Impacts of a nuclear war in South Asia on soybean and maize production in the Midwest United States

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ABSTRACT

Crop production would decline in the Midwestern United States from climate change following a regional nuclear conflict between India and Pakistan. Using Agro-IBIS, a dynamic agroecosystem model, we simulated the response of maize and soybeans to cooler, drier, and darker conditions from war-related smoke. We combined observed climate conditions for the states of Iowa, Illinois, Indiana, and Missouri with output from a general circulation climate model simulation that injected 5 Tg of elemental carbon into the upper troposphere. Both maize and soybeans showed notable yield reductions for a decade after the event. Maize yields declined 10-40 percent while soybean yields dropped 2-20 percent. Temporal variation in magnitude of yield for both crops generally followed the variation in climatic anomalies, with the greatest decline in the five years following the 5 Tg event and then less, but still substantial yield decline, for the rest of the decade. Yield reduction for both crops was linked to changes in growing period duration and, less markedly, to reduced precipitation and altered maximum daily temperature during the growing season. The seasonal average of daily maximum temperature anomalies, combined with precipitation and radiation changes, had a quadratic relationship to yield differences; small (0°C) and large (–3°C) maximum temperature anomalies led to increased yield loss, but medium changes (–1°C) had small to neutral effects on yield. The exact timing of the temperature changes during the various crop growth phases also had an important effect.

1. Introduction

In the event of nuclear war, targets in cities and industrial areas would release light-absorbing particles (i.e., black carbon, soot, or elemental carbon) into the atmosphere from fires. By blocking sunlight, elemental carbon would cause significant changes to solar radiation, temperature, and precipitation patterns. For example, evidence suggests "volcanic winters" and "years without summers" follow large volcanic eruptions such as Tambora in 1815. Under these conditions, unusual mid- to late-summer cooling and frost have caused crop failure over millions of hectares of cultivated areas (Post, 1977; Stommel and Stommel, 1979, 1983; Harrington, 1992; Oppenheimer, 2003). Less known, however, is whether similar crop failure might be caused by a regional nuclear conflict.

Vulnerability of agricultural systems to nuclear war was recognized in the 1980s and a number of studies investigated the relationship between agricultural productivity and climatic perturbations. Ehrlich et al. (1983) reported subfreezing temperatures, low light levels and high doses of UV light as drivers of large-scale decline in crop productivity in the Northern Hemisphere following a large-scale nuclear war. Harwell and Cropper (1985), in a comprehensive assessment, investigated the agricultural effects of a large-scale nuclear war using both an empirical approach and simple crop growth models and concluded that significant reduction in crop yields and associated production could occur, primarily caused by shortening of the growing season and reduction of thermal time needed by crops to reach physiological maturity. Sinclair (1986) used a physiologically-based model to simulate potential soybean production during slow climatic recovery following a nuclear winter in Midwestern U.S. That study showed that temperature reductions of 2-4°C throughout the growing season substantially reduced soybean yields.

Unfortunately, since the mid 1980s there has been a paucity of studies focusing on nuclear war effects on crop production, especially using outputs of a modern climate model. The purpose of this research is to quantify changes in the Midwestern U.S. from a regional nuclear conflict. More specifically, we used temperature, precipitation, and solar radiation anomalies produced by a modern global climate model under a regional nuclear war scenario in a sophisticated dynamic crop growth model to assess the magnitude and timing of changes in maize and soybean production in four locations. Additionally, we investigated the causes of yield changes with an eye toward adaptation options.

2. Methodology

We use a dynamic vegetation model with crop-specific capabilities to simulate yields affected by a hypothetical nuclear conflict between India and Pakistan in which 5 Tg (five million metric tons) of elemental carbon is released into the upper troposphere. Atmospheric circulation and associated changes in temperature, precipitation, and solar radiation were simulated by ModelE, a general circulation model (GCM) (Schmidt et al., 2006) from the Goddard Institute for Space Studies (Robock et al., 2007a).

Consequences of a 5 Tg nuclear war

The resulting climatic anomalies were extracted from Robock et al. (2007a), in which temperature, precipitation and radiation changes were computed for 5 Tg of elemental carbon injected into one column of grid boxes at 30°N, 70°E on 15 May. The black carbon was placed in layers that correspond to the upper troposphere (300–150 mb). Soot from the fires would quickly reach the stratosphere after a nuclear conflict. Because of a lack of precipitation and lofting of the soot by solar heating, some elemental carbon would linger there for over a decade. These particles lead to important changes in atmospheric conditions but are less dramatic than those in “nuclear winter” simulations of a massive nuclear exchange between superpowers involving 50 to 150 Tg of elemental carbon (Robock et al., 2007b). However, the changes would last longer than would be expected from volcanic cloud observations, which do not contain light absorbing elemental carbon, or on the basis of older climate models that inadequately represented the stratospheric plume rise. For more details on the climate model results, please see Xia and Robock (2012) in this issue.

The Agro-IBIS model

We used a comprehensive terrestrial ecosystem model, the Integrated Biosphere Simulator (IBIS), which can simulate: (1) energy, water and carbon exchange between plants, soil, and the atmosphere; (2) photosynthesis and respiration; (3) phenological changes in vegetation cover; (4) plant growth and plant competition; and (5) nutrient cycling and soil processes (e.g., Foley et al., 1996; Kucharik et al., 2000).

Kucharik (2003) implemented process-based models of corn, soybeans, spring and winter wheat, and management choices into IBIS, simulating both managed and natural ecosystems (Kucharik, 2003; Kucharik and Twine, 2007). The improved model, called Agro-IBIS, can be used to study coupled carbon, water, and energy balance based on the key differences in C3 and C4 crop physiology, daily phenology, and carbon allocation (Scholze et al., 2005). This improves understanding of effects of land use practices (e.g., irrigation, planting dates, bioenergy cropping systems) as well as environmental stressors (e.g., climate, water limitations) on coupled carbon-water exchange.

