

Weather Risk: How does it change the yield benefits of nitrogen fertilizer and improved maize varieties in sub-Saharan Africa?

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Abstract

The purpose of this research was to explore how weather risk affects the value of nitrogen fertilizer use and improved seed variety adoption to Sub-Saharan African (SSA) maize farmers. It contributes to the literature by providing additional broad support for the hypothesis that low rates of fertilizer use and improved seed variety adoption can be attributed to the fact that the SSA landscape is heterogeneous, so fertilizer and improved seed are not always advantageous, especially when considering the potentially high cost to farmers of obtaining fertilizer and improved seed. The analysis finds a synergy between nitrogen fertilizer and improved seed varieties. While the benefits of nitrogen tend to increase overtime without improved seed varieties and the benefits of improved seed varieties tend to decrease overtime without nitrogen, combining the two provides more sustained productivity benefits. Therefore, securing both nitrogen use and improved variety adoption is important for promoting sustained productivity increases across most of SSA. The research also contributes to the literature a methodology for calculating willingness to pay bounds that assess the importance of farmers' risk tolerances as a barrier to fertilizer use or improved seed variety adoption.

Introduction

Growth in maize yields in much of sub-Saharan Africa (SSA) has failed to keep pace with other developing and more developed regions of the world (Ray et al. 2012). A common explanation for poor growth is low levels of fertilizer use and improved seed variety adoption. But why is fertilizer use and improved seed variety adoption low? Answering this question generally for the adoption of more intensive production practices by developing country farmers has stimulated much research interest. A thoughtful review of early literature identified factors such as a lack of credit, labor, and physical capital; limited education, information, infrastructure and markets; small farm size; weak land tenure arrangements; and low risk tolerance as potential reasons (Feder et al 1985). These themes have continued to develop in more recent literature. Foster and Rosenzweig (1995, 2010), Smale et al. (1995), and Diagne and Demont (2007) explore limited information and the extent to which limited information can be rectified through learning. The importance of networks and learning by watching neighbors has received attention (e.g., Munshi 2004, Conley and Udry 2010, Abebaw and Haile 2013). Chirwa (2005) and Byerlee and Heisey (1996) raise issues of market access, while credit constraints are highlighted in Smale et al. (1995) and Croppenstedt et al. (2003). Risks attributable to crop failures and subsistence concerns are further explored by Smale et al. (1995) and Dercon and Christiaensen (2011), while Duflo et al. (2011) introduce behavioral biases in decision making, particularly as related to impatience.

Another line of argument is that farms and farmers are heterogeneous making it false to presume that fertilizer and improved seed varieties are equally beneficial to everyone everywhere. Byerlee and Heisey (1996) argued the adoption of improved seed varieties plateaued because farmer preferences were not sufficiently considered in variety development,

which survey results appear to support (e.g., Lunduka et al. 2012). While Duflo et al. (2008) found fertilizer and improved seed was profitable when used optimally, sub-optimal use, including recommendations of the Ministry of Agriculture in Kenya, was found not to be profitable. Suri (2011) and Kathage et al. (2012, 2015) explored profitability and yield concerns of fertilizer and improved seed varieties using farm level survey data from Kenya and Tanzania. Suri concludes that there are maize farmers that do not adopt improved seed varieties even though the returns are high because of the high cost of acquiring fertilizer and seed from distant distributors. She also finds some farmers switch back and forth between adoption and dis-adoption due to low returns. Kathage et al. finds that where productivity gains are high in Tanzania, farmers are typically aware of and adopt fertilizer and improved seed varieties, while awareness and adoption are low in regions with small productivity gains.

The purpose of this research is to build on two aspects of previous research by exploring how weather risk can affect the yield benefits to maize farmers of nitrogen fertilizer or improved seed variety adoption across the widely heterogeneous SSA landscape. This objective is accomplished by simulating yield distributions (at a resolution of 30 arc minutes) for traditional and improved seed varieties with and without nitrogen fertilizer. The simulated yield distributions are used to create bounds on a farmer's willingness to pay (in terms of maize yield) to adopt fertilizer or improved seed varieties. The willingness to pay bounds account for heterogeneous farmer risk tolerances. Sensitivity analysis explores how the WTP bounds change as the price of maize or cost of nitrogen fertilizer change.

Four interesting results emerge from the analysis. First, the initial adoption of nitrogen fertilizer with traditional seed varieties clearly improves the yield distribution on relatively modest portions of the SSA landscape, though the proportion of the landscape showing clear improvement increases with sustained fertilizer use. Second, the initial adoption of improved

seed varieties without nitrogen fertilizer provides larger improvements to yield distributions across a larger portion of the SSA landscape, but these improvements tend to diminish with sustained use — ultimately to the extent that in some regions farmers would be better off returning to traditional seed varieties. Third, the initial adoption of improved seed varieties and fertilizer provides large improvements in the yield distribution across most of SSA and these improvements tend to persist with sustained adoption. Finally, while the improvement in yield distributions from fertilizer and improved seed varieties remain high across most of SSA even after taking into account the world price of maize and cost of nitrogen fertilizer, the value of these improvements are diminished or even completely lost in regions where limited market access effectively drives the price of maize down and cost of nitrogen fertilizer up.

The methods and results found herein contribute to the literature in multiple ways. Methodologically, the willingness to pay bounds analysis provides a practical strategy for dealing with heterogeneous farmer risk tolerances. Empirically, the results account for the riskiness of production due to weather, while also providing a more comprehensive continental scale analysis. Previous studies accounting for risk typically focus on a more limited scope of analysis (e.g., country or village level), while also making more restrictive assumptions regarding the characteristics of farmers' risk tolerances. Alternatively, previous continental scale studies of the value of nitrogen fertilizer in SSA have not considered the riskiness of maize production due to unpredictable weather.

The next section of the paper provides a brief, intuitive overview of the conceptual framework that guides our estimation of the willingness to pay bounds on which the subsequent analysis is based. We then describe the model used to develop yield distributions across the SSA landscape. This description includes an accounting of the sources of necessary climate and soils information as well as model parameterization and calibration. The specific scenarios that are

explored are introduced with the methods, while the sensitivity analysis is detailed within the context of the results. Conclusions reiterate key findings, offer policy insights, and review important caveats.

Bounding the Willingness to Pay for Better Yields

Unpredictable weather makes maize farming inherently risky—how much will be produced is not known when seed is planted (e.g., Liben et al. 2015). This and other types of risk have a significant impact on farmer decisions such as the decision to use fertilizer or adopted improved seed varieties (see Hurley 2010 for a review); though the magnitude, and sometimes the direction of the impact, can vary. This variation is typically divided into differences in the riskiness of production faced by farmers and differences in farmers' risk tolerances. For farmers living and working in close proximity to each other, differences in the riskiness of production attributable to weather will be negligible, making risk tolerances the key to understanding variation in farmers' decisions.

Differences in farmers' risk tolerances across the sub-Saharan African (SSA) landscape make assessing the yield benefits of fertilizer or improved seed challenging because measuring these differences is generally not practical on such a broad scale. However, there are circumstances when differences in the riskiness of production are stark enough to render farmers' risk tolerances irrelevant. For example, Figure 1 (a) shows two potential yield distributions represented by red and green lines. Suppose the red distribution represents the potential yield outcomes and likelihoods if a farmer plants a traditional seed variety. Alternatively, suppose the green distribution represents the potential yield outcomes and likelihoods if an improved seed variety is planted. The way these two distributions are illustrated, the average yield for the improved seed variety appears higher than the average yield

for the traditional seed variety. Suppose this is indeed the case. Alternatively, notice that the lowest potential yields are actually associated with the improved seed variety and that the variability of yields for the improved seed variety appears higher than for the traditional seed variety. Again, suppose this is in fact the case. Is a farmer better off choosing the traditional or improved seed variety?

[Figure 1: Example Yield Distribution Comparisons]

The answer to this question is not straightforward. While farmers are typically found to prefer higher average yields holding all else constant, they also tend to avoid the chance of really low yields or excessive yield variability. So, how would the yield distribution of the improved seed variety have to change to make the answer to this question obvious? Figure 1 (b) provides an answer. If the dotted green line is the yield distribution with the improved seed variety, any farmer who prefers higher yields would choose to plant it instead of the traditional seed variety because they are assured a higher yield no matter what happens. Alternatively, if the dashed green line is the yield distribution with the improved seed variety, any farmer who prefers higher yields would choose not to plant it because they are assured a lower yield than with the traditional seed variety. How much the green distribution must shift right before it is clearly better than the red distribution and how much it has to shift left before the red distribution is clearly better provides bounds on how much improved seed must change the yield distribution either up or down so the risk tolerances of farmers are no longer relevant for choosing between the alternatives.

These intuitive bounds can be refined further if it is reasonable to presume that farmers prefer higher yields and do not like risk in the sense that they prefer a certain maize yield to an uncertain maize yield when the average of the uncertain yield equals the certain yield. For example, farmers' always prefer a yield of 5.0 ton/ha for certain compared to an equal chance at

7.5 and 2.5 ton/ha. With these two commonly employed assumptions about farmers' risk tolerances, the bounds illustrated in Figure 1 (b) can be refined using the concept of second-order-stochastic dominance (Rothschild and Stiglitz 1970, 1971) to get the willingness to pay (WTP) bounds.¹ These WTP bounds are in terms of maize yields (ton/ha) rather than the usual money metric and are useful for comparing alternative production practices because they provide a measurement of the most a farmer could pay for improved production practices while still being better off with them. For example, if both bounds are positive when comparing the green distribution to the red in Figure 1 (a), then farmers are better off with the green distribution regardless of their risk tolerances. Alternatively, if both bounds are negative, then farmers are better off with the red distribution regardless of their risk tolerances. When the lower bound is negative and the upper bound is positive, which distribution is better depends on the risk tolerances of specific farmers.

