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Better Agronomic Management Increases Climate Resilience of Maize to Drought in Tanzania

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Abstract: Improved access to better seeds and other inputs, as well as to market and financing, provides greater harvest security for smallholder farmers in Africa, boosting their incomes and increasing food security. Since 2015, a variety of agronomic measures have been introduced and adopted by smallholder farmers under a program led by the United Nations' World Food Program (WFP) called the Patient Procurement Platform (PPP). Here, we integrate a variety of agronomic measures proposed by the PPP to more than 20,000 smallholder farmers in Tanzania into 18 management strategies. We apply these across the country through grid-based crop model (DSSAT) simulations in order to quantify their benefits and risk to regional food security and smallholder farmers' livelihoods. The simulation demonstrates current maize yields are far below potential yields in the country. Simulated yields across the nation were slightly higher than the mean of reported values from 1984 to 2014. Periodic droughts delayed farmers' sowing and reduced maize yield, leading to high risk and low sustainability of maize production in most of the maize areas of the country. Better agronomic management strategies, particularly the combination of long-maturity, drought tolerance cultivars, with high fertilizer input, can potentially increase national maize production by up to five times, promoting Tanzania as a regional breadbasket. Our study provides detailed spatial and temporal information of the yield responses and their spatial variations, facilitating the adoption of various management options for stakeholders.

Keywords: climate resilience; crop model; maize; drought; Tanzania

1. Introduction

Sub-Saharan African (SSA) is known to be the only region in the world where per capita food production has remained stagnant or declined for over 40 years [1,2]. This status of food insecurity, characterized by food insufficiency, volatility of food prices, high poverty rates, and vulnerability to multi-dimensional shocks, such as extreme weather and climate change, is compounded by pressures such as fast-growing population and soil fertility decline, and increasing land constraint on densely rural populated areas [3]. There has been an increasing awareness that SSA must produce more and better food to make its own green revolution, particularly in small-scale, low-productivity farms, on which two-thirds of its people depend [4,5].

Smallholder farmers are the crucial player for production growth and poverty alleviation, but their limited access to better seeds (e.g., high-yielding hybrid seed) and other inputs, as well as to market and financing, constrains their capacity to increase production and reduce resilience [1]. Improving farming practices and enhancing food production for smallholder farms have been investment priorities for both public and private donors, such as the European Commission and the Bill & Melinda Gates

Foundation. This has triggered important agricultural development initiatives in Africa, such as the Patient Procurement Platform (PPP) led by the United Nations (UN) World Food Program (WFP) [6] and Tanzania's Staples Value Chain funded by U.S. Agency for International Development (USAID) [7]. Improved agronomic management, such as better fertilizer and seed, access to regional or global market and finance, and involving smallholder farmers in the supply chain, can increase regional food security and help build resilience through increasing food production and income opportunities. For example, in a consortium of leading public and private sector organizations, the PPP enables more than 50,000 farmers in three African countries (Tanzania, Rwanda, and Zambia), to access loans, to purchase and plant seeds and harvest high-quality crops, to expand production, and to earn a more stable income.

Maize is the most important food crop in SSA, consumed by 50% of the population and the largest source of calories [8,9]. Tanzania is SSA's fourth largest producer, after South Africa, Nigeria, and Ethiopia, producing 5.3 million tons of maize in 2013 [10]. Due to a historical national surplus and potential export opportunities of maize to South and East Africa, Tanzania's government has included improved maize productivity as one of their major goals in an effort to become a regional breadbasket. Despite the importance of maize, yields remain low in Tanzania [11]. Low productivity in Tanzania is a result of the traditional, rain-fed cultivation techniques employed by the smallholder segment, which produces most of Tanzania's maize. Besides the low yield, high production variability due to weather extremes is another risk, particularly for the livelihoods of smallholder farmers. Drought is by far the natural hazard that is most cited by researchers to have caused crop failure with a range of devastating impacts on the socioeconomic development of the African countries [12]. In Africa as a whole, an estimated 40% of the region's maize faces periodic drought stress, leading to yield losses of 10–25% [13,14].

A number of studies have been conducted in Tanzania to understand yield benefits to various management practices [7–9]. To date, however, nationwide studies are relatively rare to quantify the potentials and associated risks of integrated management strategies, in terms of their capacity to promote regional food security and coping with extreme events, such as drought. Through the lens of the PPP [6], this study aims to (a) quantify the constraints and risks faced by Tanzania's maize production sector, (b) devise management strategies that can increase maize productivity, and (c) examine the risks associated with these strategies and their implication for smallholder farmers.

2. Method

2.1. Study Area

The United Republic of Tanzania (hereafter Tanzania) is selected as a case study region from three countries included in the pilot WFP PPP program. Tanzania has the second largest area planted with maize in Africa, after Nigeria, and it is the fourth largest maize producer in Sub-Saharan Africa. According to UN FAO (United Nation Food and Agriculture Organization) data, in Tanzania approximately 4.15 million hectares of land were planted with maize in 2014 [10]. Maize provides 60% percent of dietary calories and more than 35% of utilizable protein to the Tanzanian population. It is also a major source of income for the majority of smallholders. Maize is produced for both human consumption and the market with approximately 40% sold, mostly locally. Annual per capita consumption is 73 kg.

2.2. Data

2.2.1. National Maize Production and Yield Data

Historical crop production reports are scarce, particularly at the sub-national level. From the Tanzania National Bureau of Statistics, we obtained national-level data on maize yield covering the period from 1995 to 2008 (inclusive). The mean maize yield during the period was less than 1.5 t/ha, with annual yield variations ranging between 10% and 20% (0.94–1.71 t/ha).

2.2.2. Farm Survey

Increased application of inorganic fertilizer and improved crop varieties are vital to increase the productivity of the SSA smallholder famer [15]. Despite that many agronomic practices have been made available and accessible through governmental and private interventions, such as the PPP, smallholder farmers' adoption of the practices are impacted by many factors. To investigate the extent of technology adaptation in Tanzania and the factors that create this pattern, a large data set was obtained from the Tanzania National Bureau of Statistics. This comprises the National Agriculture Sample Census Survey for 2007/2008, consisting of 16,472 rural households in 3509 villages. The farm survey questionnaire covered issues relating to population demographics, infrastructure, poverty, gender, and crop and livestock production. Over 12,000 of the surveyed households (approx. 76%) grew maize in the year 2007/2008. However, only 611 households (less than 5%) reported using inorganic fertilizer, and 2434 (less than 20%) using improved seed (such as high-yielding hybrid seeds), respectively [16]. We also conducted semi-structured interviews with a variety of stakeholders, including academic, international, and private organizations, including NGOs (No-government organizations) [16].

