all three management practices influencing yield in an additive fashion, such that the greatest median effect sizes come with the combination of all three (Table 5-6). This same trend is also apparent in the number of millet plants per plot, which is an indication of germination or maturation success, but is not clear in the other analyses. With only one exception (low inorganic, no inorganic, local groundnut), all treatments in the Step 1 trials on average resulted in a positive increase over the control, although without disaggregation and some assessment of variability, these trends are only suggestive.

Discussion

The official "best management practices" that are currently being recommended in Senegal and The Gambia regarding the use of inorganic fertilizers and certified seeds do not appear to be widely appropriate for farmers in this region. The common prescription that farmers should adopt certified "improved" seeds to increase their yield is particularly inappropriate, as the pairwise comparisons of the Step 2 trials found that new varieties of millet had, on the whole, a negligible influence on yield, while the new groundnut varieties were overall an improvement, but perhaps not at the dramatic level that is often stated or implied by the recommendation or worth the additional investment. This average effect is also no measure of reliability, and in both cases the new seeds were also sometime dramatically outperformed by the local variety.

The Step 1 trials that tested this adoption effect against alternative management options suggest that the effect of this single practice alone, which comes at a high cost for the certified seed, may often be outweighed by the potentially cheaper use of local organic amendments and locally available inorganic fertilizers. Similarly, the Step 1 trials found that while the recommended high inorganic fertility amendment on the average drastically improved yield, the effect size was in fact far less than when integrated with local crop residue or animal manure. While many recommendations focus on new seed stocks and inorganic fertilizers, others focus exclusively on organic amendments, which where found in the Step 1 trials to be potentially valuable but not highly effective on their own, at least not at the rate that farmers' identified as being pragmatically reasonable. Higher application rates of organic amendments are likely to have a greater effect, but would come with increased labor cost and may simply be unobtainable in some spatial and social circumstances.

This is not to say that using new seed stocks, inorganic fertilizers, and organic amendments are not potentially useful management practices, but rather that specific recommendations are not guaranteed and perhaps not even reliable. The original reductionist experiments that led to these recommendations and the observed maximum effect sizes in these farmer field trials indicate that these alternative practices have the potential to dramatically increase yield. However, it is no more appropriate to assume from these maximums that the practices are broadly adapted and robustly effective than it would be to assume from the minimum effect sizes that they are reliably maladaptive and ineffective. The problem here is that with "best," these alternatives are presented as simple and reliable prescriptions, whereas they are in fact something more like "optimal practices" or "sometimes best practices." The failures of the current official recommendations to reflect the trends observed in these preliminary results should not lead to the question "well then what IS the best practice?" In this region, as perhaps in most agricultural systems, the diversity of relevant factors might be such that there are simply no simple and broadly "best" recommendations. Strong evidence for this is the wide range of harvest measurements and effect sizes, which indicates that there are many other factors influencing the effectiveness of these practices.

An alternative strategy is to present farmers not with specific "best practices" prescriptions, but rather with alternative options, such that they can identify for themselves what might be most appropriate for their own circumstances. Such options are "adaptive" rather than assumed to be "adapted" or "best," for this model encourages farmers to continue to adapt, alter, and combine the identified practices rather than strive to adopt specific practices. For example, the recognition of the importance of high quality seed stocks can lead to multiple adaptive responses, such as stronger selection of personal seed stock, local sourcing of higher quality seed of existing varieties, or purchasing of nationally certified seed or new varieties. Similarly, the observed effectiveness of reasonable levels of locally available organic amendments and of lower than recommended levels of inorganic fertilizer suggests that these inputs have incremental value than a threshold for effectiveness, as might be assumed from the current recommendations.

The active role of farmers in the agricultural research can also help to identify alternative interpretations to what a scientist might conclude from the statistical results alone. For example, the failure of the millet trials in the Ziguinchor region was largely the result of birds destroying the early maturing varieties, leading the farmers to abandon the trials. However, follow up surveys found that these farmers were not overly concerned by this and were instead planning on delaying planting of early maturing varieties and/or planting larger fields where scaring tactics would be more efficient. Similarly, the higher rainfall and longer rainy season in this region has led agronomists to assume that short season crops are not needed or even not appropriate, yet many of the participating farmers recognized the potential of the new varieties to meet marketing niches, such as fresh early groundnut, and to allow for successive or relay cropping. While maximizing yield or input efficiency are common targets of agronomic studies, they are only two of the many characteristics that a farmer must consider when adopting and adapting alternative management practices.