Yield Distributions

Using WTP bounds to assess the yield benefits of nitrogen fertilizer or improved seed varieties when farmers are faced with unpredictable weather requires information on yields for traditional and improved seed varieties with and without nitrogen fertilizer under a range of possible weather outcomes. While such necessary information for forming yield distributions could be obtained from field experiments or survey data, the field and survey data we are aware of is lacking in terms of geographical and temporal extent for our purpose. Therefore, to gain insight across all of SSA where crop production takes place, we chose to develop yield distribution information using crop growth models and the distribution of historical weather outcomes.

¹ See Appendix A, particularly equations A7 and A7', for the precise definition of the WTP bounds.

The crop model used to simulate maize growth and yield was the CERES-Maize model (Jones et al. 1986) which is one of the suite of models in the Decision Support System for Agrotechnology Transfer (DSSAT) v4.5 (Jones et al. 2003, Hoogenboom et al. 2015). The CERES-Maize model describes daily phenological development and growth in response to environmental factors (soils, weather and management). Modelled processes include the duration of growth stages; growth of vegetative and reproductive plant parts; extension growth of leaves and stems; senescence of leaves; biomass production, and partitioning among plant parts, and root system dynamics; and yield and yield components of maize. The model includes subroutines to simulate nutrients (nitrogen and phosphorus) and water balances in soil and plants, giving it the capacity to simulate the effects of nutrient deficiency and soil water deficit on photosynthesis and pathways of carbohydrate movement in the plants.

In this study, the DSSAT model was used to simulate rainfed maize yield across SSA at a resolution of 30 arc-minute (about 60 km at the equator) for rainfed maize growing areas identified by the Spatial Allocation Model (SPAM) (You and Wood 2006). The primary data needed to run DSSAT includes weather, soil, maize variety characteristics, and information on farmers' management practices representing the modeling unit area. The weather data variables include daily solar radiation, maximum and minimum temperatures, and precipitation, typically obtained from the nearby weather station for field-scale studies. For this regional study, we used AgMERRA, a global gridded weather dataset (Ruane, Goldberg, and Chryssanthacopoulos 2015) that provides global-scale baseline weather data for 31 years (1980-2010). For the soil data, DSSAT requires detailed soil property information for each layer, which can be measured *in situ* for field-scale studies. For this regional-scale study, we used the HC27 Generic Soil Profile Database (Koo and Dimes 2013), which was developed using the reanalysis of ISRIC-WISE International Soil Profile Dataset (Batjes 1995) converted to a DSSAT-compatible format (Romero

et al. 2012) and resampled to the 30 arc-minute resolution based on the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009). For each grid cell, a monthly planting window was defined using the resampling of the CCAFS Generic Rainfed Crop Calendar data on 5 arc-minute grids obtained from CCAFS (<http://ccafs-climate.org>). Within the planting month, DSSAT was set to simulate the seed planting when the available soil moisture in the top 10 cm layer is above 10%.

While the model is capable of simulating balances of nitrogen and phosphorus, only nitrogen balance was simulated. This is due to the predominant role of nitrogen fertilizer in crop productivity potential in SSA overall (Zhang et al. 2015) and the agronomic characteristics of nitrogen (i.e., its relatively higher mobility and generally more immediate yield responses in maize than phosphorus), as well as the lack of detailed phosphorus data to appropriately initialize the phosphorus balance subroutine. Hence, the overall simulated yields from the model maybe overestimated in the areas where soil phosphorus is severely limiting for maize cultivation and not managed by applications of phosphorus fertilizer. For the nitrogen fertilizer input, 40 kg[N]/ha was split applied at 50:50 (i.e., 20 kg[N]/ha each) on the planting date and 10 days before flowering.

The CERES-Maize Model also requires genetic coefficients that are calibrated and evaluated using experimental data. The genetic coefficients for the improved maize varieties used in this study were obtained from previous International Maize and Wheat Improvement Center (CIMMYT) work that calibrated and evaluated benchmark maize varieties developed for specific maize mega environments in Africa (Tesfaye et al. 2015). The coefficients for the traditional varieties were taken from two old maize varieties that belong to the Katumani Composite with

long and short maturity length.² They have been commonly grown by African farmers for more than 15 years.

In order to develop the type of distributional data needed for our weather risk and WTP bounds analysis, DSSAT was run repeatedly for each grid cell using different weather sequences as illustrated in Table 1. In Table 1, the rows reflect 30 different replications of weather, while the columns represent 30 different seasons of weather. Yield distributions were formed from the 30 replicates in a seasonal cross section (e.g., the chosen simulation year). Cross sections were used instead of time series because DSSAT is history dependent making the time series of yield serially correlated. With cross sections, the yield realizations are not correlated. Furthermore, looking at the distribution of yield across different cross sections makes it possible to control for the length of the cropping history which is particularly important in low input cropping systems that can mine soils of important nutrients over time.

[Table 1: Weather Year Used in DSSAT Yield Simulations by Simulation Year and Replication]

In summary, for each of the 3,854 30 arc minute grid cells in SSA with some maize production in 2005 and each year of a thirty year crop history, DSSAT was used to simulate distributions for an improved and traditional seed variety with and without 40 kg[N]/ha of nitrogen fertilizer.

Results

The first set of results compares the estimated yield distribution for the traditional variety with and without nitrogen, the improved and traditional varieties without nitrogen, and the improved

² To explore the sensitivity of our results to our choice of the traditional seed variety, we used two different varieties parameterized for the DSSAT model denoted as CM1509 and CM1510, whose genetic coefficient values are included in Appendix B (Table B3). Results for CM1509 are reported here, while the same figures and tables for CM1510 can be found in Appendix B.

variety with and the traditional variety without nitrogen. These distributional comparisons focus on yields, while ignoring the cost of nitrogen fertilizer or improved seed varieties relative to the price received for maize. Therefore, we follow up these results with a sensitivity analysis that shows how the added cost of fertilizer relative to the price of maize changes the reported yield benefits.

Table 2 reports the WTP bound descriptive statistics. Figure 2, 3, and 4, panels (a) and (c) plot these WTP bounds (the upper bound on the vertical and lower bound on the horizontal axis) for a one and ten year cropping history for each 30 arc minute cell. The points in Figure 2, 3, and 4, panels (a) and (c) are colored in red to indicate farmers are clearly better off without nitrogen, improved seed varieties, or both; green to indicate farmers are clearly better off with nitrogen, improved seed varieties, or both; and yellow to indicate that the best option depends on a farmer's specific risk tolerances. The geographic distribution of these red, green, and yellow points are shown in Figures 2, 3, and 4, panels (b) and (d) for the one and ten year cropping histories.

[Table 2: Willingness to Pay (WTP) Bound (ton/ha) Descriptive Statistics]

[Figure 2: Traditional Variety With versus Without 40 kg/ha of Nitrogen Fertilizer in Year 1 and 10 Years After Adoption]

[Figure 3: Improved versus Traditional Varieties Without Nitrogen Fertilizer in Year 1 and 10 Years After Adoption]

[Figure 4: Improved Variety With 40 kg/ha of Nitrogen Fertilizer versus Traditional Variety Without Nitrogen Fertilizer in Year 1 and 10 Years After Adoption]

The top third of Table 2 and Figure 2 address the question of how adding nitrogen fertilizer to traditional seed varieties affects yield distributions across SSA. The results are different between the initial year and 10th year of repeated use. In the initial year, nitrogen fertilizer use is clearly the best option on only 32 percent of the 24.8 million hectares of cropland. After ten years, nitrogen use is clearly the best option on 49 percent of the cropland.

The increase in the yield benefits of nitrogen fertilizer with sustained use are illustrate in the shifting geographic extent of yellow in Figure 2 (b) to green in Figure 2 (d), which is particularly evident in Angola, Congo and Nigeria. As might then be expected, the average and median bounds on the WTP increase as the years of nitrogen fertilizer use increases. The improvements to sustained use are not uniformly positive however as the percentage of cropland with more risk increases from 2 to nearly 5 percent. Visually, this result is most apparent in Cameroon and Eastern Tanzania where the geographic extent of yellow in Figure 2 (b) yields to red in Figure 2 (d). A possible explanation for these results is that without nitrogen fertilizer, traditional maize varieties tend to mine naturally occurring soil nitrogen. Adding nitrogen fertilizer helps to stop (or at least slow this mining) in most regions, which improves soil productivity in future years (e.g., Nkonya et al. 2005).

The middle third of Table 2 and Figure 3 address the question of how switching from traditional to improved seed varieties without adding nitrogen fertilizer affects yield distributions across SSA. Again, the results are different between the initial and tenth year of adoption, but the difference is now in the opposite direction. In the first year, improved seed varieties are clearly better on 87 percent of cropland, falling to 77 percent after ten years of repeated use. Furthermore, after ten years, improved seed varieties result in clearly worse yield distributions on about 4.5 percent of cropland as compared to only 2.6 percent in the first year of adoption. Geographically, the deterioration of the benefits to the adoption of improved seed varieties is most apparent in Eastern and South Eastern SSA. A possible explanation for these results again relates to mining naturally occurring soil nitrogen. A major target of improved maize breeding is nitrogen use efficiency. Switching to varieties with greater nitrogen use efficiency, makes it possible to utilize more nitrogen annually, which becomes problematic overtime if there is no supplemental nitrogen to bolster naturally occurring nitrogen. Comparing the results in the top

and middle third of Table 2, and Figure 2 with 3, the yield distribution benefits of switching to improved seed varieties appear larger than using nitrogen fertilizer with traditional seed varieties even after ten years of adoption. Though in the initial year of adoption there is a larger proportion of cropland with more risk due to adoption of improved seed varieties when compared to fertilizer adoption.