In Tanzania, weather and access to improved inputs are the most important drivers of crop production losses, followed by information asymmetries in input markets and the underutilization of agronomic best practices. Most farmers tend to use low-quality or no inputs for traditional rain-fed food crops, increasingly threatened by rainfall volatility. Limited productivity also drives low volumes and overall profits for farmer, further reducing their attractiveness for commercial banks. The key drivers that shape farmers' decisions regarding technology adoption were the level of productivity and resilience to risks, particularly to drought. Based on the survey and the interviews, we constructed 18 technology packages representing strategies that smallholder farmers had likely adopted. We emphasize two factors related to seed (cultivar), drought tolerance and maturity group, and one factor related to input: inorganic fertilizer. These comprise a set of management strategies (a–s) as Table 1 and we use these for a suite of crop model simulations.

Table 1. Technology strategies that could be adopted by smallholder farms.

ID	Technology Strategy	Cultivar Trait—Drought Tolerance		Cultivar Maturity Group			N Fertilizer Application Amount (kg/ha)			
		Without	With	Short (120 Days)	Middle (140 Days)	Long (160 Days)	0	30	60	90
a	Historical	x			x		x			
b	Short-N60	x		x				x		
c	Short-N90	x		x					x	
d	Short-N120	x		x						x
e	Middle-N60	x			x			x		
f	Middle-N90	x			x				x	
g	Middle-N120	x								x
h	Long-N60	x				x		x		
i	Long-N90	x				x			x	
j	Long-N120	x				x				x
k	D-Short-N60		x	x				x		
l	D-Short-N90		x	x					x	
m	D-Short-N120		x	x						x
n	D-Middle-N60		x		x			x		
o	D-Middle-N90		x		x				x	
p	D-Middle-N120		x		x					x
q	D-Long-N60		x			x		x		
r	D-Long-N90		x			x			x	
s	D-Long-N120		x			x				x

2.3. Crop Model Simulation

Due to the lack of reported yield time series at local farm scale, we generated a baseline run for historical yield in 1984–2013 at a 10 km resolution over Tanzania using the CSM-CERES -Maize crop model, namely, the cropping system model-crop environment resource synthesis—maize. CSM-CERES-Maize, which is part of the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.6 [17], is a process-oriented maize growth model that has been widely used in simulation studies to evaluate maize production. CSM-CERES-Maize simulates maize phenological stages, growth and development, biomass production, and grain yield based on soil characteristics, daily weather, fertilizer applications, irrigations, sowing date, plant population, and other management practices, such as tillage.

Gridded inputs used to drive the model include weather, soil, and management data (e.g., sowing window). Daily weather (maximum, minimum temperatures, precipitation, total radiation, and humidity) from a 30 year period (1984–2013) was extracted from ERA (the European Center for Medium-Range Weather Forecasts Re-Analysis) -Interim reanalysis dataset. ERA-Interim is the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA-Interim covers the period extended from 1979 to near-real time, providing a range of 3 hourly upper-air parameters [18]. The quality of ERA-Interim has been evaluated by comparing with ground-based and remote sensing observations and other reanalysis products [19,20]; results suggested ERA-Interim provided reliable air temperature in tropical forest areas and reduced bias in precipitation. We processed ERA-Interim based temperatures, rainfall, and total solar radiation fields to daily maximum and minimum temperature, precipitation, and radiation, respectively and used bilinear interpolation to sub-sample these at the 10 km grid of the model [21].

Soil parameters (soil texture, bulk density, Ph, organic carbon content, and fraction of calcium carbonate for each of five 20 cm thick soil layers) were obtained from the International Soil Profile Data set (WISE) [22]. Soil parameters were allocated to each simulation grid cell based on the spatially dominant soil type taken from the digital Soil Map of the World (DSMW) [23]. Soil retention and hydraulic parameters were calculated using pedotransfer functions [24]. Soil parameters for organic soils missing in WISE data set were adopted from Boogaart et al. [25].

The crop calendar data set was obtained from the University of Wisconsin's Center for Sustainability and Global Environment (SAGE). This data set is produced by digitizing and geo-referencing existing observations of crop sowing and harvesting dates, at a resolution of 5′ [26]. The data set provides ranges of crop sowing and harvesting dates for different crops in each grid at year around 2006. A crop-specific gridded data set (by 5′) of nitrogen fertilizer application for the world (around the years of 1999 or 2000) was used in our simulation to setup current fertilizer application rate for maize in each grid cell. This data set was developed by University of Minnesota, based on a spatial disaggregation method fusing both national and subnational fertilizer application data from a variety of sources [27].

Model has been calibrated and validated in previous works. Parameters related to crop genotype traits of maize cultivars were adopted from previous calibrations in East Africa [28,29] under the Agricultural Model Inter-Comparison Project (AgMIP). Information of seed traits in PPP farm survey indicates a difference of cultivars in days to maturation. We therefore selected three types of cultivar from the AgMIP cultivar pool (Katumani, Dekal, Dekalb) to represent the short (120), middle (140), and long (160) maturity groups, respectively, and applied to all grid cells.

A technology that was preferred by farmers is crop with higher drought resistance. Thus, we added a set of options for drought tolerance into the seed trait (Table 1). Drought tolerant crops tend to extract soil water more effectively and from deeper soil layers. We simulated drought tolerance of a cultivar by changing between two features in the soil file: one is to mimic a deeper soil profile, usually with less rooting in surface layer but more at layers below 30 cm, and another to mimic more effective extraction, decreasing low water limit (LL) somewhat, thus increasing the amount of crop available water. These adjustments are uniform across all soil types due to lack of experimental analysis justifying such responses.

Although the time for sowing is a crucial management strategy in SSA, information on exact sowing date is often not available in SSA [30]. The PPP farmers interview indicated that actual sowing date varies between years and regions, largely depending on the timing of precipitation [6]. We simulated this practice by applying an automatic sowing in the simulation: maize was planted at the day when the 3 day accumulative rainfall amount before the day exceeds 25 mm, or the day after the window, if no day meets the condition.