Especially significant is the ability of Agro-IBIS to include crop management options — planting and harvest dates, fertilizer application, cultivar selection and irrigation (Kucharik and Brye, 2003). In particular, the mechanistic corn growth model uses physiologically based representations of C4 photosynthesis (Farquhar et al., 1980; Collatz et al., 1992), stomatal conductance (Ball et al., 1986), and respiration (Amthor, 1984). Soil moisture and leaf-nitrogen stress functions reduce the maximum photosynthetic capacity (V_{max}) of the plant. The partitioning of dry matter assimilated to the various carbon pools (leaf, stem, root, grain) changes according to crop phenology (Penning de Vries et al., 1989).

Agro-IBIS simulations of carbon, nitrogen, energy and water cycling variables have been extensively validated in optimally fertilized and unfertilized corn agroecosystems in southern Wisconsin from 1995 to 2000 (Kucharik and Brye, 2003). Regional-scale calibrations and validations for mean corn and soybean yields were also made in the Upper Mississippi drainage basin (Donner and Kucharik, 2003) for the 1985–1994 period. More recent work has compared simulated crop biophysical and phenological development with satellite data (Twine and Kucharik, 2008), and Sacks and Kucharik (2011) analyzed the impact of trends in crop management and phenology on yields, evapotranspiration (ET), and energy balance across the Midwest.

<u>Perturbation of contemporary climate data</u>

The Agro-IBIS model requires daily inputs of maximum and minimum temperature, precipitation, solar radiation, relative humidity, and wind speed. Where subdaily quantities are required, empirical relationships from Campbell and Norman (1998) are used. To generate a new daily dataset incorporating effects of a nuclear war, the daily observed values of minimum and maximum temperature, precipitation, and solar radiation were uniformly perturbed using monthly anomalies of these quantities for 10 consecutive years (Robock et al., 2007a). For the temperature variables and solar radiation, monthly anomalies were added to daily quantities uniformly over each month. The temperature anomalies were weighted; 80% of the anomaly was added to the maximum and only 20% to the minimum temperature, following Robock (1988) and (1991). For precipitation, we calculated total observed rainfall for the month in question, divided the monthly anomaly by the observed monthly total, then reduced the precipitation on days that it occurred by that fraction for each day. While evidence suggests that increases in the fraction of diffuse sunlight can impact crop growth (Spitters, 1986), these increases were not considered. Neither did we take into account the very large losses of stratospheric ozone and associated increase in ultraviolet light following a nuclear conflict (Mills et al., 2008).

Preliminary analysis indicated that reductions or increases in yields are significantly impacted by the weather conditions of the control run. Therefore we generated a synthetic control climate data set for 300 years by randomly selecting 10 individual years, 30 times, from the original 29-year (1979-2007) daily time series, assuming no year-to-year autocorrelation. This 300-year data set provided 30 realizations of each year of the 10-year segments so that the distribution of yield associated with year-to-year variations in climate for each analysis year could be examined. Finally, this synthetic data set was perturbed by 10 years of monthly anomaly data 30 times following the same method.

Experiments

We conducted two experiments using both observed and perturbed climate data. For each, Agro-IBIS was run for 300 years using twelve 0.25° x 0.25° grid cells centered at four locations in the Midwest (Table 1, Figure 1). The sites are located in an arc-shaped pattern in the Midwestern U.S., an area with tremendous agricultural productivity. They are also located along an east to west summer precipitation gradient, but with similar mean annual temperature. We modeled the yield of maize and soybeans, which are the most abundant crop types grown in the Midwest, while keeping ambient atmospheric CO_2 concentrations consistent with the year 2000 (370 ppm). In each case, all management practices including nitrogen-based fertilizer use (150 kg/ha for maize, 25 kg/ha for soybeans (NASS, 2011)) and irrigation (if necessary) were allowed. For each run, the planting date was driven by combinations of running mean temperatures (min/max) reaching a designated threshold, which differed for each crop. The other phenological stages (e.g., emergence, flowering, maturity) were driven by growing degree day (GDD) accumulations. All runs were initiated from identical soil C and N conditions determined by a spin-up procedure where the soil biogeochemistry model was executed more frequently than the model time step to bring soils into equilibrium without having to simulate thousands of years of actual time (Kucharik et al., 2000). Thus the coupled C-N cycle was allowed to feed a realistic amount of N for uptake through N-mineralization. The irrigation module was activated automatically – and mostly in more arid locations – when soil available water content reached 50% of the maximum in any location, and water was subsequently added to reach 100% available water. It is possible that following a conflict, farmers would try to adapt to changing climate by shifting varieties, planting early or late, or irrigating to mitigate yield losses. None of these adaptation strategies were tested here, but we discuss below how effective these might be (e.g., Sacks and Kucharik, 2011).

To assess the accuracy of Agro-IBIS crop yield predictions, we compared simulated yields to reported production in each location. The reported data were extracted from the National Agricultural Statistics Service (NASS) database http://quickstats.nass.usda.gov/?source_desc=CENSUS for the county in each state that the simulation site was located. Ten years of data (1996-2005) were extracted from the database and compared to the modeled yields simulated with daily climate observations for the same period.

To better understand the relationship between climatic conditions and simulated yields, we compared seasonally averaged weather conditions to predicted yields for maize and soybeans under nuclear war conditions. We defined the growing season as months from June through August (climatological summer), and averaged temperature and radiation, and summed precipitation daily values over this period for each year of the 300-year synthetic data set.

To assess changes in crop yields, we calculated the difference in predicted quantities with and without nuclear perturbation in the form of relative change from the control scenario using

$$\text{yield change (\%)} = \frac{nuclear - control}{control} * 100 .$$

In this formulation, negative values indicate reduction in yields. The difference results were represented both as a probability distribution and as averaged values across 30 realizations of each model year for 10 consecutive years to quantify year-to-year variation following the conflict.