The bottom third of Table 2 and Figure 4 address the question of how switching to improved seed with 40 kg/ha of nitrogen fertilizer affects yield distributions across SSA. The key result that supports our hypothesis regarding the importance of supplemental nitrogen for avoiding nitrogen mining, particularly with improved seed varieties, is that the improved seed varieties with nitrogen initially leads to improvements in the yield distributions across almost the entire landscape, and these improvements are largely, though not completely, maintained even after ten years at the top end of the yield distribution. At the bottom end at the yield distribution, the proportion of cropland with more risk declines from 0.51 percent in the initial year of adoption to 0.45 percent after ten years.

The result in Table 2 and Figures 2-4 show how fertilizer and improved seed varieties can affect yield distributions across SSA without considering the potential added cost of more intensive production to farmers. To take these costs into account, we determine how much additional maize (ton/ha) would need to be produced to cover the cost of 40 kg/ha of nitrogen given maize and fertilizer prices. The monthly average world maize price ranged from 0.15 to 0.33 \$/kg with an average of 22.3 \$/kg between June 2009 and April 2016 (IFPRI 2016). The price of urea between 2010 and 2014 reported in FAO (2015) ranged from 0.289 to 0.421 \$/kg. Using a urea price of 0.35 \$/kg, maize price of 0.25 \$/kg, and taking into account urea is 46 percent nitrogen, the cost of 40 kg/ha of nitrogen fertilizer in terms of maize is 122 kg/ha.

Given the maize price of fertilizer, we can determine if any change in the yield distribution due to using fertilizer and improved seed is enough to cover the cost of fertilizer by comparing this price to the lower WTP bound. If the lower WTP bound is larger than the price, there is a large enough improvement in the yield distribution to cover the cost of fertilizer (assuming no transportation or other costs). Alternatively, if the upper WTP bound is lower than this price, there is not a large enough improvement in the yield distribution to cover the cost of fertilizer. For a price between the WTP bounds, the result is indeterminate, again depending on a farmer's specific risk tolerance. The results of this analysis are reported in Figure 5, which illustrates the sensitivity of our results in terms of the proportion of cropland with clearly more and clearly less risk as the 122 kg/ha maize price of nitrogen fertilizer is scaled between 0 to 20 times. Figure 6 further illustrates these results geographically for nitrogen fertilizer prices of 122 and 20×122 kg/ha maize.

[Figure 5: Sensitivity Analysis for Improved Variety With 40 kg/ha Nitrogen Fertilizer versus Traditional Variety Without Nitrogen Fertilizer in Year 1 and 10 Years After Adoption]

[Figure 6: Sensitivity Analysis for Improved Variety With 40 kg/ha Nitrogen Fertilizer at a Price of 122 kg/ha and 20×122 kg/ha of Maize versus Traditional Variety Without Fertilizer in Year 1 and 10 Years After Adoption]

Figure 4, panels (b) and (d) are virtually indistinguishable from Figure 6, panels (a) and (c). The reason for such a small difference is found in the lower third of Table 2, which shows the mean WTP bounds are more than an order of magnitude larger than the maize price of nitrogen fertilizer. Similarly, the standard deviations of the WTP bound are much larger than the price. This suggests that the material cost of fertilizer, given world prices, is not substantial compared to the potential yield benefits it could provide with improved seed varieties across much of SSA. However, Figure 6, panels (b) and (d) show that if actual fertilizer (and improved seed variety) costs substantially outpace the material costs due to transportation and many other

factors, then the yield benefits of the adoption of fertilizer and improved seed varieties can be quickly dissipated by these costs over a broad landscape.

Conclusions

The purpose of this research was to explore how weather risk affects the value of nitrogen fertilizer use and improved seed variety adoption to Sub-Saharan African (SSA) maize farmers. Empirically, it contributes to the literature by providing additional and broader support for the hypothesis that low rates of fertilizer use and improved seed variety adoption can be explained by the fact that the SSA landscape is heterogeneous, so fertilizer use and improved seed variety adoption is not always advantageous, especially when considering the potentially high cost to farmers of obtaining fertilizer and improved seed.

Methodologically, it contributes willingness to pay bounds to the literature that can be used to assess the importance of farmers' risk tolerances as potential barriers to fertilizer use and improved seed variety adoption. While this methodology was applied to fertilizer and improved seed in SSA maize production using simulated yield distributions, its applicability can be extended to comparing other technology bundles in other regions of the world, using benefit metrics other than yield, and using distributions generated from survey or experimental as well as simulation data.

The analysis points to important synergies between nitrogen fertilizer and improved seed varieties that are particularly interesting from a policy perspective. While the benefits of nitrogen use tends to increase overtime without improved seed varieties and the benefits of improved seed varieties tend to decrease overtime without nitrogen, combining the two provides larger and more sustainable productivity benefits. Therefore, from a policy perspective, securing

both nitrogen use and improved seed variety adoption is important for promoting sustained maize productivity increases across most of SSA. It is also interesting to note that the yield benefits of improved seed varieties tended to be much larger than the yield benefits of using nitrogen fertilizer, particularly in the earlier years of adoption. This result suggests that securing higher levels of adoption may be obtained by sequentially introducing farmers to improved seed varieties before encouraging the use of nitrogen fertilizer because farmers are more likely to see larger improvements faster and with less additional effort.

Two caveats of our analysis are its focus on yield and use of simulated yield distributions. Depending on a farmer's commercial versus subsistence orientation, maize yield may not be the only or most important factor guiding behavior, meaning yield may not be the best metric for our analysis. The advantage to using crop growth models to simulate yield distributions is that they can be systematically and cost effectively applied across a wide area. The disadvantage is that they are inherently limited in the extent to which they can capture idiosyncratic differences in the production environment across a widely heterogeneous landscape. It should be also noted that the models do not capture all abiotic and biotic constraints that crops will face in the fields. This study focused on two broadly important abiotic constraints, soil water and nitrogen. The yields estimated from the model should be considered achievable assuming other constraints are well managed. While both experimental trial and farmer survey data offer obvious alternatives for generating yield distributions that will be more sensitive to these idiosyncratic differences, experimental trial data is relatively costly to generate and survey data, in addition to being costly, can be hopelessly confounded by various socio-economic factors. Therefore, alternative strategies for characterizing yield distribution are not without their own caveats.

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Table 1: Weather Year Used in DSSAT Yield Simulations by Simulation Year and Replication

Replication	Simulation Year							<i>Distribution</i> Cross-Sections →
	1	2	3	...	28	29	30	
1	1981	1982	1983	...	2008	2009	2010	
2	1982	1983	1984	...	2009	2010	1981	
3	1983	1984	1985		2010	1981	1982	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
28	2008	2009	2010	...	2005	2006	2007	
29	2009	2010	1981	...	2006	2007	2008	
30	2010	1981	1982	...	2007	2008	2009	

Time-Series →

Table 2: Willingness to Pay (WTP) Bound (ton/ha) Descriptive Statistics

	Year 1		Year 10	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound
	<i>Traditional with versus without 40 kg/ha N</i>			
Mean	0.28	0.10	0.48	0.24
Standard Deviation	0.55	0.31	0.63	0.49
Median	0.00	0.00	0.13	0.00
Inter-Quartile Range	0.26	0.01	0.86	0.30
[Min, Max]	[-0.23, 3.29]	[-1.60, 1.90]	[-0.18, 3.13]	[-0.86, 2.55]
Less Risk (%)	31.69		49.48	
More Risk (%)	2.03		4.89	
	<i>Improved versus Traditional without N</i>			
Mean	2.58	1.77	1.49	0.82
Standard Deviation	1.88	1.78	1.41	1.23
Median	2.45	1.55	1.04	0.46
Inter-Quartile Range	2.89	2.67	1.89	1.33
[Min, Max]	[-1.26, 9.42]	[-3.08, 8.65]	[-1.70, 7.41]	[-3.08, 6.84]
Less Risk (%)	86.52		76.58	
More Risk (%)	2.57		4.52	
	<i>Improved with 40 kg/ha N versus Traditional without N</i>			
Mean	3.47	2.59	2.91	2.15
Standard Deviation	1.72	1.72	1.39	1.42
Median	3.25	2.45	2.83	2.16
Inter-Quartile Range	2.16	2.24	1.82	2.05
[Min, Max]	[-1.68, 10.26]	[-3.58, 9.29]	[-1.70, 7.70]	[-3.08, 7.17]
Less Risk (%)	95.80		94.42	
More Risk (%)	0.51		0.45	
Million Hectares			24.8	
Cells			3,854	