2.4. Analysis

We evaluated the performance of each technology strategy by its effect on maize productivity and potential to reduce yield risks caused by adverse weather relative to the baseline scenario. First, strategies were compared in terms of their capacity to promote national productivity, indicated by the mean yield across the 30 years. We aggregated national maize production from simulated gridded yield, with reported maize areas of 2000 [31]. Smallholder farmers depend on subsistence farming and can rarely insure crops against adverse weather, any fluctuations in crop yields may undermine their livelihoods, which in turn influence future production behaviors [32–34]. We thus look at the distribution of minimum yields over the 30 years for all strategies and associated poor harvest to examine the implications for smallholder farms We considered as a poor harvest yield below the subsistence line of 1 t/ha [5] and computed its prevalence in terms of area and occurrence rate. This analysis was conducted beyond current maize areas to all simulation grids, attempting to facilitate future maize production for smallholder farmers by providing detailed risk profiles and their spatial variations across the whole country.

Third, we scrutinized each strategy and quantified its potential to mitigate production risks caused specifically by precipitation-related events, such as drought. First, we examined the relationship between annual yield and sowing date, as sowing depends on rainfall onset and has been perceived as delayed in recent years. Second, we investigated the relationship between yearly yield and growing-season rainfall. These relationships were then used to create a linear projection model to estimate yield loss due to precipitation-related events. For example, based on the annual distribution of growing-season precipitation (possibility density function), we calculated an insufficient precipitation event with an occurrence of 100 year return (p = 0.01) and applied them into statistical models as predictors.

Moreover, we identified drought risk areas for maize production under current technology and adopted technology scenarios. Drought risk was defined as the key cause of a significant negative relationship between maize yield and precipitation, regardless of other causes of yield shortfall, such as temperature, pest, and diseases. We applied this definition to all technology strategies on all simulation grid cells to compare the risks facing smallholder farms, if a given strategy is adopted nationwide.

3. Results and Discussion

3.1. Simulated Smallholder Maize Production in Tanzania

Maize production in smallholder farms in Tanzania is characterized by low productivity, large year-to-year variability, and dependency on rainfall [35]. Through a national-scale grid-based simulation for the period of 1984–2013, we attempted to reproduce these characteristics. The simulation was conducted with common management strategies currently practiced by smallholder famers, i.e., low fertilizer application, middle maturity cultivar, and rainfall-dependent sowing. We kept these settings static and universal for regions within a given simulation due to during insufficient information of the nation's heterogeneous production areas.

Simulated historical maize yield averaged across the country over the period (1995–2008) was 1.28 t/ha, similar to the reported figure of 1.21 kg/ha (Figure 1). This yield similarity between the simulation and reported confirms the dominant and prevailing low-investment practices in Tanzania. Simulated yield variability denoted as Coefficient of Variability (CV) was 8.1%, lower than the reported value of 16.2%. This indicates climate variation explains roughly 50% of reported yield variability for maize in Tanzania. A value that significantly higher than its global mean of 39% [36], suggests the high dependence of Tanzania's maize production on weather. However, simulation-based estimates tended to overestimate reported national yield for most years, likely due to lack of consideration of year-to-year changes in areas planted with maize and the lack of representation in the model of other biophysical stresses, such as extreme temperature, pests, and diseases.

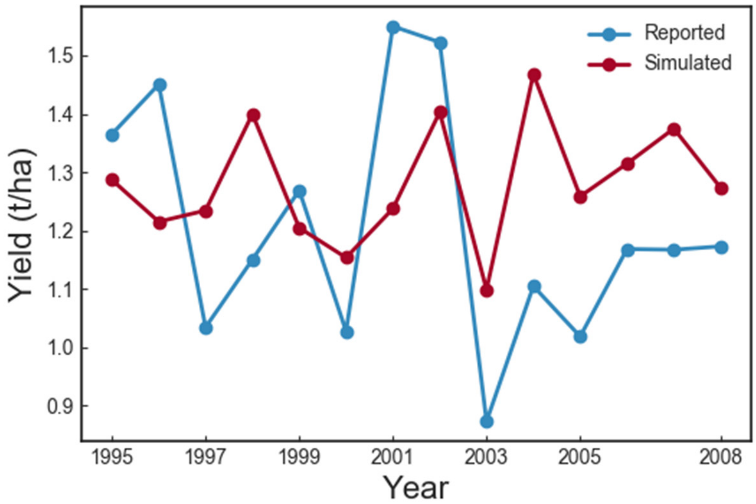

Figure 1. Simulated and reported national maize yields in Tanzania.

3.2. *Importance of Rainfall on Tanzania's Maize Production*

Precipitation is important for Tanzania's smallholder maize production for two reasons. First, sowing is highly dependent on rainfall onset, which is highly variable [35] and delayed under recent climatic warming trends in the region [6]. Second, production is highly dependent on seasonal rainfall and thus, increasingly threatened by rainfall variability and deficit during the growing season [13].

Crop model simulations revealed substantial variability of sowing date due to changes in annual rainfall patterns. First, sowing date averaged across areas planted with maize in 2000 [31] demonstrated a large inter-annual variation by up to 27 days (Figure 2a). Second, substantial number of locations (grid cells) exhibited delay of the sowing, likely due to climate change, indicated by a moving of sowing day from a bimodal distribution at the first decade to a bell shape with peak around the 20th day from the beginning of sowing window (Figure 2b).