Embedded investigations are an effective stand-alone research method and particularly valuable in understudied systems, but they can also be integrated with other experimental and observational approaches. The rapid recent development of remote sensing data and spatial analysis offers powerful new observational tools, and to combine these with embedded experiments is to investigate complex agricultural systems from both within and from literally thousands of miles away. This potential integration can test the reliability of alternative practices while also identifying the variables that might be relevant, thereby providing a more complete alternative to piecemeal and reductionistic interpretations of complexity. Soil conditions and precipitation patterns are two factors that are critical to production in the rainfed agricultural system of Senegal and The Gambia, but both are often treated in spatially simplistic ways. This region is mostly flat and formed primarily from weathered sandstone, resulting to uplands soils that are sandy and of low-organic matter by global standards, and as a result considered relatively homogeneous. The latitudinal precipitation gradient is often assessed by annual mean only and classified as semi-arid or as a dichotomy between a drier Sahel ecotype in the north and a wetter Sudan-Savannah in the south. However, remote sensing data and spatially explicit estimates offer much higher resolution information of soil and precipitation, including soil characteristics at 250m resolution and decades of daily rainfall estimates at 10km (Love et al 2004, Novella & Thiaw 2013, Hengl et al 2015). The resulting maps clearly show that simple spatiotemporal estimates of soil and precipitation are both inappropriate and unnecessary (Figures 1-3).

Conclusion

These preliminary results illustrate the risks associated with making general agricultural recommendations based largely on reductionistic studies of complex systems. The method presented here of using farmer field trials as a form of embedded investigation to assess alternative practices is particularly appropriate for diverse or understudied complex agricultural systems. This approach can be used to both estimate the robustness of a practice and test assumptions of how the system works. It is not, however, a replacement of other experimental and observational methods, but rather a practical compliment that can offer novel insights into complex interactions.

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Tables

Table 1) Organizations participating in the on-going project in Senegal and The Gambia. The names of the Senegalese organizations are translated from French.

Organization	Description
Concern Universal (Senegal/The Gambia/Guinea Bissau office)	Non-government organization (International, UK-based)
Senegalese Network of Farmer and Breeder Organizations (RESOPP).	Farmer cooperative and nationally certified seed producer (Senegal, multi-region)
The Rural Cooperative of Pambal	Farmer cooperative (Senegal, Thies region)
The Agricultural Cooperative of Malicounda	Farmer cooperative (Senegal, Thies region)
The Agricultural Cooperative of Kélle Guèye	Farmer cooperative (Senegal, Louga region)
The Rural Cooperative for the Inclusive Development of Missirah	Farmer cooperative (Senegal, Tambacounda region)
The Cooperative for Sibassor Local Development	Farmer cooperative (Senegal, Kaolack region)
Constructing the Peace	Non-government organization (Senegal, Ziguinchor region)
Njawara Agricultural Training Center	Non-government organization (The Gambia, North Bank region)
Africa Geodata	Gambia-based spatial analysis consultancy
University of California, Santa Cruz	American University

Table 2) Number of trials included in the statistical analysis as per crop, region, and trial type, out of a maximum of eight trials per Location X Crop X Step. Some farmer field trials were unsuccessful due to a combination of factors including insufficient training and support for some farmers, the complexity of the harvest protocol, and local disturbances. All locations were grouped together for analysis but disaggregated by crop and step.