Figure 1: Example Yield Distribution Comparisons

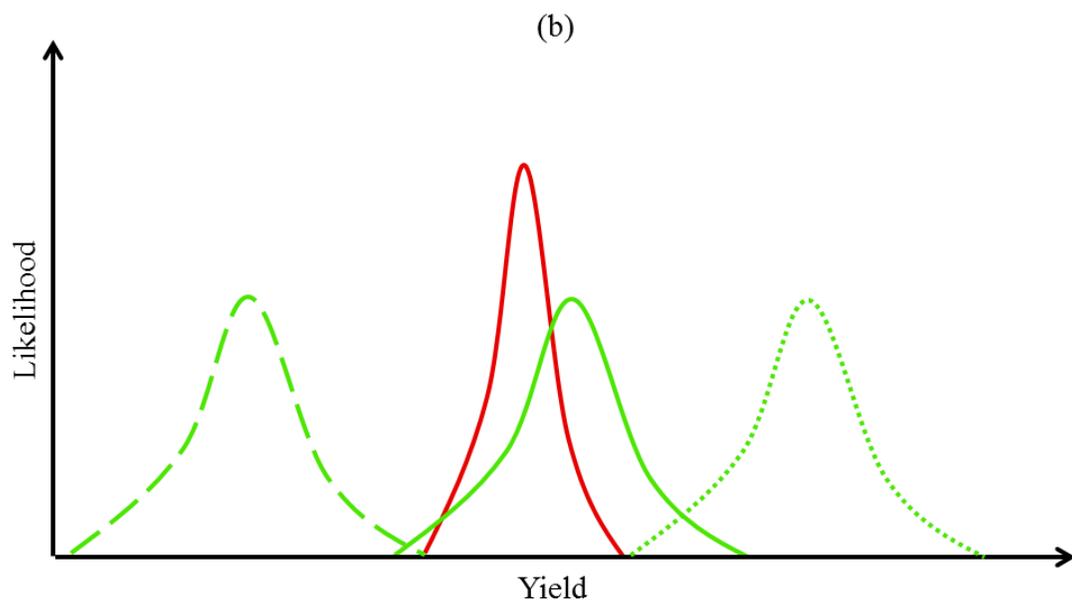
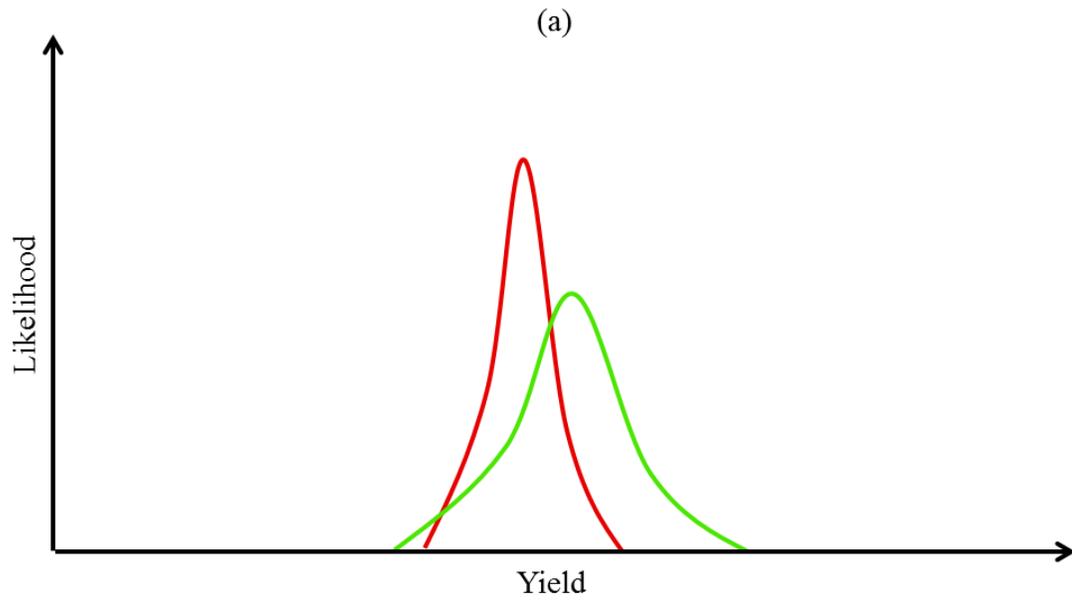


Figure 2: Traditional Variety With versus Without 40 kg/ha of Nitrogen Fertilizer in Year 1 (Panels (a) and (b)) and 10 Years After Adoption (Panels (c) and (d))

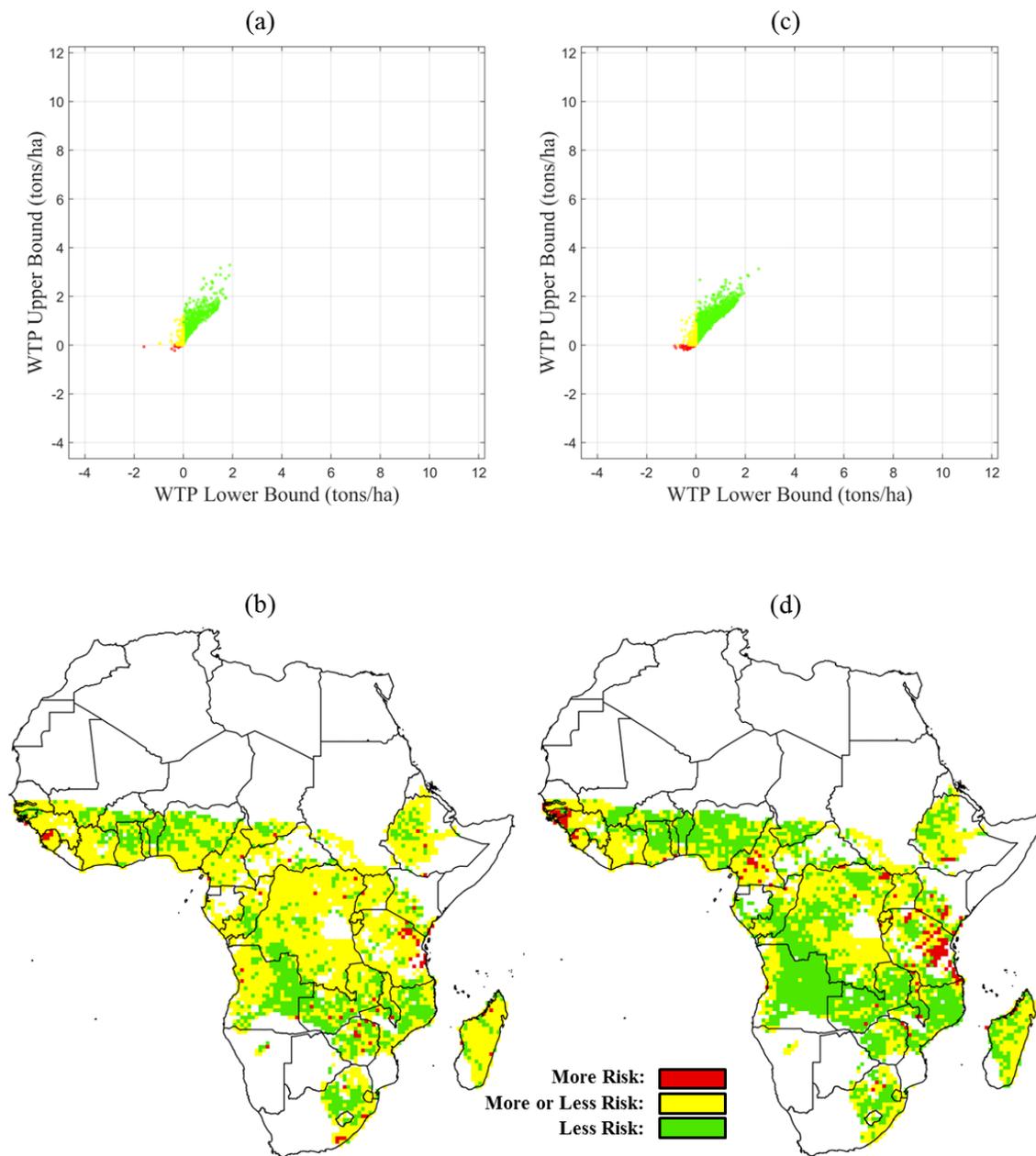


Figure 3: Improved versus Traditional Varieties Without Nitrogen Fertilizer in Year 1 (Panels (a) and (b)) and 10 Years After Adoption (Panels (c) and (d))