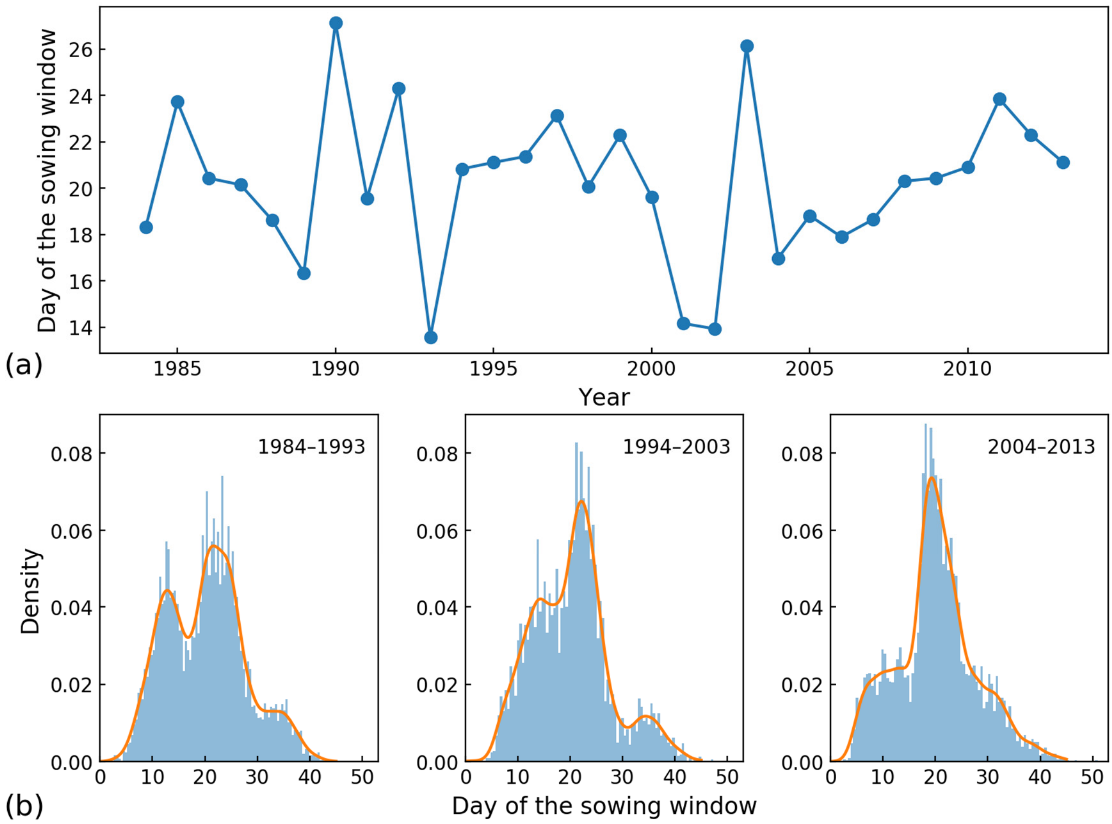

Figure 2. Changes in sowing date of maize related to rainfall onset: (**a**) National mean of the sowing date represented by the starting day of sowing within the planting window; (**b**) Distribution of sowing dates for areas under maize cultivation over three decades. Sowing date over the country is represented as the day from the start of planting window due to large spatial variation of the planting calendar. Gridded sowing window information is obtained from ref [26] and is based on data for 2006.

Of all the 7494 simulation grid cells, 48.8% experienced delayed sowing from the first to second decade, with a mean delay by 3.5 days (Figure 3a), and 39.1% grids experienced delay from the second to third decades, with a mean lateness of 6.2 days largely concentrated in the northeastern part of the country (Figure 3b). This is confirmed by farmers' perceptions that delays in rainfall patterns are now a common occurrence: "We have supposed to plant in February and March but the seeds that been sown have not got rainfall until now (mid-March)" [6]. However, sowing date fluctuates in most areas with a large part of the country not showing detectable changing trends in sowing date during the time period considered here. This is likely caused by periodic precipitation patterns and our sowing window is limited to the fixed time window in the source data set.

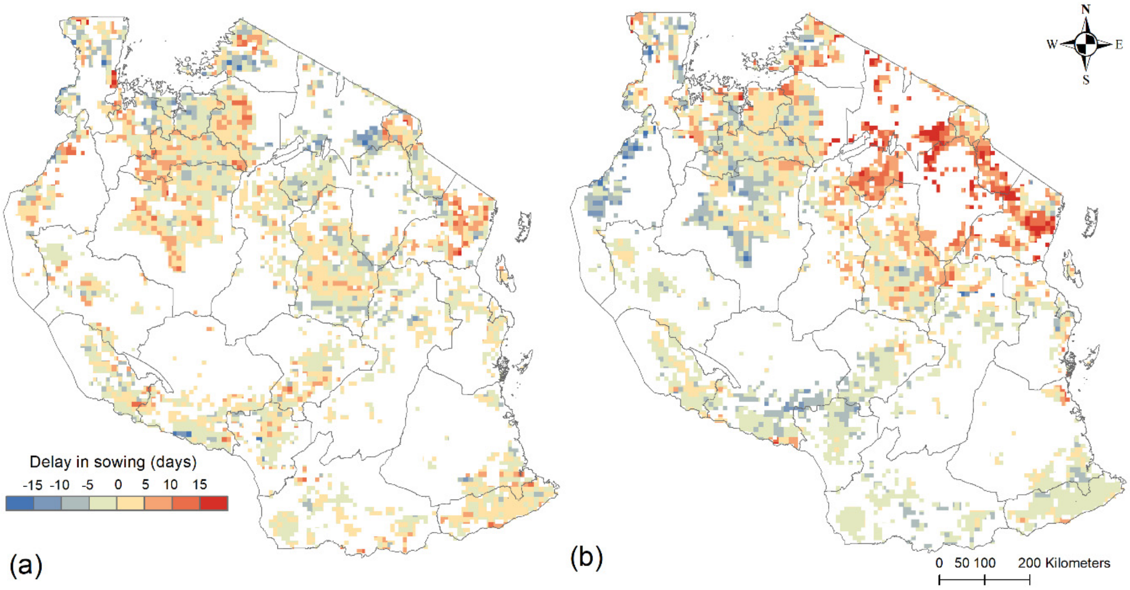

Figure 3. Spatial patterns of the changes in maize sowing date between decades: (**a**) changes from 1984–1993 to 1994–2003, (**b**) changes from 1994–2003 to 2004–2013.

Even a minor delay of sowing poses large detrimental effects on maize production, as it substantially increases drought risk, affecting crop grain filling. We found negative relationships between days of delay and maize yield at both national and regional scales. A day of sowing delay could lead to 0.8% decrease of the maize yield across the country (Figure 4a). For example, the maximum delay scenario (27 days) from 2002 to 2003 equates to a 23.5% reduction in national maize yield in Tanzania, seriously undermining the country's food supply.