3. Results

Expected changes in climatic variables

Figure 2 shows expected changes in three climatic variables under the regional nuclear conflict scenario as reported in Robock et al. (2007a), averaged over all four sites. In the decade following the 5 Tg event, all variables depict negative anomalies, indicating significant drying and cooling of the lower atmosphere, as well as a reduction in solar radiation. For the last five years the precipitation anomalies were small. Temperature displays more negative than positive anomalies, indicating significant cooling through the decade. Solar radiation has a large drop in the first year, recovers gradually through the period, but remains negative partly because of strong absorption of sunlight by black smoke even after 10 years (Robock et al., 2007a). The precipitation anomaly varies the most across sites, followed by temperature and radiation, as indicated by the large spread around the mean value in Figure 2. Solar radiation does not exhibit a very strong variation between sites. Robock et al. (2007a) showed that when averaged globally and annually, the temperature anomaly reduces to –0.5°C in year 10, but anomalies in the Midwest do not exhibit this behavior; even in year 10, the anomalies are noisy, and very cool summers still can occur.

Performance of the crop model

In general, there is considerable agreement between modeled and observed yields (Figure 3). Across all sites, maize yield ranges from 8 to 12 t/ha both under simulated and observed conditions. Agro-IBIS predictions for maize are generally higher than observed values. The mismatch is least (1 t/ha difference) in the IA site and most in MO (4 t/ha difference). For soybeans, predictions are well within the range of reported mean values across all sites but in contrast to maize simulations, reported yields are higher in two of four cases. The spread of modeled yields is also larger than observed variation in both crops. Possible causes of yield mismatch and differences in variability are provided in the discussion section. But for all locations and crops, the results are within error bars of both modeled and observed quantities.

Climatic drivers of simulated yields

There is fairly strong correlation between climatic conditions of the growing period and simulated yields. Both crops respond linearly and positively to growing season precipitation availability (Figures 4 and 5). There is a three-fold increase in yields of both crops over a 400 mm (100 – 500 mm) precipitation range across non-irrigated sites. In the case of seasonal maximum temperature, both yields respond negatively to increases in maximum temperature, although soybeans appear to have greater sensitivity than maize. The relationship between minimum temperature and yields is much weaker or non-existent. Available insolation is moderately correlated with yields although the correlation is better with yield of soybeans than maize yields. One reason for the solar radiation effect may be that it drives maximum temperatures during the day; as radiation increases, maximum temperatures rise, leading crops to accelerate their GDD accumulation quicker, with fewer calendar days to accumulate biomass. Also, increased radiation associated with increases in maximum temperature and decreases in precipitation may lead to greater evapotranspiration, causing soil moisture stress to increase.

To test effects of different forcing variables on maize under the nuclear scenario, we ran a multiple linear regression model to predict yield with the four forcing variables. When all were included, they explained about 44% of the variability; precipitation and maximum temperature were statistically significant while minimum temperature and radiation were not. In the full model, precipitation had significant positive effect and tmax had significant negative effect. For each 100 mm increase in precipitation, maize yields would be expected to rise 1.2 t/ha. For each degree increase in maximum temperature, yields would be expected to fall 0.45 t/ha.

For soybean, the full model explained almost 58% of the variability; precipitation, tmax, and radiation were significant while tmin was not. As with maize, precipitation had significant positive effect, while all other forcing variables affected yield negatively. The effect of minimum temperature was negative but not significant. In the full model, each 100 mm increase in precipitation would raise maize yield 1.2 t/ha; each 100 mm increase in precipitation would raise soybean yield 0.4 t/ha. For each Celsius degree increase in tmax, soybean yield would decrease 0.29 t/ha.

Expected yield changes under the 5 Tg scenario

Figures 7 and 8 show the histogram distribution of relative and absolute changes in maize and soybean yields. Negative values indicate decreases and positive values indicate increases following the 5 Tg event. The great sensitivity of the ecological model to variations in weather affects the results of the nuclear run because it is weather conditions through which yield effects of a nuclear war are assessed. Therefore we present most yield change results as a probability distribution rather than a single value. The first year in each model result was unimportant because the hypothetical war did not start until mid-May in year one, so changes in climate that year were small.

For maize, the relative changes are normally distributed with a mean around –10% and equal magnitude of spread when averaged across all locations. The mean change ranges from -7% at IL to <–12% at the IA site with similar variation in all sites. The 5 Tg event occasionally increases maize yields a small amount in all locations but the likelihood of this is fairly small; when averaged over all locations, the probability of yield increase is <15%, using the normal probability density function. In each case, the maximum yield change could be as low as –50%. Again the likelihood of this extreme decline is low.

Relative changes in soybean yields also show a normal distribution but with greater variable mean value, ranging from a 6% decline in IL to more than 12% in MO. Variability in each location is also much higher for soybeans than for maize yields, exceeding 20% in one location. Like maize, soybean yields are predicted to decline following the 5 Tg event; this result is reflected in the bulk of the distribution being negative. However, more results indicate reduction in maize than in soybeans.

Of interest is how yield change results would evolve over time following the 5 Tg event. Figures 9 and 10 display predicted relative changes in maize and soybean yields for the sites considered here. For maize, mean relative change is predicted to be more than a 20% decline in year five, with all years showing production losses through year seven. Productivity then recovers and begins to vary in years 8-10 by ~5-10%. The decline could reach 40% on one occasion (year 5 at the IL site) while increase could be 10% at year 10 (Figure 9) depending upon which decade in the 30 years is chosen as the unperturbed state. In general, the number of years of decline is greater than the number of years of increase (8 of 10 vs. 2 of 10). Even for years with significant mean increase in yield (e.g., year 10), some experiments suggest a decline. In fact, every year examined has one or more negative changes. Moreover, the temporal profile of yield change across 10 years is curvilinear, having little or no decline early in the decade, greatest decline in the middle, and a potential increase at the end. Variation also increases with this trend.

Soybean yields show similar trends but with much greater variation. As with maize, mean soybean yields are expected to decline by as much as 20% in the mid-decade although the beginning and end of the decade could see significant increases in yields (20% on average). While this is true for the mean change, each year has at least one negative change.