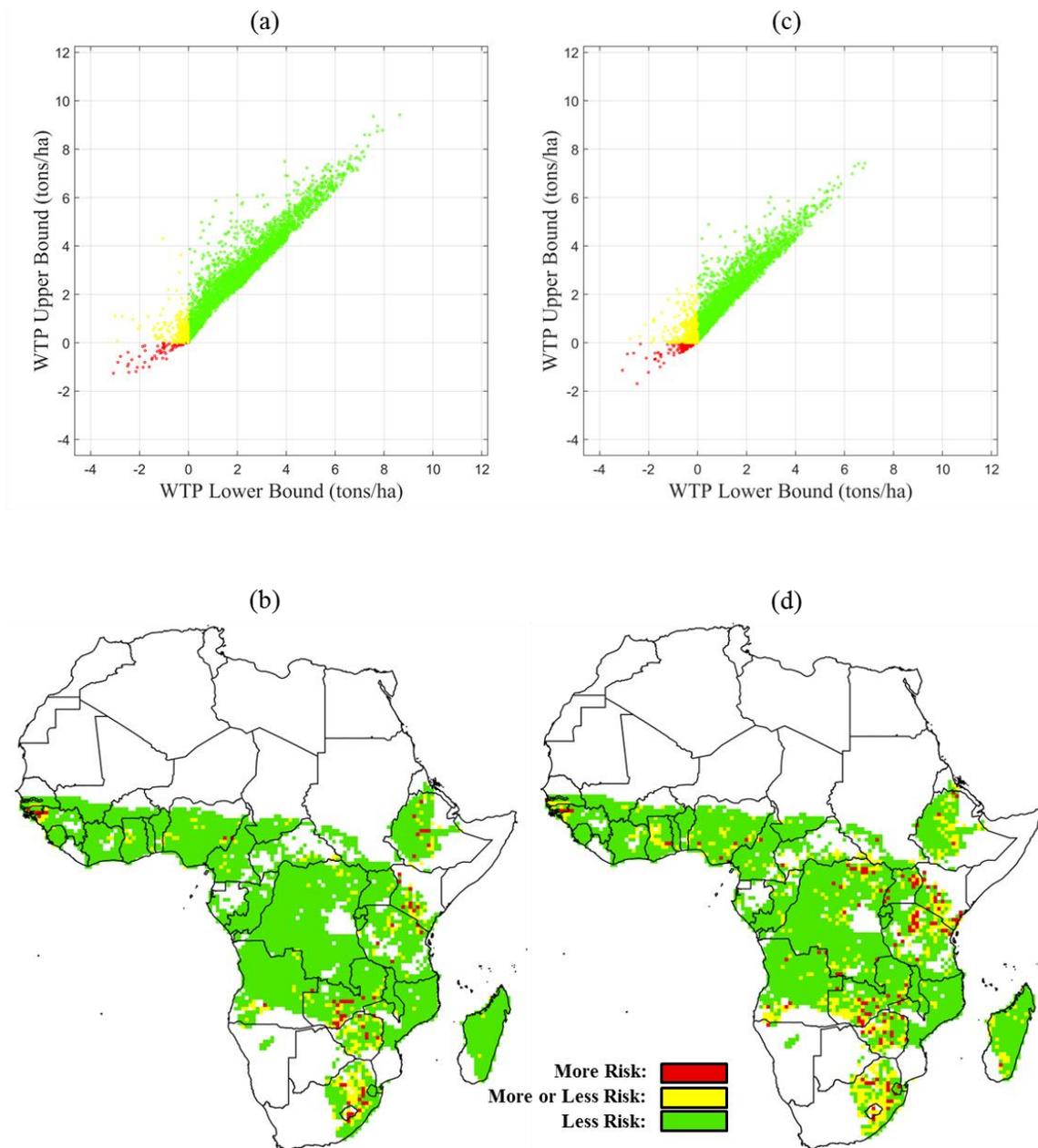


Figure 4: Improved Variety With 40 kg/ha of Nitrogen Fertilizer versus Traditional Variety Without Nitrogen Fertilizer in Year 1 (Panels (a) and (b)) and 10 Years After Adoption (Panels (c) and (d))

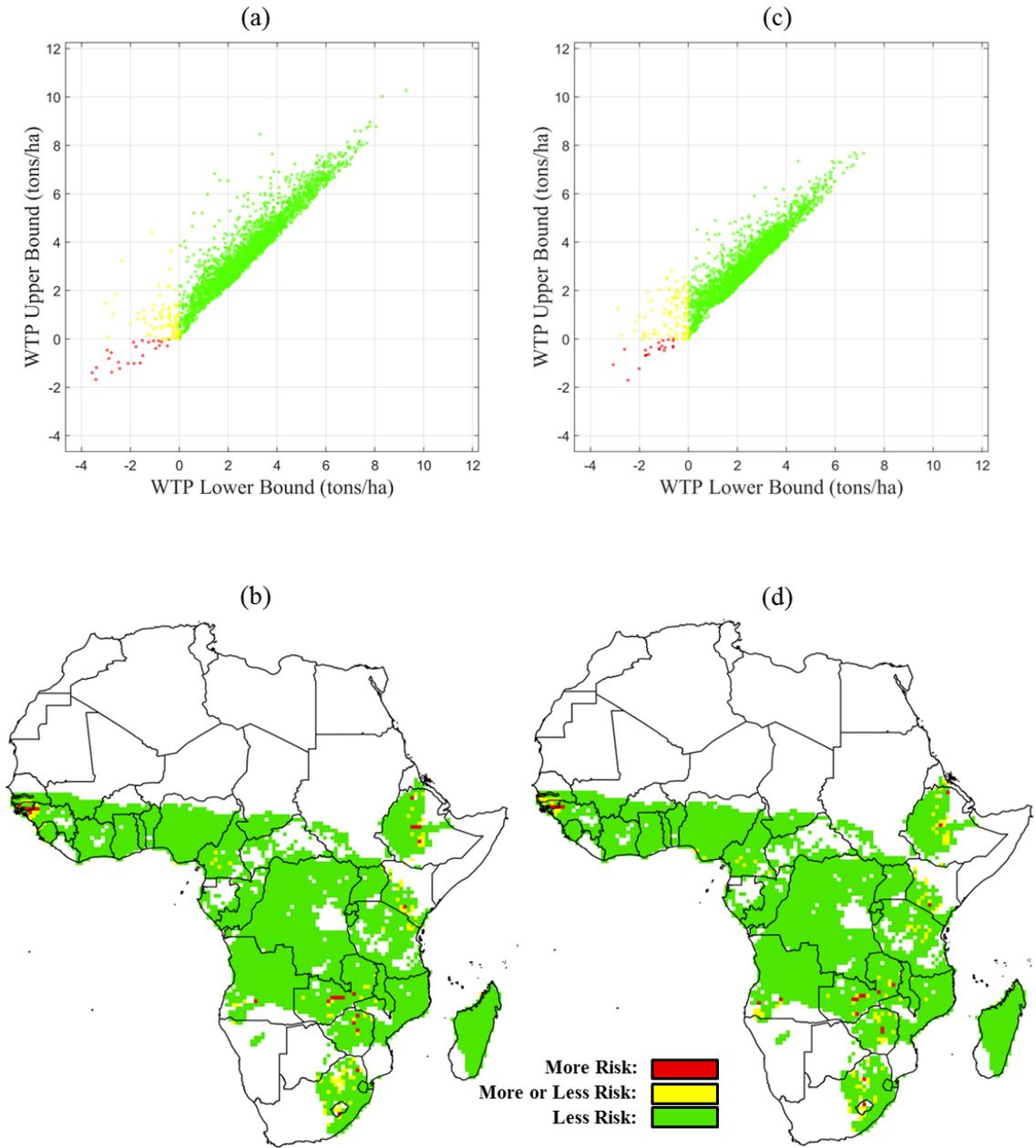


Figure 5: Sensitivity Analysis for Improved Variety With 40 kg/ha Nitrogen Fertilizer versus Traditional Variety Without Nitrogen Fertilizer in Year 1 (Panel (a)) and 10 Years After Adoption (Panel (b))