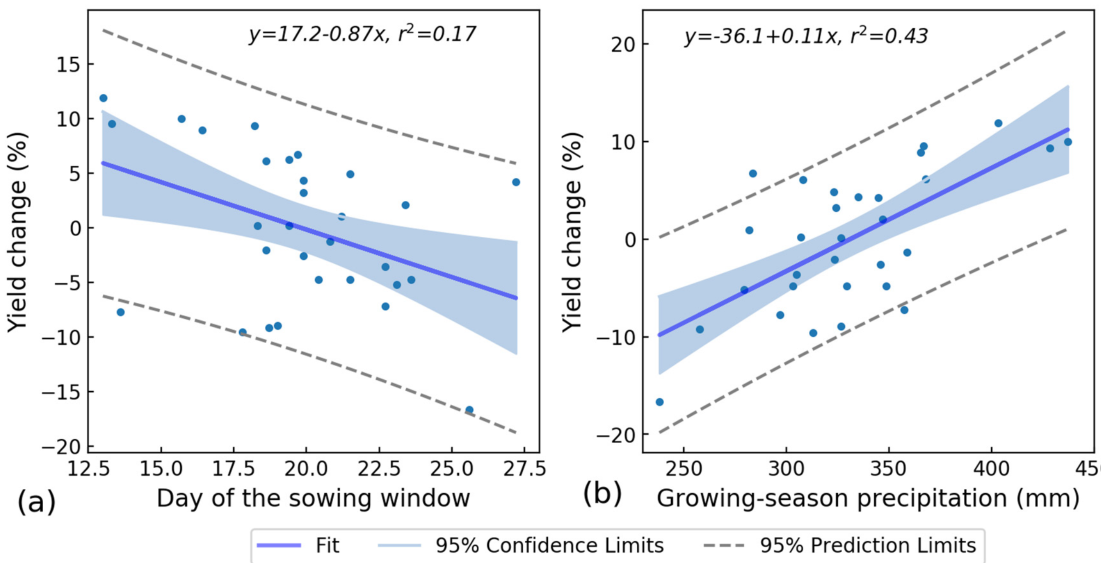

Figure 4. Relationships between simulated national maize yields and (**a**) sowing date and (**b**) growing-season rainfall. Yield, sowing date, and growing-season rainfall are national means across the country, weighted by gridded maize area of 2000 [31]. Sowing date is normalized as the day of the sowing window as in Figure 4.

The simulations also confirmed the negative effects of insufficient rainfall on Tanzania's maize production. Simulated national yield with current management was positively associated to growing-season rainfall, with R^2 = 0.432 (Figure 4b). This suggests that over 40% of the yield variability can be explained by growing-season precipitation. This estimate is higher than previous reports of over 20% of maize yield variability in Tanzania explained by precipitation [35,37]. This is likely because our estimate takes into account the effects of both precipitation variability and its impact on sowing date. Based on the relationship between national maize yield and growing-season precipitation, we estimated a one-hundred-year drought like 1985 could damage the national maize production by 9.7%, similar to estimated production loss at the global level caused by drought [38].

Furthermore, late sowing showed different effects across regions due to differences in precipitation patterns and crop responses. Maize production in southern Tanzania was more susceptible to yield damage by late sowing, reflected by their significant and negative correlation between late sowing and yield ($p < 0.05$) (Figure S1a). In these areas, if the sowing was postponed by 5 days due to late rainfall, up to 10% of yield would be lost (Figure S1b).

Unlike the effect of late sowing, insufficient rainfall has more widespread effects on Tanzania's maize production. Rowhani et al. analyzed the relationship between maize yield and precipitation from 1992 to 2005, concluding that there was a significant relationship between maize yield and seasonal mean precipitation, with an increase in precipitation favoring yield [35]. Our simulation confirmed this finding. The simulated annual yield was significantly and positively correlated to growing-season precipitation in over 70% grids (Table 2), implying that the majority of the country has been affected by insufficient rainfall. Furthermore, estimated yield loss due to deficit of rainfall was substantial in many areas, with larger production damages on smallholder farmers. For example, with a 100 year insufficient rainfall event, the estimated yield loss averaged across the villages participating the PPP was 29.3% (indicated by red dots in Figure 5), pushing the production of smallholder farmers in these areas down to the subsistence line, i.e., less than 1 t/ha [5]. In addition, this susceptibility to insufficient rainfall emerged beyond current maize area. Simulation over all grids indicated the susceptibility was prevailing over most of its arable land, except the western districts, e.g., Kigoma, Katavi, and Rukwa (Figure S2a). Estimated yield loss due to deficit of rainfall was even larger in southeast, central, and northeast areas, where a large portion of the land was not under maize cultivation (Figure S2b). With periodic occurrence and increasing frequency of insufficient rainfall, this prevalence of yield damages with insufficient rainfall indicates the high and widespread drought risks for smallholder farmers in Tanzania, constraining their expansion of maize cultivation areas through conventional land clearing practices.

Table 2. Mean, minimum maize yields, poor harvest areas and occurrence rate across Tanzania.

Maturity Group	Fertilizer Input (kg/ha)	ID	Mean Yield (kg/ha)	Minimum Yield (kg/ha)	Poor Harvest Rates (Percentage/Count)	Occurrence Rate (%)	ID	Mean Yield (kg/ha)	Minimum Yield (kg/ha)	Poor Harvest Rates (Percentage/Count)	Occurrence Rate (%)
		Without Drought Resistance Varieties					**With Drought Resistance Varieties**				
Current	0	a	1247	707	80% (7494)	33.1	-	-	-	-	-
Short	60	b	2319	1504	24% (1765)	12.0	k	2332	1608	18% (1383)	12.4
	90	c	2325	1496	23% (1723)	12.4	l	2350	1633	17% (1294)	12.6
	120	d	2324	1484	23% (1700)	12.8	m	2357	1645	16% (1212)	12.9
Middle	60	e	3923	1658	45% (3371)	12.3	n	4078	1961	33% (2457)	12.5
	90	f	3999	1725	44% (3318)	11.9	o	4210	2031	33% (2475)	12.1
	120	g	4013	1725	44% (3289)	11.9	p	4238	2038	34% (2539)	11.9
Long	60	h	5224	2583	21% (1570)	12.7	q	5162	2813	24% (1804)	13.1
	90	i	5559	2540	25% (1865)	11.9	r	5801	2926	24% (1810)	13.0
	120	j	5833	2528	25% (1837)	12.1	s	6172	2930	23% (1749)	13.4

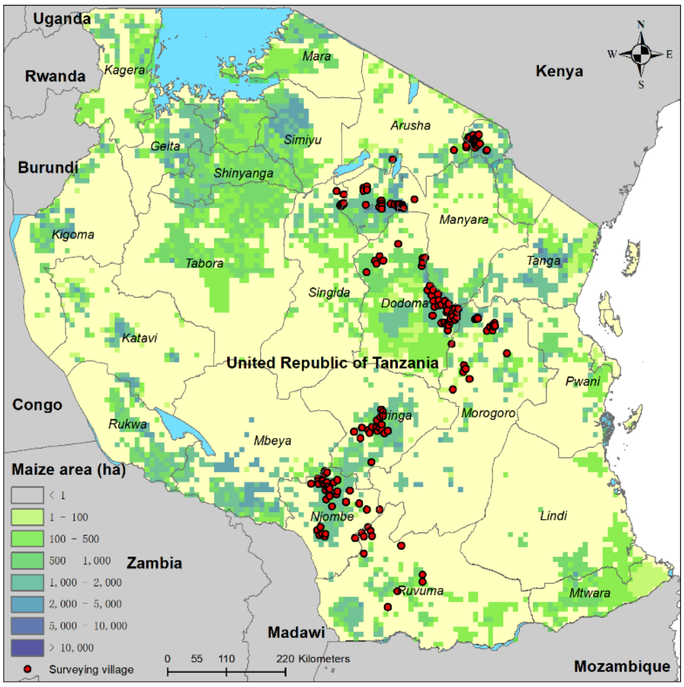

Figure 5. Study area and villages participating in the World Food Program Patient (WFP) Procurement Platform (PPP) 2016. Participating villages are indicated as red circles. Background image: maize area in 2000.