Location	Millet		Groundnut	
	Step 1	Step 2	Step 1	Step 2
Louga	5	8	7	7
Matam	0	3	0	3
Thies	5	5	2	6
Kaolack	5	7	0	2
The Gambia	5	5	7	8
Ziguinchor	0	0	5	8
Tambacounda	2	3	2	6

Total	**23**	**39**	**21**	**40**

Table 3) Median, maximum, and minimum plot-level harvest measurements for millet and groundnut Step 2 trials

Variety	**Threshed kg / ha**			**# Plants or tillers / plot**			**Dry kg / 100 plants or tillers**		
	Median	*Max*	*Min*	**Median**	*Max*	*Min*	**Median**	*Max*	*Min*
Millet									
Local	**676**	*1690*	*281*	**233**	*523*	*45*	**1.76**	*6.44*	*0.39*
Souna 3	**754**	*1674*	*120*	**220**	*789*	*43*	**1.95**	*6.46*	*0.66*
Sosat	**640**	*2002*	*223*	**216**	*537*	*38*	**1.53**	*6.58*	*0.39*
Gawane	**736**	*1458*	*76*	**205**	*674*	*31*	**1.63**	*6.97*	*0.54*
Thialack	**816**	*1994*	*124*	**231**	*755*	*63*	**1.93**	*4.76*	*0.57*
Combined new	**740**			**214**			**1.77**		
Groundnut									
Local	**1109**	*2292*	*42*	**322**	*1101*	*91*	**1.75**	*6.72*	*0.06*
Fleur 11	**1300**	*2630*	*150*	**293**	*1492*	*130*	**2.06**	*6.4*	*0.38*
7333	**1538**	*2493*	*152*	**293**	*880*	*141*	**2.16**	*5.44*	*0.14*
55-437	**1611**	*2840*	*200*	**420**	*910*	*166*	**2.29**	*3.85*	*0.31*
GH 119/20	**1392**	*2800*	*24*	**306**	*815*	*108*	**2.30**	*4.33*	*0.11*
Combined new	**1418**			**320**			**2.16**		

Table 4) Median, maximum, and minimum treatment effect across all Step 2 trails, calculated as the % different of treatment plots from the adjacent control plot within each trial.

Variety	**Threshed kg / ha**			**# Plants or tillers / plot**			**Dry kg / 100 plants or tillers**		
	Median	*Max*	*Min*	**Median**	*Max*	*Min*	**Median**	*Max*	*Min*
Millet									
Souna 3	**+ 2%**	*+ 300%*	*- 59%*	**+ 3%**	*+ 140%*	*- 62%*	**+ 1%**	*+ 69%*	*-70%*
Sosat	**- 14%**	*+ 99%*	*- 75%*	**- 10%**	*+ 88%*	*- 44%*	**- 3%**	*+ 147%*	*- 63%*
Gawane	**- 12%**	*+ 150%*	*- 71%*	**- 8%**	*+ 95%*	*- 60%*	**0**	*+ 527%*	*- 74%*
Thialack	**+ 2%**	*+ 200%*	*- 59%*	**+ 9%**	*+ 207%*	*- 53%*	**+ 1%**	*+ 254%*	*- 60%*
Combined new	**- 3%**			**- 3%**			**0**		
Groundnut									
Fleur 11	**+ 18%**	+ 338%	*- 59%*	**+ 2%**	*+ 97%*	*- 37%*	**+ 4%**	*+ 539%*	*- 59%*
7333	**+ 29%**	*+ 262%*	*- 65%*	**0**	*+ 169%*	*- 52%*	**+ 1%**	*+ 521%*	*- 55%*
55-437	**+ 27%**	*+ 638%*	*- 44%*	**+ 17%**	*+ 201%*	*- 30%*	**+ 7%**	*+ 692%*	*- 57%*
GH 119/20	**+ 14%**	*+ 171%*	*- 80%*	**+ 3%**	*+ 168%*	*- 67%*	**- 1%**	*+ 160%*	*- 67%*
Combined new	**+ 22%**			**+ 5%**			**+ 3%**		

Table 5) Median treatment effect across all Step 1 millet trials, calculated as the % different of treatment plots from the adjacent control plot within each trial.