<u>What are the drivers of yield change in the nuclear scenario?</u>

From the adaptation perspective, an interesting question regarding simulated changes in yields under the nuclear scenario is: what are the climatic determinants of these changes? To answer, we examined the relationship between changes in climatic quantities and the difference in yields between the control and nuclear runs for both crops (Figures 11 and 12). With maize, there is a strong quasi-linear correlation between precipitation and yield, where a large precipitation decline (0–50 mm / growing season) results in a 1-3 t/ha decline in yield while increases in precipitation lead to neutral or positive changes (Figure 11 upper left). Differences in both maximum and minimum temperatures averaged over the growing season have non-linear correlations with yield changes, suggesting a larger decline when these quantities exhibit extreme negative or positive changes, but smaller yield decreases are expected when changes are small (Figure 11 upper right and lower left). Changes in available radiation following a nuclear event have an expected relationship with yields where large decreases in insolation also lead to large decreases in yield. The values for no change in precipitation or temperature also do not cross the zero line. This is partially because the synergistic impact of all the simultaneous perturbations (precipitation + temperature + radiation) contribute to the yield reduction.

The climatic response of soybean yield differences parallels that of maize. With precipitation, there is strong but non-linear response; any decline in rainfall leads to a decline in yields but increases in precipitation suggest small yield increases. The response of soybeans to both minimum and maximum temperatures are harder to interpret; they suggest increases in both quantities (rather than a decrease caused by a regional nuclear war) affect yields more. The radiation response of soybean yields is strongly non-linear; the greatest yield decline occurs when insolation is reduced by the average amounts. There is little or no yield effect when large or small decreases occur.

The temporal variation in yield over 10 years as shown in Figures 9 and 10 does not conform to modeled climatic anomalies as expected. While the greatest precipitation, temperature, and radiation reductions occur in years 2-5, the yield response to these anomalies is highest in year five for all sites and crops. This is particularly apparent in soybean yield variations (Figure 10). To further investigate this pattern, we analyzed the relationship between yield difference and the maximum temperature and precipitation difference by individual years (Figure 13). The anomalous fifth year decline appears to be caused not by temperature decrease as expected, but rather by an increase. That is, both crops experience the largest drop in yields when maximum temperature increases. In fact, when the temperature anomaly in Figure 2 is averaged over the growing season on year five, the anomaly is positive. When applied to maximum temperature as required by the model, this anomalous increase in maximum temperatures negatively affects yields since there is a negative relationship between maximum temperatures and yields as shown earlier. For maize, the decline is smaller in years one, eight, and ten than in years two, three, and four. On the other hand, soybean yields are less sensitive to large reductions in maximum temperatures as exhibited by years one, two, four, eight, and ten. When maximum temperatures are increased, soybean yields also experience the largest reductions as in year five following the event.

Unlike the maximum temperature response, yield changes due to precipitation are less apparent in the anomalous year five. Instead, precipitation response mimics what was shown in

Figures 10 and 11. Thus, a year with a large reduction in rainfall corresponds to the largest reduction in yield for both crops. However, as the precipitation anomaly switches from negative to positive, yields respond positively as in year ten, although it is difficult to tease apart the combined effects of temperature and precipitation as drivers of yield change.

Another interesting question concerns changes in planting and harvest dates. The changes in these dates are important for two reasons. First, crop yield is partially determined by the length of the growing period. Thus change to the length of the period will affect production (Kucharik, 2006; Kucharik, 2008; Lobell and Field, 2008; Sacks and Kucharik, 2011). Second, the crop growth simulations were conducted under a zero adaptation assumption. Given the wide range of cultivars that span short to long growing seasons where corn and soybeans are planted, one adaptation strategy would be to consider subtle climate changes and offer appropriate varieties to farmers for their particular region. By reporting potential changes in the growing period of these crops, this paper seeks to quantify subtleties associated with a 5 Tg event.

To understand the impact of the nuclear scenario on the length of the growing season, we also investigated the relationship between changes in planting dates prognostically determined by Agro-IBIS and changes in crop yield (Figure 14). The results show that the nuclear event is always accompanied either with no change or later planting for both crops and the magnitude of changes in the planting date has a non-linear impact on yield decline: up to a 10-day delay in sowing brings little or no change, but beyond 10 days yield reduction accelerates for both crops. When we examine the relationship between changes in yields and changes in the length of the growing period, maize yields experience little or no change when the length of the growing period remains the same or extended but maize yields drop precipitously as the growing period is progressively shortened (negative numbers); the largest reduction occurs when the growing period is reduced by 40 days. This finding also applies to soybeans, although the rate of yield decline increases faster than maize yields as the number of days in the growing period is reduced.

4. Discussion and conclusions

The results of this research suggest that both maize and soybeans may experience notable yield reductions in the event of a nuclear conflict and these reductions are beyond the natural variation of both crops. The expected decline in yield would have potential implications for food and bioenergy feedstocks in a major agricultural region. The United States is the world's largest producer and exporter of corn; the Midwest supplies 80% of this production. If yield declines as suggested here were to occur, overall production would be significantly depressed for several years following the nuclear conflict, affecting both market conditions and livelihoods. While the economic impacts are not explored here, they are likely to be large, given the prominence of the contribution of corn and soybeans to domestic market needs for food, feed, and fuel as well as to agricultural exports.

These findings agree with the previous studies on changes in crop productivity under a nuclear winter scenario. The present study goes beyond earlier studies by examining much smaller climate changes from a regional nuclear war and by providing more comprehensive assessment, using a sophisticated ecological model, numerical output from a modern climate model, and a probability-based assessment of yield changes. We suggest that such an assessment is needed to provide reliable information to stakeholders and policy makers in other regions where agricultural production volume has the capacity to affect global food supply.

Unlike global climate change caused by radiative forcing, the changes created by a nuclear conflict would have different duration: the radiative forcing from greenhouse gases are expected to persist for a century or more while that generated by a nuclear conflict is likely to last for only a decade (Toon et al., 2008). Nevertheless, the economic and societal consequences of yield changes resulting from this short-lived climatic alteration could eclipse the long-term changes from greenhouse gas emissions that allow ample time for development and application of a variety of adaptation strategies to mitigate yield losses.