3.3. Better Management Practices Increase National Productivity

All management strategies considered here substantially increased national maize yield (Figure 6), with a potential two to five times increase of national production depending on the strategy. Given 2013 production of 5.3 million tons of maize, a basic investment on seeds and chemical fertilizer could potentially increase national production up to 25 million t/year without expansion of land under cultivation, and can largely secure the import demand imposed by other African regions, such as eastern and southern Africa. Same as controlled experiments conducted in Africa, such as ref [39], strategies with later maturity, drought resistant seed, and highest nutrient input exhibited the largest potential to increase national production (five times), whilst strategies of early maturity maize with less fertilizer generated lowest production growth (1.8 times). Spatial variation in yield increases under different management strategies, demonstrating different yield responses in specific weather and soil conditions. The spatial variation in yield responses was larger with higher-yielding strategies (Figures S3 and S4), suggesting varying investment returns for smallholder famers among regions. For example, northern Tanzania exhibited larger yield increase than the south, particularly northwestern Tanzania (Figure S3). Districts Mara in the north and Kigoma in the westernmost part are likely to have the highest yield return of over 7 t/ha under strategy s (long-season and drought resistance maize and 120 N input) (Figure S3).

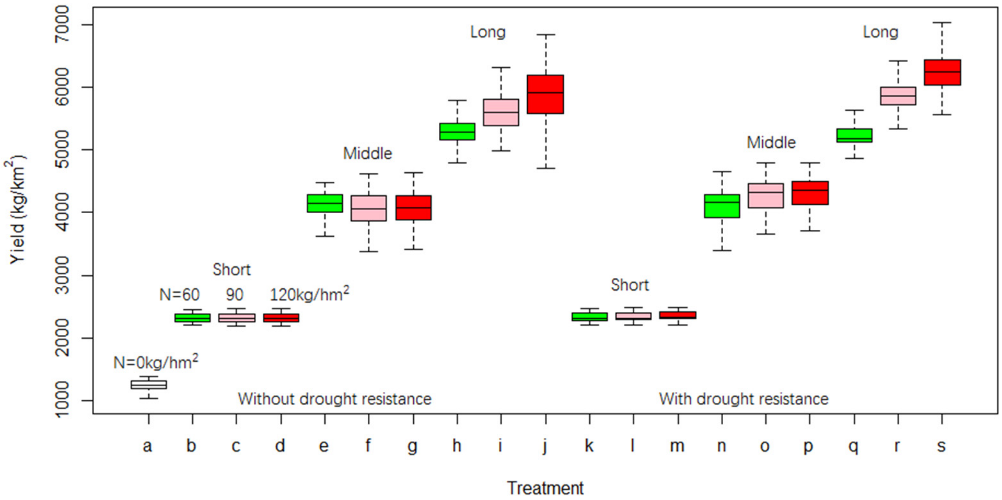

Figure 6. Changes in national maize yields and their ranges under the management strategies a–s outlined in Table 1.

Higher yields tend to increase yield ranges over the 30 years due to periodic abiotic shocks, such as extreme weather, but estimated yield variability does not increase with all strategies in our simulation. Changes in yield variability are reflected by simulated yield range (difference between maximum and minimum yield), standard deviation (SD), and coefficient of variability (CV) (Figure 6). All strategies with long and middle maturity maize demonstrated increased range and SD on national maize yield. For example, the range of national maize yield for strategy j (long maturity with 120 kg N) was 2416 kg/ha, 7 times the range for the yield with current management (355 kg/ha). However, because strategies with larger yield range and SD usually experienced higher mean yield, larger range and SD are not always translated to greater yield variability in statistics. For instance, the CVs of most improved strategies (3.4–9.0%) are slightly higher or even lower than the CV with current management (7.1%), suggesting that adoption of better management practices does not increase yield variability. Moreover, strategies with short maturity varieties all experienced reduced range and SD, reducing the CV by half with current management, which demonstrates the potential of the strategies to fulfill the dual goal to increase crop yield and reduce variability.

3.4. Better Management Practices Decrease the Prevalence of Poor Harvest

All improved management strategies demonstrated big potentials to mitigate the prevalence and occurrence of poor harvests for smallholder farmers. This was indicated by the substantial shrinkage of areas exposed to periodic poor harvest under adverse weather (Table 2 and Figure S5). Of 7494 simulation grid cells, 80% (5844) experienced poor harvest at least once over the 30 years under current management (strategy a). The poor harvest areas are distributed over the majority of the country except a small portion in the west (e.g., the districts Tabora and Katavi), implying widespread harvest failure for smallholder farmers. Improving seeds and adding fertilizers substantially decreased the prevalence of poor harvest, reducing the areas to 23%, 44%, and 24%, respectively, under management groups with short (strategies b–d), middle (strategies e–g), and long season varieties (strategies h–j). Meanwhile, improved managements substantially reduced the occurrence rate of poor harvest, from 1 in 3 years under current management to 1 in 10 years under most improved strategies (Table 2).

Although characterized by low mean yields over the years, strategies with short-season varieties showed the highest potential to decrease the areas experiencing poor harvest, concentrated in northeastern, central, and southeastern Tanzania. These reductions are significant for smallholder farmers, meaning more stable production while less investment in seeds under variable climate. These results are consistent with previous understanding that adopting short-season varieties is a preferred economical option for small holder farmers to escape bad weathers such as drought or heat waves, and stabilize their incomes [13,40]. However, we found similar potential of the high-yielding varieties (e.g., long-season) in alleviating the prevalence of poor harvest, but with a stronger ability to boost farmers' incomes. For example, strategies h–j (with long-season varieties) reduced the poor harvest areas by similar magnitudes as strategies b–d (short-season varieties), whilst doubled the mean and minimum yields of the strategies b–d (Table 2 and Figure 7). Our result suggests that investment in higher-yields varieties is not only able to secure smallholder farmers' food supply and incomes, but also enhances their capacities to cope with production shocks caused by adverse weather.