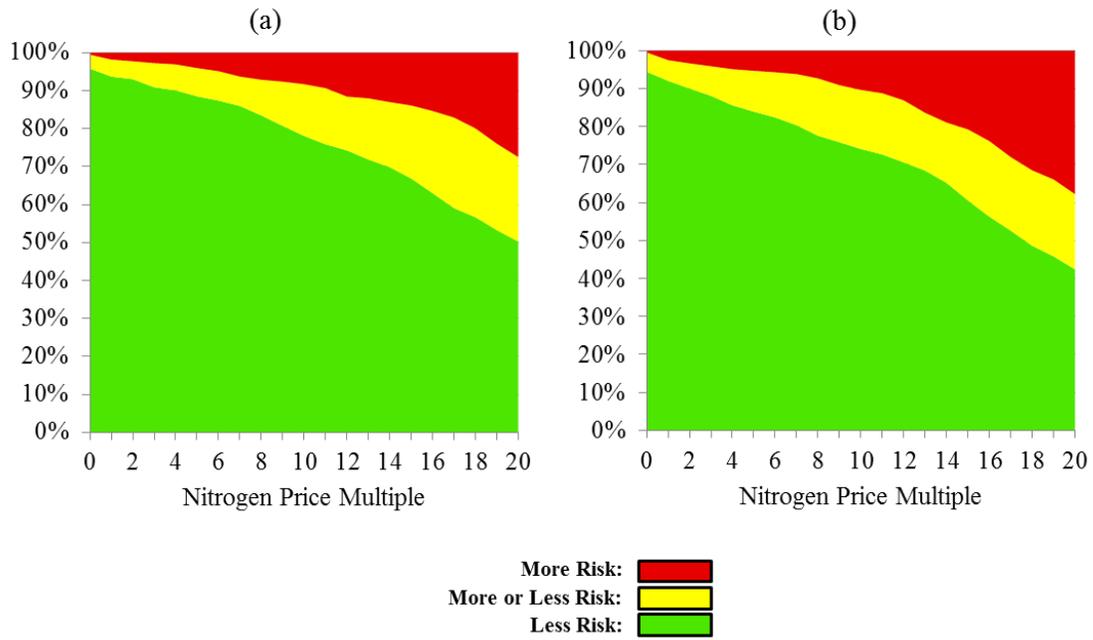
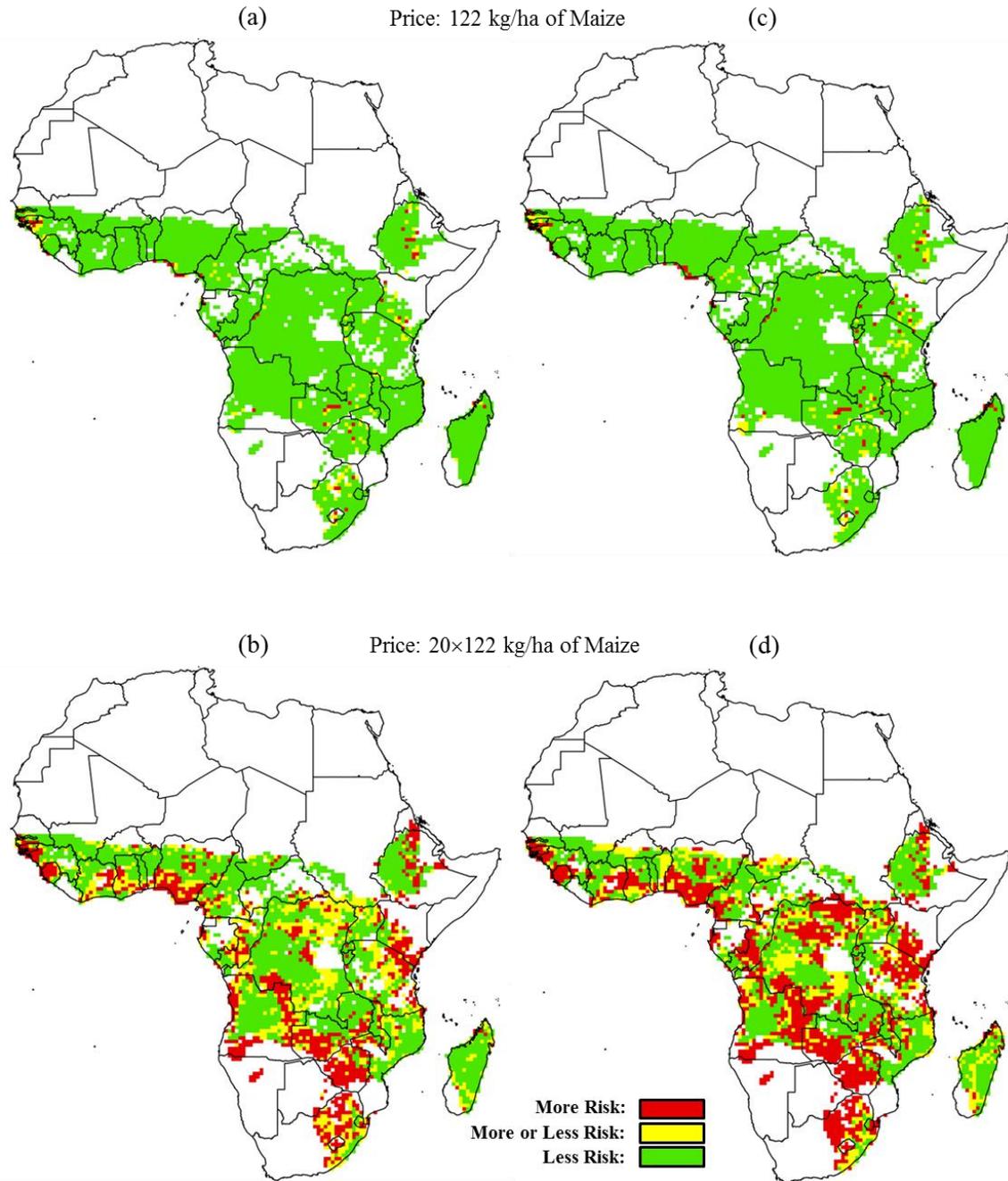


Figure 6: Sensitivity Analysis for Improved Variety With 40 kg/ha Nitrogen Fertilizer at a Price of 122 kg/ha and 20×122 kg/ha of Maize versus Traditional Variety Without Fertilizer in Year 1 (Panels (a) and (b)) and 10 Years After Adoption (Panels (c) and (d))



Appendix A: Theoretical Motivation

The purpose of this appendix is to provide the theoretical motivation for the upper and lower willingness to pay (WTP) bounds used to compare traditional and improved seed varieties with and without fertilizer. We begin with some notation. Let $F^k(x)$ be the distribution function and $f^k(x)$ the density for production alternative k where $x \in [x_k^L, x_k^U] \subset \mathbb{R}$. For our application, x represents maize grain yields (ton/ha) and the production alternatives are traditional and improved seed varieties with and without 40 kg/ha of nitrogen fertilizer. For other applications, x will often represent profit or net returns, but could represent any real valued measure used by farmers to make a decision. Production alternatives may represent a farmer's current practice versus the adoption of a new pesticide, pest scouting regime, seed variety, or any other possible change to the current production practice.

Consider two such alternatives denoted by $k \in \{r, g\}$. We assume farmers exhibit risk averse, expected utility preferences such that alternative g is strictly preferred to alternative r if and only if

$$A1 \quad EU^g = \int_{x_g^L}^{x_g^U} U(x) f^g(x) dx > \int_{x_r^L}^{x_r^U} U(x) f^r(x) dx = EU^r$$

where $U(x)$ is a continuous and twice differentiable Bernoulli utility function such that $U'(x) > 0$ and $U''(x) < 0$. The assumption $U'(x) > 0$ is often referred to as monotonicity and it implies that more x is preferred to less or, in our case, farmers prefer higher yields. The assumption $U''(x) < 0$ is a concavity assumption that implies risk aversion. An individual is risk averse if she prefers a certain outcome to an uncertain outcome with equal expected values. For example, a risk averse individual always prefers \$100 for certain compared to an equal probability of \$200 or \$0.

Building on the intuition presented in Figure 1 (b), consider the question: What is the most a farmer would be willing to pay (in terms of x) to be able to switch from alternative r to g ?

The answer to this question is

$$\text{A2} \quad wtp = \sup_t \left\{ t: \int_{x_g^L}^{x_g^U} U(x-t) f^g(x) dx > \int_{x_r^L}^{x_r^U} U(x) f^r(x) dx \right\},$$

which generally depends on $U(x)$, $f^g(x)$, and $f^r(x)$, though Rothschild and Stiglitz (1970, 1971) show that it is possible to derive less precise sufficiency conditions that only depend on $f^g(x)$ and $f^r(x)$. To understand how, we first transform the distribution of $f^g(x)$ by defining $x = x^o + t$ and the distribution $f^r(x)$ by defining $x = x^o$, which yields $f^{g^o}(x^o) = f^g(x^o + t)$ for $x^o \in [x_g^L - t, x_g^U - t]$ (zero otherwise) and $f^{r^o}(x^o) = f^r(x^o)$ for $x^o \in [x_r^L, x_r^U]$ (zero otherwise). Let $x^L = \min\{x_k^L - t, x_k^U - t, x_r^L, x_r^U\}$ and $x^U = \max\{x_k^L - t, x_k^U - t, x_r^L, x_r^U\}$ and rewrite the comparison in equation A2 based on these transformed distributions:

$$\text{A3} \quad \int_{x^L}^{x^U} U(x^o) f^{g^o}(x^o) dx^o > \int_{x^L}^{x^U} U(x^o) f^{r^o}(x^o) dx^o.$$

Integrating equation A3 by parts yields

$$\begin{aligned} \text{A4} \quad & U(x^U) F^{g^o}(x^U) - U(x^L) F^{g^o}(x^L) - \int_{x^L}^{x^U} U'(x^o) F^{g^o}(x^o) dx^o > \\ & U(x^U) F^{r^o}(x^U) - U(x^L) F^{r^o}(x^L) - \int_{x^L}^{x^U} U'(x^o) F^{r^o}(x^o) dx^o \text{ or} \\ & - \int_{x^L}^{x^U} U'(x^o) F^{g^o}(x^o) dx^o > - \int_{x^L}^{x^U} U'(x^o) F^{r^o}(x^o) dx^o \end{aligned}$$

where $F^{g^o}(x^o)$ and $F^{r^o}(x^o)$ are the cumulative distributions for $f^{g^o}(x^o)$ and $f^{r^o}(x^o)$.

Integrating equation A4 by parts yields

$$\begin{aligned} \text{A6} \quad & -U'(x^U) \int_{x^L}^{x^U} F^{g^o}(z) dz + U'(x^L) \int_{x^L}^{x^L} F^{g^o}(z) dz + \int_{x^L}^{x^U} U''(x^o) \int_{x^L}^{x^o} F^{g^o}(z) dz dx^o > \\ & -U'(x^U) \int_{x^L}^{x^U} F^{r^o}(z) dz + U'(x^L) \int_{x^L}^{x^L} F^{r^o}(z) dz + \int_{x^L}^{x^U} U''(x^o) \int_{x^L}^{x^o} F^{r^o}(z) dz dx^o \text{ or} \\ & U'(x^U) \int_{x^L}^{x^U} (F^{r^o}(z) - F^{g^o}(z)) dz - \int_{x^L}^{x^U} U''(x^o) \int_{x^L}^{x^o} (F^{r^o}(z) - F^{g^o}(z)) dz dx^o > 0 \end{aligned}$$

where z is a variable of integration. Sufficient conditions for equation A3 to be true are then $F^{r^o}(z) \geq F^{g^o}(z)$ for all $z \in [x^L, x^U]$, strictly so for some $z \in [x^L, x^U]$. Thus, the largest possible t that still satisfies equation A3 provides a bound on the WTP where the distribution g , adjusted by t , is preferred to the distribution r , yielding the definition

$$A7 \quad wtp^{LB} = \sup_t \{t: F^{r^o}(z) \geq F^{g^o}(z) \text{ for all } z \in [x^L, x^U], \text{ strictly so for some } z\}.$$

Alternatively, consider

$$A3' \quad \int_{x^L}^{x^U} U(x^o) f^{r^o}(x^o) dx^o > \int_{x^L}^{x^U} U(x^o) f^{g^o}(x^o) dx^o,$$

which by analogous arguments has the sufficiency conditions $F^{g^o}(z) \geq F^{r^o}(z)$ for all $z \in [x^L, x^U]$, strictly so for some $z \in [x^L, x^U]$. Thus, the largest possible t that satisfies equation A3' also provides a WTP bound. This WTP bound is where the distribution r is always preferred to the distribution g adjusted by t , yielding the definition

$$A7' \quad wtp^{UB} = \inf_t \{t: F^{g^o}(z) \geq F^{r^o}(z) \text{ for all } z \in [x^L, x^U], \text{ strictly so for some } z\}.$$

Note the expression $\int_{x_g^L}^{x_g^U} U(x-t) f^g(x) dx$ is decreasing in t , which immediately implies

three additional results. For all continuous and twice differentiable $U(x)$ such that $U'(x) > 0$ and $U''(x) < 0$,

- $wtp^{UB} \geq wtp^{LB}$,
- $wtp^{UB} \geq wtp^{LB} > 0$ if $EU^g > EU^r$, and
- $0 > wtp^{UB} \geq wtp^{LB}$ if $EU^r > EU^g$.