Millet						
Threshed kg						
	No Organic		**Millet Husk**		**Animal Manure**	
High Inorganic	101%	105%	179%	192%	221%	182%

Low Inorganic	53%	82%	103%	100%	124%	157%
No Inorganic		33%	28%	22%	54%	91%
	Local	**Souna 3**	**Local**	**Souna 3**	**Local**	**Souna 3**
# Plants						
	No Organic		**Millet Husk**		**Animal Manure**	
High Inorganic	58%	43%	83%	95%	77%	102%
Low Inorganic	21%	29%	50%	55%	73%	73%
No Inorganic		8%	18%	23%	38%	45%
	Local	**Souna 3**	**Local**	**Souna 3**	**Local**	**Souna 3**
Threshed kg / plant						
	No Organic		**Millet Husk**		**Animal Manure**	
High Inorganic	13%	25%	30%	45%	35%	33%
Low Inorganic	14%	29%	23%	16%	17%	33%
No Inorganic		7%	1%	0	1%	5%
	Local	**Souna 3**	**Local**	**Souna 3**	**Local**	**Souna 3**

Table 6) Median treatment effect across all Step 1 groundnut trials, calculated as the % different of treatment plots from the adjacent control plot within each trial.

Groundnut						
Dry plucked kg						
	No Organic		**Millet Husk**		**Animal Manure**	
High Inorganic	51%	108%	79%	135%	97%	143%
Low Inorganic	17%	49%	65%	90%	69%	115%
No Inorganic		29%	28%	52%	45%	90%
	Local	**Fleur 11**	**Local**	**Fleur 11**	**Local**	**Fleur 11**
# Plants						
	No Organic		**Millet Husk**		**Animal Manure**	
High Inorganic	9%	11%	12%	11%	12%	16%
Low Inorganic	9%	9%	14%	14%	11%	14%
No Inorganic		8%	7%	8%	6%	12%
	Local	**Fleur 11**	**Local**	**Fleur 11**	**Local**	**Fleur 11**
Dry plucked kg / plant						
	No Organic		**Millet Husk**		**Animal Manure**	
High Inorganic	39%	61%	51%	71%	27%	50%
Low Inorganic	- 4%	34%	30%	40%	33%	62%
No Inorganic		21%	15%	30%	32%	30%
	Local	**Fleur 11**	**Local**	**Fleur 11**	**Local**	**Fleur 11**

Figures:

Figure 1) Administrative boundaries of Senegal, The Gambia, and Guinea-Bissau and general trial locations, with each circle contained 60 farmer field trials in 2015. The background image is the mean annual rainfall from 2001-2015 as calculated at 10km resolution from the daily estimates of the Rainfall Estimator Version 2 (RFE2), then smoothed at a higher resolution for presentation.