Our results also confirm earlier findings (e.g., Kucharik, 2006, 2008) that suggest that in midlatitude locations, changes in temperature and solar radiation play a greater role than precipitation in reducing yields. Based on observational evidence, recent work by Kucharik (2006, 2008) has shown that increases in the growing season and the timing of sowing and harvest dates due to increases in temperatures and changes in agricultural technology (e.g., better hybrids) have contributed to increased corn and soybean yields. In our study, cooler conditions associated with a nuclear conflict, which may shorten the frost-free growing season, could lead to fewer calendar days for crops to intercept radiation and perform photosynthesis. In contrast, should temperatures increase with nuclear conflict generated short-term climate change during the growing season, accelerated rate of growing degree day accumulation could contribute to crops progressing through their phenological stages more quickly, with fewer calendar days to accumulate biomass. Thus, temperature changes can create a myriad of feedbacks affecting yield; some could be positive, and some negative, but the time of year these temperature anomalies occur is critical. Our results indicate that average lower temperatures in spring associated with the nuclear conflict could delay planting, but depending on the course of temperature accumulation during the rest of the season, crops could achieve physiological maturity at an earlier or later date. While later planting could be an adaptation option to limit this temperature effect, one needs to consider the increased risk of encountering killing temperatures before physiological maturity occurs (Sacks and Kucharik, 2011). While there are some subtleties in Agro-IBIS pertaining to optimum planting date (determined by running mean temperatures in spring) and an optimum hybrid for each grid cell based on GDD requirements, our analysis emphasizes the impact of cooler spring conditions on delayed planting, shorter growing period and lower yields.

Given present uncertainty about location-specific environmental effects of a regional nuclear conflict, this study has helped to interpret the impacts of global climate change in the Midwest U.S. under a nuclear war scenario. One benefit of this downscaling may be to help prioritize adaptation strategies. The potential for adapting maize-soybean systems to climate change is well documented (e.g., Lobell et al., 2008; Ainsworth and Ort, 2010). These strategies may include development of new technologies that permit crops to be more drought- and cold-resistant and have different carbon allocation strategies (Lopes et al., 2011). For example, the trend toward earlier corn planting in the U.S. (e.g., Kucharik, 2006) is supported by development of temperature-activated polymers applied to seeds. Moreover, planting densities have increased, and harvest index has also increased through the development of stay-green hybrids (Tollenaar and Lee, 2010). Farming has become more efficient with new and better equipment to boost productivity. Where water is limited, irrigation may be a solution. The Midwest is not generally considered a water-limited region so a small investment in irrigation infrastructure could alleviate the reduced precipitation expected as a result of a regional nuclear war.

The approach adopted in this study, linking an ecological model and a climate model has several limitations. With respect to climate change predictions, we only considered the means of the regional climate system; we did not assess changes in its variability. While the use of randomly selected years of observed data perturbed by monthly anomalies allows for some variation in day-to-day weather, true variability, including climatic extremes, is not captured. Also contributing to this issue is the monthly time scale of anomalies generated by the climate model. Therefore our perturbation approach is somewhat conservative, as monthly means tend to smooth individual daily extremes that may lead to crop failure. Recent work by Mills et al. (2008) suggests that extreme cold events are likely in a nuclear scenario and should be included in future works involving crop productivity. Also, we used the results of a single GCM to perturb observed data in our model. It is well-known that in greenhouse gas-based radiative forcing experiments for longer time periods there could be significant variation in predicted climatic conditions among different models, even when all models are forced with the same emission scenarios. It is uncertain whether different GCMs would respond similarly to a short-lived aerosol forcing resulting from a regional nuclear war.

While GCM output suggests that the largest precipitation, temperature, and radiation changes occur in years 2–5, the yield response to these anomalies is greatest in year five for all sites and crops. However, given that the GCM results used in this study reflect only one scenario and one climate model, the effects could be coincidental, as a regional conflict could bring about considerable variability in worldwide climate conditions. Thus the results presented here are indicative of the amplitude of effects that could result in the Midwest or elsewhere. Yet the Robock et al. (2007a) study involved three runs whose mean is used here, so variability may already be reduced: it is possible that for any individual realization there might be greater extremes.

Crop simulation models are important tools to test whether global atmospheric changes are likely to have an impact on crop yields. Confidence in them depends on their ability to reliably and accurately characterize crop growing cycles and yields. To this end, the Agro-IBIS model has performed well, predicting yields of maize and soybean crops as expected as the model has been specifically validated at other sites across the Midwest U.S. (i.e., at the individual site level at Arlington, Wisconsin; Mead Nebraska; and Bondville, Illinois), as well as regionally with USDA county level data and MODIS observations of greenness and (Leaf Area Index) LAI (please see Kucharik et al., 2001; Kucharik and Brye, 2003; Kucharik, 2003; Kucharik and Twine 2007; Twine and Kucharik, 2008; Twine and Kucharik, 2009). Although the mean values of modeled and observed yield quantities do not exactly match, the modeled yields are within errors bars of observed yields. Several reasons can be given to explain the apparent mismatch between the yields. First, we used ten years (1995-2006) of yield data from USDA that are being averaged and we know that U.S. summer crop yields are generally increasing at a rate of about 1.3% per year (NASS). Agro-IBIS is calibrated to simulate what the most current (e.g., 2012) yields are, so it is expected, particularly for corn, that the yields are higher than the longer-term averages as no "technology" curve was implemented in Agro-IBIS as part of these simulations. Since the USDA yields are representative of ~2000 (mid point of 1995-2006), there are 12 years between that value of yield and the most current value simulated by Agro-IBIS ~2011. With an average increase in yields of 1.3% per year, the current yields would be about 14% higher than the values on the graph for observed and that would clearly close the gap between observed and simulated. The issue of declining model performance for corn as one goes from counties in IA, IL, IN to MO – which was first noticed when Agro-IBIS was regionally validated with USDA county level yield data (Kucharik, 2003) – is partially explained by the fact that counties with higher number of harvested acres in the USDA data generally lead to a better comparison with Agro-IBIS (especially for corn) because averaging occurs over many more combinations of weather, soils, and management sets. In fact the MO site has the least area of planted acres of both crops of all sites. Therefore, this is not necessarily a model issue, but rather a quality of data (and what county averages truly represent) when comparing results from a point simulation (grid cell, or collection of grid cells) to county averages.