That is, wtp^{LB} is a lower bound, while wtp^{UB} is an upper bound on the WTP for alternative g instead of alternative r . Furthermore, if both WTP bounds are positive, then any risk averse individual will prefer alternative g to r . Conversely, if both WTP bounds are negative, then any

risk averse individual will prefer alternative r to g . Thus, the willingness to pay bounds reported in the main text are derived from the definitions in equations A7 and A7'.

Appendix B: Supplementary Tables and Figures

Table B2: Willingness to Pay (WTP) Bound (ton/ha) Descriptive Statistics

	Year 1		Year 10	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound
	<i>Traditional with versus without 40 kg/ha N</i>			
Mean	0.11	0.02	0.22	0.07
Standard Deviation	0.35	0.12	0.45	0.24
Median	0.00	0.00	0.00	0.00
Inter-Quartile Range	0.01	0.00	0.18	0.00
[Min, Max]	[-0.18, 2.43]	[-0.36, 1.56]	[-0.18, 2.40]	[-0.67, 1.73]
Less Risk (%)	15.70		22.74	
More Risk (%)	0.91		4.93	
	<i>Improved versus Traditional without N</i>			
Mean	2.97	2.10	1.78	0.97
Standard Deviation	2.36	2.33	1.85	1.73
Median	3.00	2.16	1.57	0.71
Inter-Quartile Range	3.64	3.69	2.75	2.23
[Min, Max]	[-2.08, 11.48]	[-3.06, 10.69]	[-2.82, 8.97]	[-3.50, 7.91]
Less Risk (%)	77.61		67.95	
More Risk (%)	10.65		17.78	
	<i>Improved with 40 kg/ha N versus Traditional without N</i>			
Mean	3.84	2.95	3.18	2.33
Standard Deviation	2.22	2.24	1.84	1.91
Median	3.66	2.95	3.16	2.44
Inter-Quartile Range	2.73	2.94	2.32	2.47
[Min, Max]	[-2.10, 12.25]	[-3.30, 11.26]	[-2.77, 9.27]	[-3.42, 8.44]
Less Risk (%)	89.55		86.73	
More Risk (%)	2.72		2.52	
Total Hectares			24.8	
Cells			3,854	

Table B3: Genetic coefficient values of traditional varieties used in the CERES-Maize model

	CM1509 (Long maturity)	CM1510 (Short maturity)
P1: Thermal time from seedling emergence to the end of juvenile phase (expressed in degree days above a base temperature of 8 °C) during which the plant is not responsive to changes in photoperiod.	238.6	125.0
P2: Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h)	0.5	0.5
P5: The thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C)	654	560
G2: Maximum possible number of kernels per plant	450	450
G3: Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)	8.5	9.5
PHINT: Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	75	75

Figure B2: Traditional Variety With versus Without 40 kg/ha of Nitrogen Fertilizer in Year 1 (Panels (a) and (b)) and 10 Years After Adoption (Panels (c) and (d))

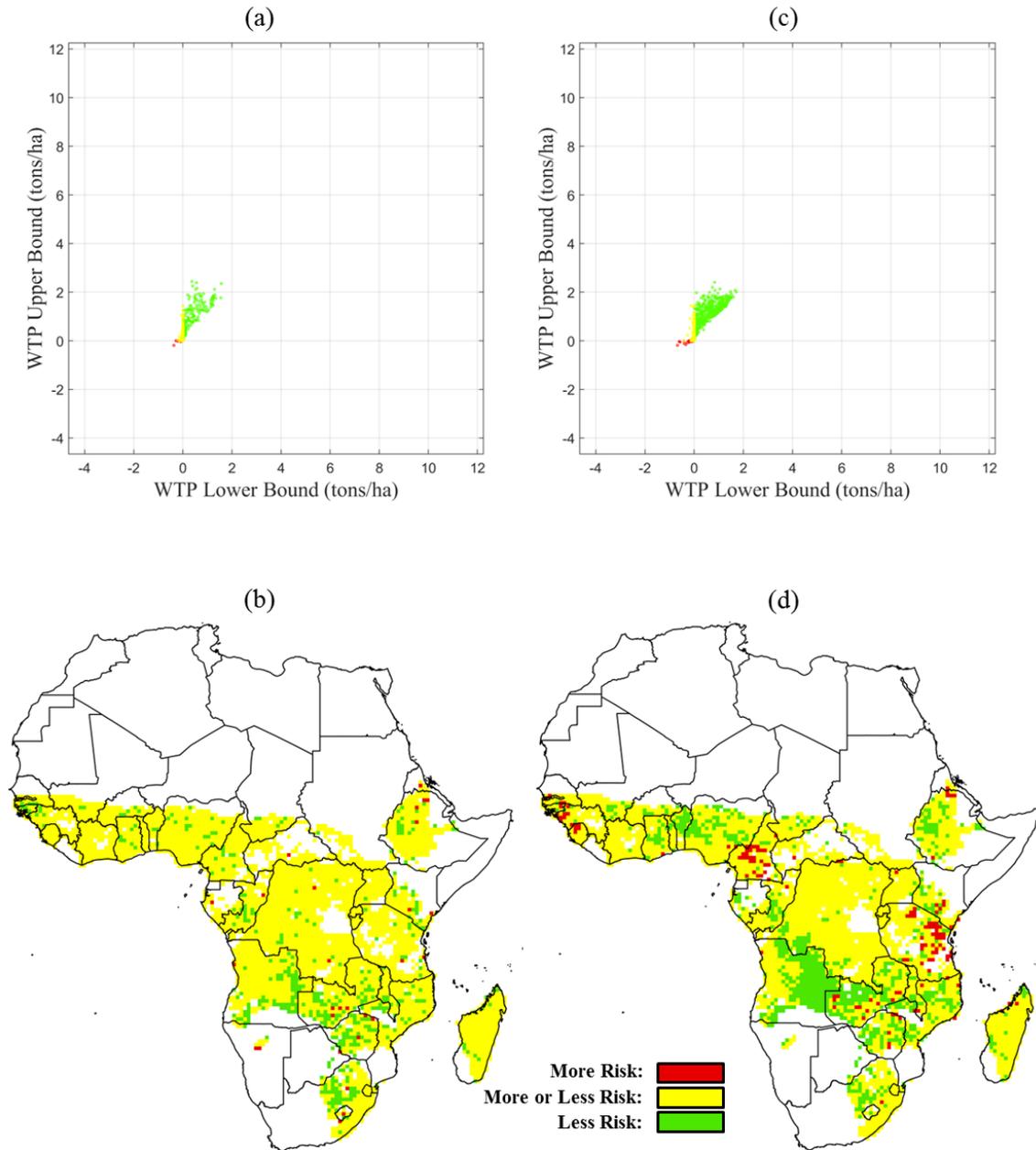


Figure B3: Improved versus Traditional Varieties Without Nitrogen Fertilizer in Year 1 (Panels (a) and (b)) and 10 Years After Adoption (Panels (c) and (d))