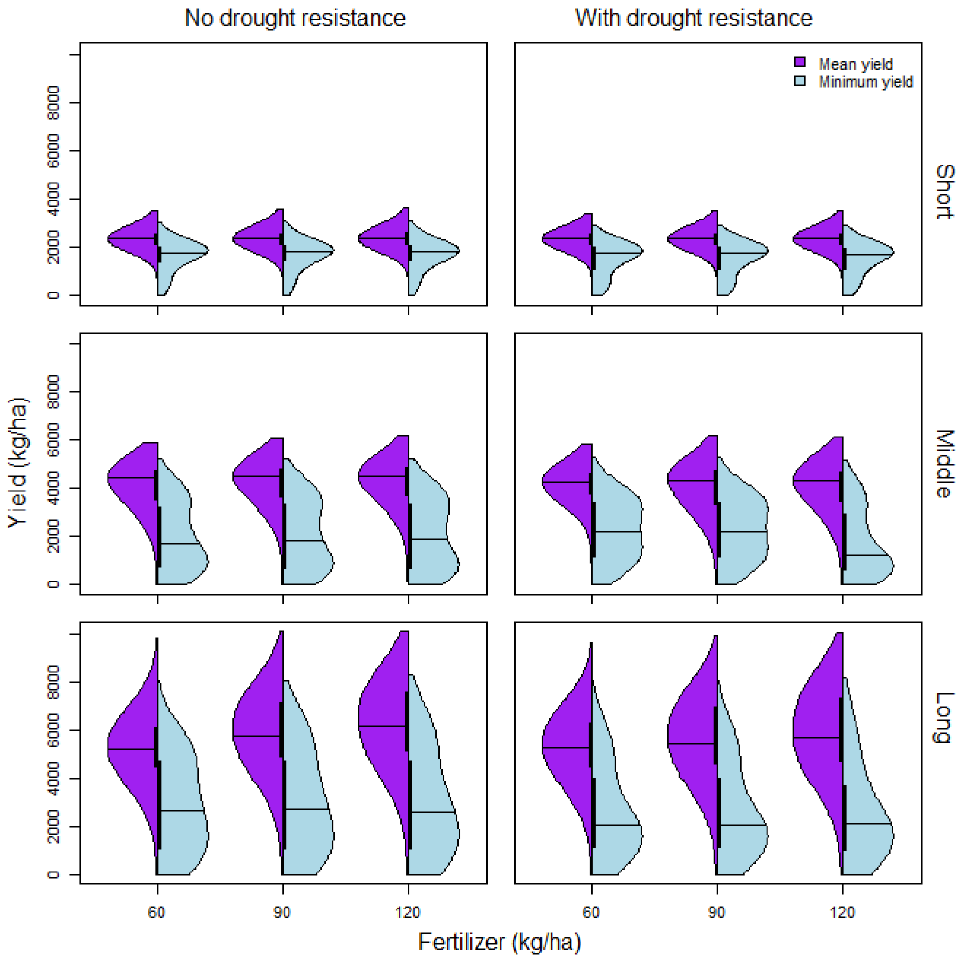

Figure 7. Distribution of mean and minimum yields over the 30 years for all simulation grids and management strategies.

An increase in fertilizer application from 60 to 120 kg/ha led to a small increase of maize yields. This was indicated by small changes in yield distributions between strategies within the same maturity group varieties (Figure 7). Only strategies with highest-yield maize (long-season) exhibited moderate increases with more fertilizers, suggesting increased efficiency of fertilizer with higher-yields seeds. Fertilizer increase also had limited effect on the prevalence and occurrence of poor harvest (Table 2 and Figure S6). We consider our simulation likely overestimated the roles of fertilizers because of the simplification in the simulation regarding fertilizer application. For example, we neglected fertilizers of phosphorus and potassium due to lack of detailed information on soil nutrient content and assumed they were unlimited in the soils. This might overestimate the effects of nitrogen given the widespread high P depletion and unbalanced application among N, P, K in Africa [4]. Although fertilizer is currently the core strategy for securing the food production in many African countries [41], our result suggests that applying higher mineral fertilizer may not be the best option for smallholder farmers in terms of its cost-benefit ratio.

Although gene-modified drought resistant maize is increasingly adopted in Africa [13], our results suggest a relatively weak role of drought resistant maize in increasing yields, i.e., maize varieties with and without drought resistance have similar yield distributions (Figure 7). Plant drought resistance involves a series of mechanisms, including drought avoidance by adjusting morphological structure (such as root depth) or growth rates, and drought tolerance through stomatal movement and photosynthesis. However, we only considered the adjustment of root depth and root density in the soil profile as a means to increase the water extraction capacity of the crop, which largely under predicts the capacity of drought tolerance. Despite the underestimation, some management strategies explicitly reveal the great potentials of drought resistant crops in mitigating the production risks for smallholder farmers, particularly the strategies with middle maturity varieties and low to middle fertilizer application rates. For example, there were 3318 grids exhibiting poor harvests (<1 t/ha) during years of adverse weather under strategy f (middle maturity varieties and 90 kg/ha N inputs), while this number went down to 2457 for simulations with drought resistant varieties (Table 2). This suggests that drought resistance could be an efficient option to cope with weather shocks, mitigating the risks of yield failure for smallholder farmers.

3.5. Drought-Related Risks under Improved Management Practices

As drought is one of the major climatic disasters in Africa, we further estimated the yield loss caused by drought related shocks-late sowing and insufficient growing-season rainfall (Table 2 and Figures S7 and S8). Not surprisingly, strategies with short maturity maize exhibited largest capacity to deal with delayed sowing and insufficient growing-season precipitation. With a 5 day delay of the sowing, national maize yield dropped by around 3% with strategies b–d (short with 60, 90, and 120 N fertilizers, respectively), which was half of the strategies e–g with middle maturity maize, and 70% of the strategies h–j with long-season varieties. Adopting drought resistant maize further diminished yield loss to 2% (strategies k–m). Similarly, short-season maize demonstrated the highest potential to cope with insufficient growing-season rainfall. Compared to yield loss of 10.7% for strategies e–g with middle-season maize and 13.7% with long-season varieties, strategies b–d with short-season varieties experienced only 2.5% yield loss under a one-hundred-year insufficient rainfall event. Adopting drought resistant maize could neutralize or even reverse the yield losses, pushing the yield responses to zero or positive (strategies k–m). This shows the potential of strategies with short maturity and drought resistant maize to reduce drought risks and stabilize national food production.