While it is possible to adjust various parameters in Agro-IBIS to match observed yields perfectly but this may inadvertently lead to a model "over fitting" results issue. There is no guarantee that by changing a few parameters, the model will agree better across all sites because fundamental issues that likely contribute to variation in yields from year to year as well as across sites will not be accounted for. The best way to go about judging model performance would be to run many additional runs of varied management, including pesticide, herbicide treatments, N, P, K, manure variations; tillage differences, planting dates, hybrid selections, and soil nutrient status at the beginning of the season but this would move the current research away from the primary purpose of assessing yields effects of nuclear a war. So while it is possible to make the Agro-IBIS model match observed yields exactly, this approach would not necessarily be simulating yield average values from about 10-15 years ago, especially considering that the current work is not about model fitting and calibration for the past, but about looking at potential yield responses for some point in time.

It is also important to note that this research focused on only the Midwest U.S. and on only two crop types. While the region covered is small, it represents an area with significant crop production connected to global food, feed, and, increasingly, fuel supplies. For example, maize is an important ingredient in many food products in the form of fructose sugar, feed for livestock, and in recent years, increasingly used to make ethanol for fuel. Therefore, any disruption to crop production in the Midwest could be felt around the world.

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Table 1. Location of sites tested.

site	location	latitude/longitude	description
IA	Southwest Iowa	42.0ºN -95.0ºW	mixture of cropland, prairie and savanna
IL	Central Illinois	40.0ºN -89.0ºW	mixture of cropland and prairie
IN	Northern Indiana	41.0ºN -87.0ºW	drift plains, croplands, and sandy areas
MO	N Central Missouri	40.5ºN -92.0ºW	mixture of forests and croplands

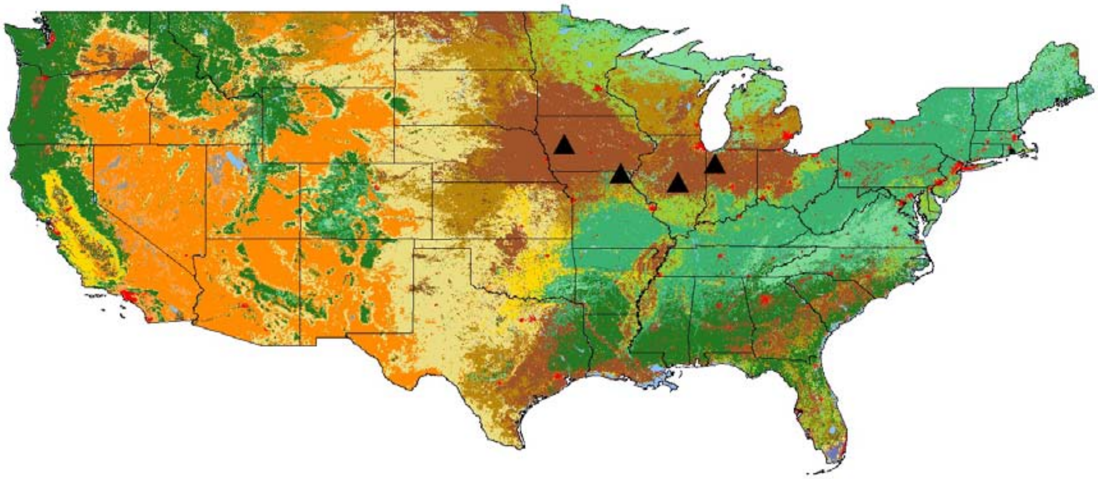

Figure 1. Locations of experiment sites, depicted as black triangles on a generalized land cover map. The dark brown color represents the intensive crop growing areas of the Midwestern U.S.