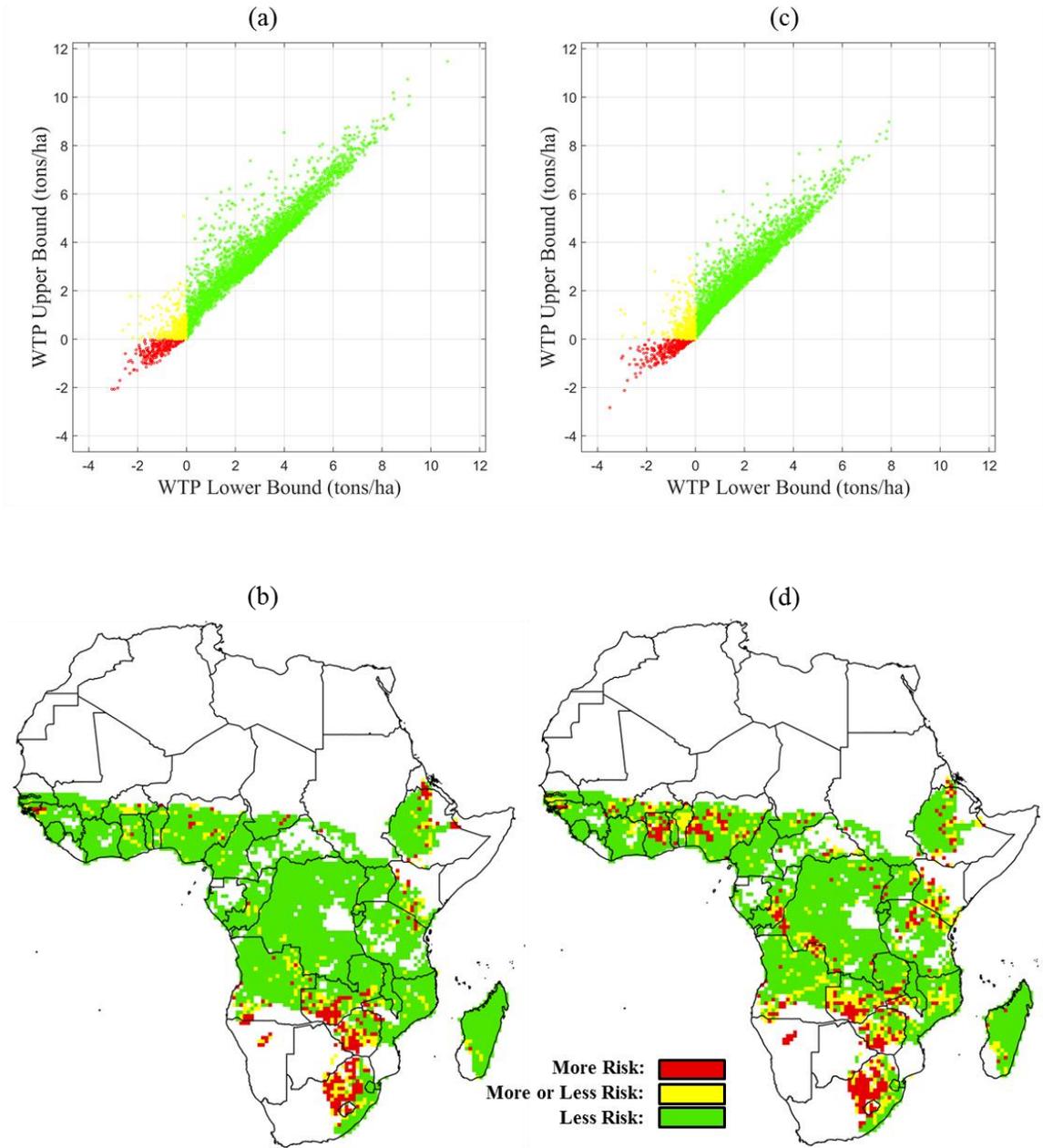


Figure B4: Improved Variety With 40 kg/ha of Nitrogen Fertilizer versus Traditional Variety Without Nitrogen Fertilizer in Year 1 (Panels (a) and (b)) and 10 Years After Adoption (Panels (c) and (d))

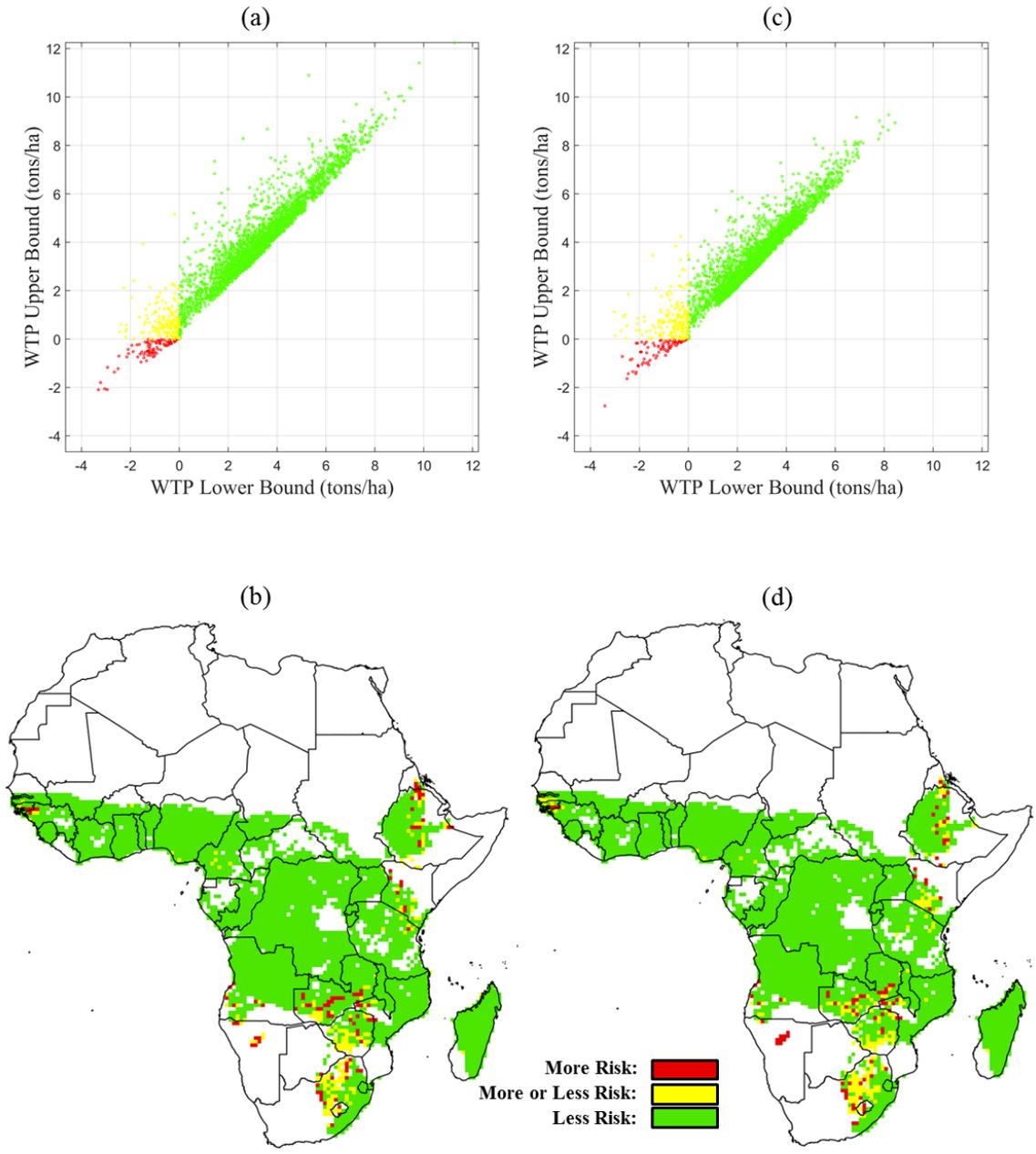


Figure B5: Sensitivity Analysis for Improved Variety With 40 kg/ha Nitrogen Fertilizer versus Traditional Variety Without Nitrogen Fertilizer in Year 1 (Panel (a)) and 10 Years After Adoption (Panel (b))

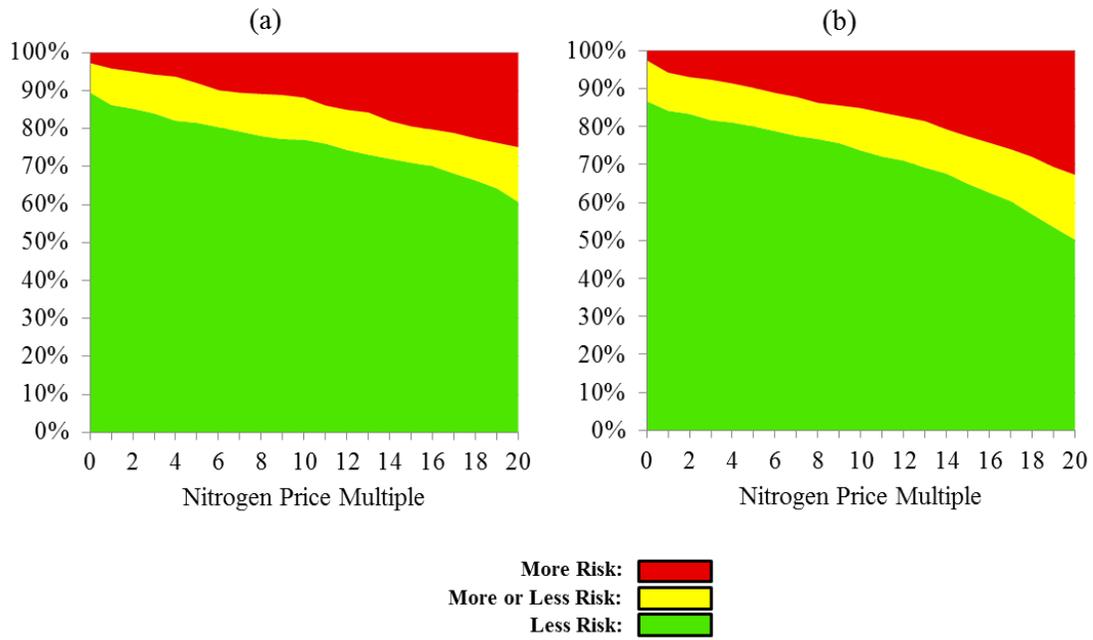


Figure B6: Sensitivity Analysis for Improved Variety With 40 kg/ha Nitrogen Fertilizer at a Price of 122 kg/ha and 20×122 kg/ha of Maize versus Traditional Variety Without Fertilizer in Year 1 (Panels (a) and (b)) and 10 Years After Adoption (Panels (c) and (d))