The decreased drought risks under strategies with short maturity and drought resistance maize are significant for smallholder famers. First, smaller areas are susceptible to late sowing and insufficient rainfall with strategies using short maturity maize than those using middle or long maize varieties. For example, only 8% of the simulation grid cells had significant and decreased maize yields due to delayed sowing under strategies b–d and k–m (using short maturity varieties), far less than the strategies using middle or long maturity varieties (i.e., 20%). Only a few maize area in districts of central, northeastern, and southern Tanzania exhibited detectable yield loss to insufficient rainfall with short maturity and drought resistance maize, which is half of the area under current and improved strategies with middle or long varieties (Figure S8). Second, strategies with short and drought resistance crops demonstrated substantial potentials to offset yield loss caused by drought related shocks. For instance, estimated yield losses 31%~42% for a one-hundred-year insufficient rainfall event under strategies e–j and n–s could be largely decreased to 10% with strategies k–m by adopting drought resistant and short maturity varieties.

Although most effective strategies for coping with drought related shocks are these with short-season varieties, their long-term benefits are smaller than those of high yielding strategies with middle maturity varieties for instance. This is indicated by total land productivities in the long term such as the mean yield over 30 years, and capacity to cope with poor harvest such as occurrence of yields less than 1 t/ha. Adoption of the improved management strategies depends on a range of factors, including short versus long-term costs and benefits, shocks such as climatic disasters and their magnitudes and occurrence rates, yield responses to drought risks and their spatial variations, etc.—all of which are worth further investigation.

4. Conclusions

With the gridded simulation approach, this study verified stakeholders' perceptions about the risks facing Tanzania's maize production-low productivity and high dependence on growing-season precipitation. Our simulations confirmed previous observation that historical maize production was significantly and positively correlated to growing-season rainfall. Past rainfall pattern has significantly impacted smallholder farmers by varying their sowing. By examining the performance of 18 management strategies in promoting national maize yield, the simulation identified the strategy by using long maturity, drought resistance varieties, with high fertilizer input, can elevate the national maize production by up to five times, in currently available cultivation areas. The 18 strategies exhibited different effectiveness in coping with two local drought-related shocks: late rainfall onset and insufficient growing-season rainfall. By quantifying the risks in terms of the yield loss and the susceptible area caused by the shocks, we found that the management strategies with short-season and drought-resistant maize cultivars appeared as the best way to cope with drought shocks and stabilize the maize production. However, high-yielding strategies provided the promising capacity to increase smallholder farmers' yield and reduce their harvest failures in the long-term.

Some limitations of our study are worth noting. First, we neglect many other stresses that damage the maize production in Tanzania, including pests, diseases, and climate disasters, like extreme heat waves. This implies that our estimate is likely to overestimate the role of some management strategies. Second, a few measures demonstrate small roles in affecting yield, such as drought-tolerant maize, likely due to our simplified assumption related to drought response of plant. This might underestimate the contribution of widespread application of gene-modification maize in Africa [42], suggesting follow-up studies should target on such uncertainties and improve the embodiment in the models for large number of gene-modification traits. Third, since we introduce agronomic measures only based on the yield performance, management adoption is the function of cost and output, hampering by other factors such as markets, our suggestion may not apply in all conditions, given the large heterogeneity of the production conditions and markets. Finally, model input data and the data processing subject to uncertainties due to data availability, limitation of spatial resolution, and the processing method. For example, the ERA-Interim reanalysis has coarse spatial resolution (e.g., 80 km) and less skill for global precipitation [18], which particularly affected our simulation, such as sowing date, and the post analysis, such as yield loss due to sowing delay, resulting in unphysical horizontal line patterns in their spatial distributions (Figures S1 and S7).

Despite the limitation, this study is trying to link farm-scale survey, current and prescribed management practices, and process-based model, to provide spatial and temporal information about the advantage and disadvantage of a variety of management strategies. Our results have several implications to stakeholders, such as policymakers and smallholder farmers. For example, our results convey the following messages to policymakers: First, national production could be increased by up to five times if high-yielding strategies could be applied nationwide. Second, high yield often associates with high variability, but applying fast growing and drought resistant varieties could potentially reduce the variability, while moderately increasing current yield. Last, drought would still be the main stress, even with the introduction of better managements, requiring substantial investment of infrastructure, such as the irrigation system. The spatial details of our results also provide vital information for smallholder farmers to adopt improved management practices, such as high-yielding varieties and high fertilizer input: a good combination to reach a higher yield, but requiring more investment. Drought resistant maize may not be an effective option to boost yields, but instead to keep the yields above a reasonable level or offset the harvest loss at the years with bad weathers. Nevertheless, adoption of the management strategies are subject to varying, depending on the location, weather conditions and yield responses. A climate-smart management could be expected to boost crop yields while increasing resilience to climate risk, based on our results and reliable weather forecasting.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4433/11/9/982/s1, Figure S1: Areas with yield susceptibility to sowing delay and their estimated yield loss: (a) Correlation Coefficient between yields and days of sowing delay, (b) estimated yield loss due to a 5-day delay. Figure S2: Areas with yield susceptibility to insufficient growing-season rainfall and their estimated yield loss: (a) Correlation Coefficient between yields and growing-season precipitation, (b) estimated yield loss for a one-hundred-year insufficient rainfall event. Figure S3: Distribution of (a) mean and (b) minimum yields over the 30 years for management strategies along latitudes. Figure S4: Spatial patterns of simulated mean yields over years of 1984–2013 under management strategies a–s outlined in Table 1. Figure S5: Spatial patterns of simulated minimum yields over years of 1984–2013 under management strategies a-s outlined in Table 1. Grey color indicates areas that experienced at least once over the 30 years a poor harvest (i.e., yield below 1 t/ha). Figure S6: Possibility of poor harvest (i.e., yield below 1 t/ha) over the 1984–2013 time period under management strategies a–s outlined in Table 1. Figure S7: Yield loss due to a 5-day delay of sowing under management strategies a–s outlined in Table S1. White areas indicate either positive yield change or insignificant relationship between sowing delay and simulated yields. Figure S8: Yield loss due to insufficient growing-season rainfall (one-hundred-year event) under management strategies a–s outlined in Table 1. White areas indicate either positive yield change or insignificant relationship between growing-season rainfall and simulated yields.

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