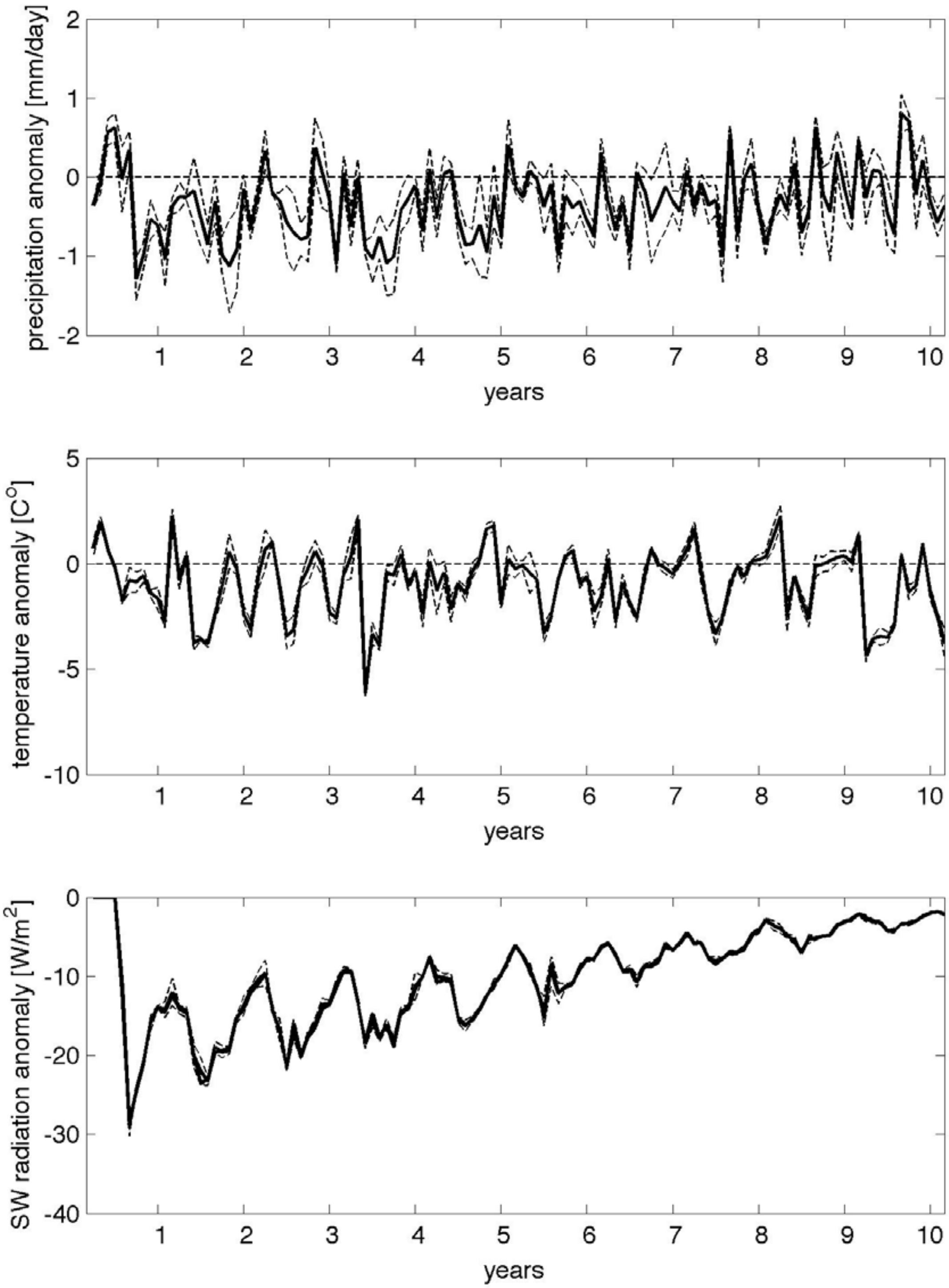

Figure 2. Predicted temporal changes in precipitation, air temperature, and net shortwave radiation following a 5 Tg nuclear conflict. The thick black line represents the mean anomaly across the four sites while the broken line around the mean is the standard deviation across all sites. Data from Robock et al. (2007a).

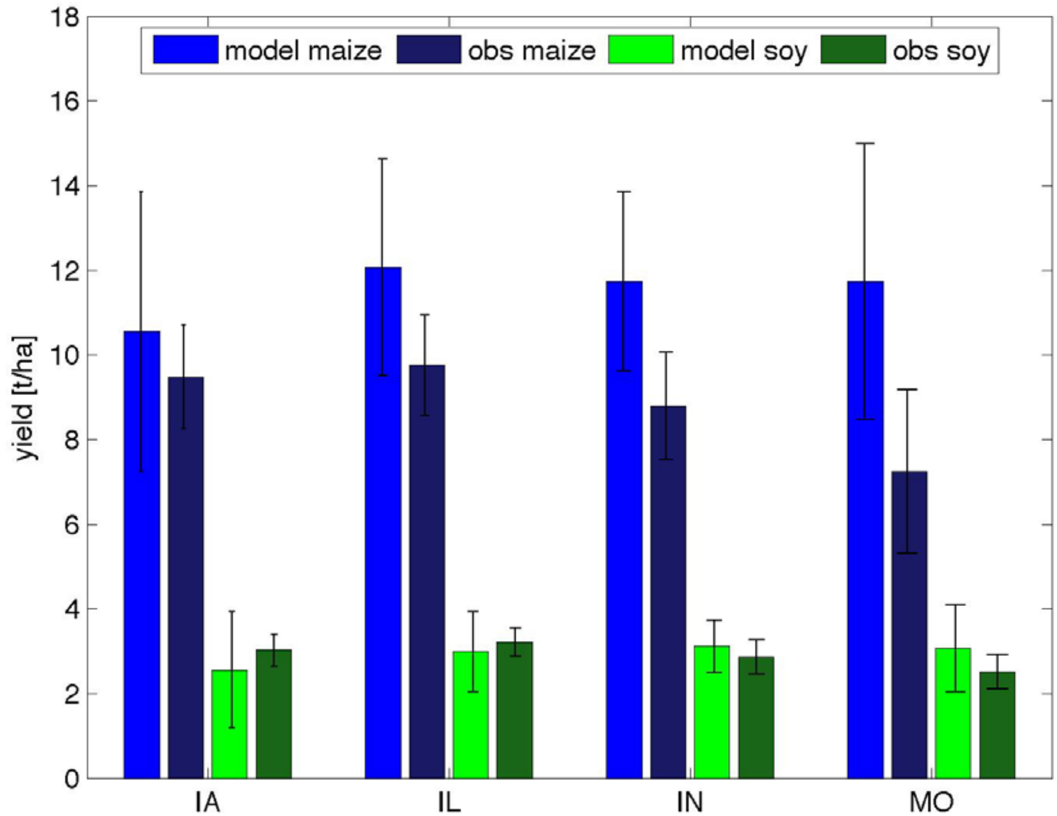

Figure 3. Comparison of modeled and reported mean yields of maize and soybean in locations considered in this study. The error bar represents the variation in the form of one standard deviation across years. The reported yields are averaged over 10 years (1996-2005).