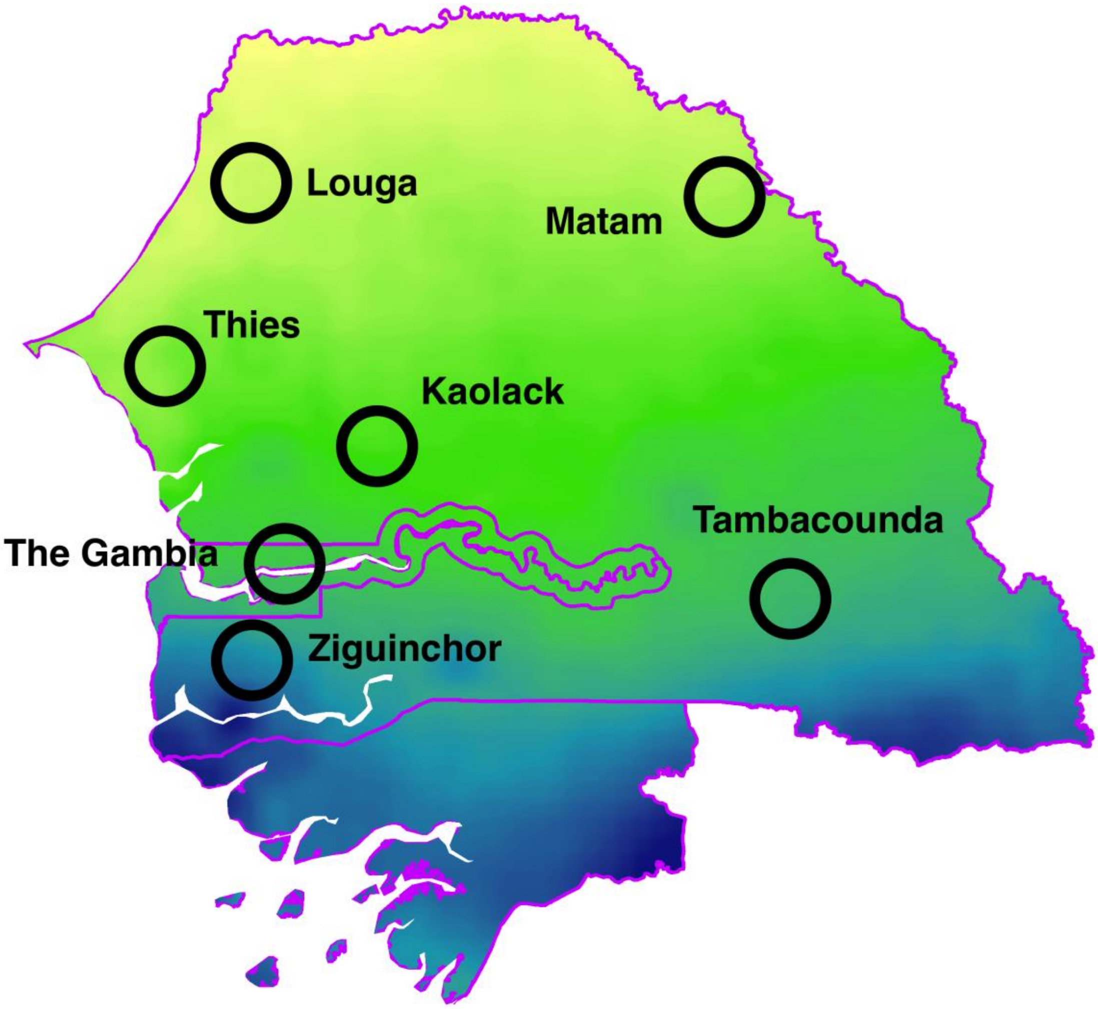

Figure 2) Spatial patterns of A) % sand and B) SOC organic carbon (g/kg soil) in the top 15 cm of the soil, as estimated by the Africa Soil Information Service (Hengl et al 2015).

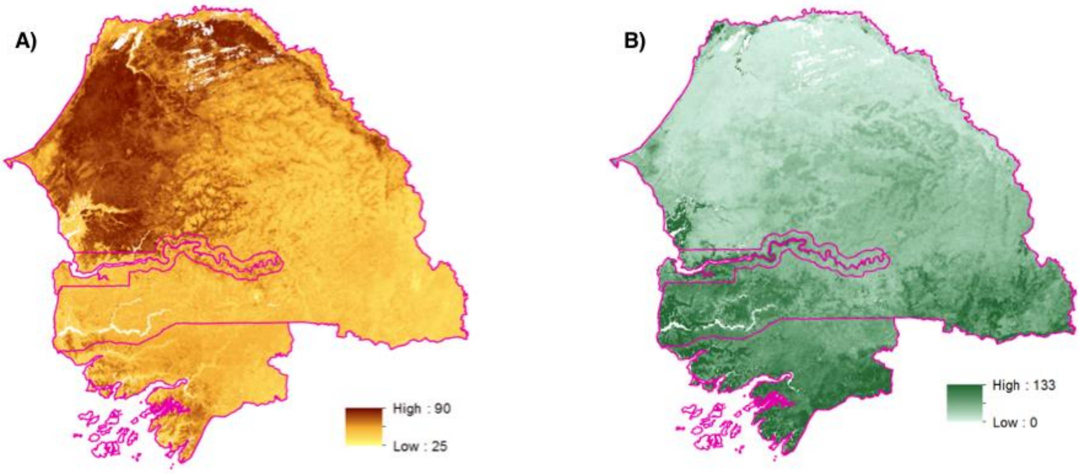

Figure 3) Spatial comparison of the 2015 rainy season and the mean of 1983 to 2015, presented as A) % difference in total precipitation and B) % difference in length of season, calculated as the number of days between the first and last day with greater than 10 mm of precipitation and correcting for outlier events. The values are calculated at 10 km resolution using the Africa Rainfall Climatology v.2.0 (ARC2) dataset, then transformed to a higher resolution and smoothed for presentation (Novella and Thiaw 2013). This dataset is less accurate than the RFE2, but with a longer timescale is more suitable for temporal comparisons.