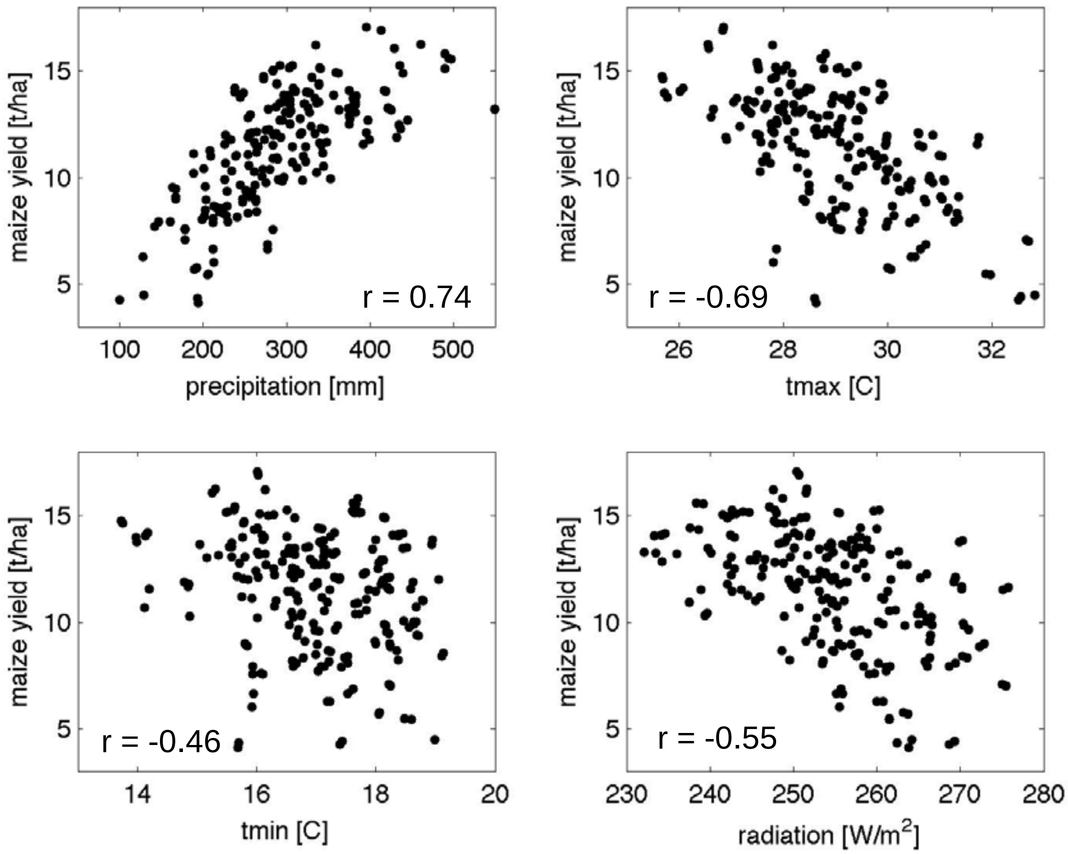

Figure 4. Climatic controls of modeled maize yields in Midwestern U.S. under nuclear war conditions. Data are from all sites. Climate data represent the average growing season conditions between June and August. For precipitation, the growing season sum is shown and for temperature and radiation variables, the average is shown. The Pearson correlation coefficient (r) is provided for reference.

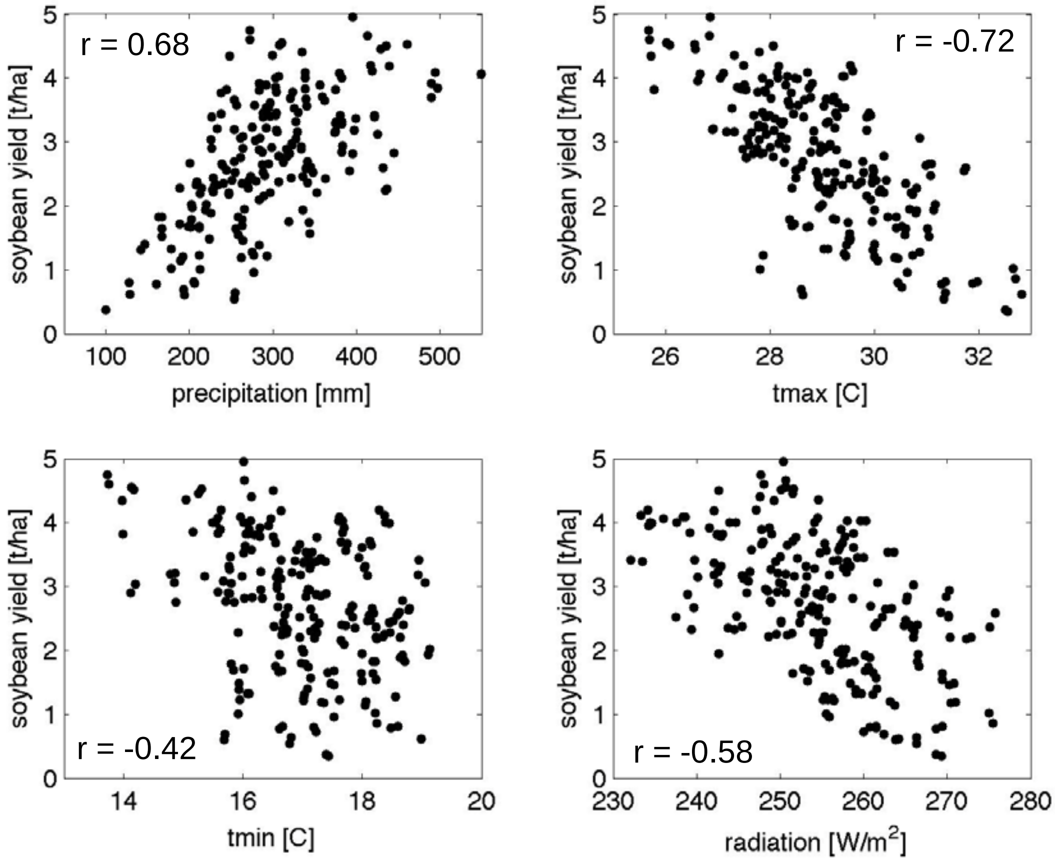

Figure 5. Climatic controls of modeled soybean yields in Midwestern U.S. under nuclear war conditions. Data are from all sites. Climate data represent the average growing season conditions from June through August. For precipitation, the growing season sum is shown and for temperature and radiation variables, the average is shown. The Pearson correlation coefficient (r) is provided for reference.

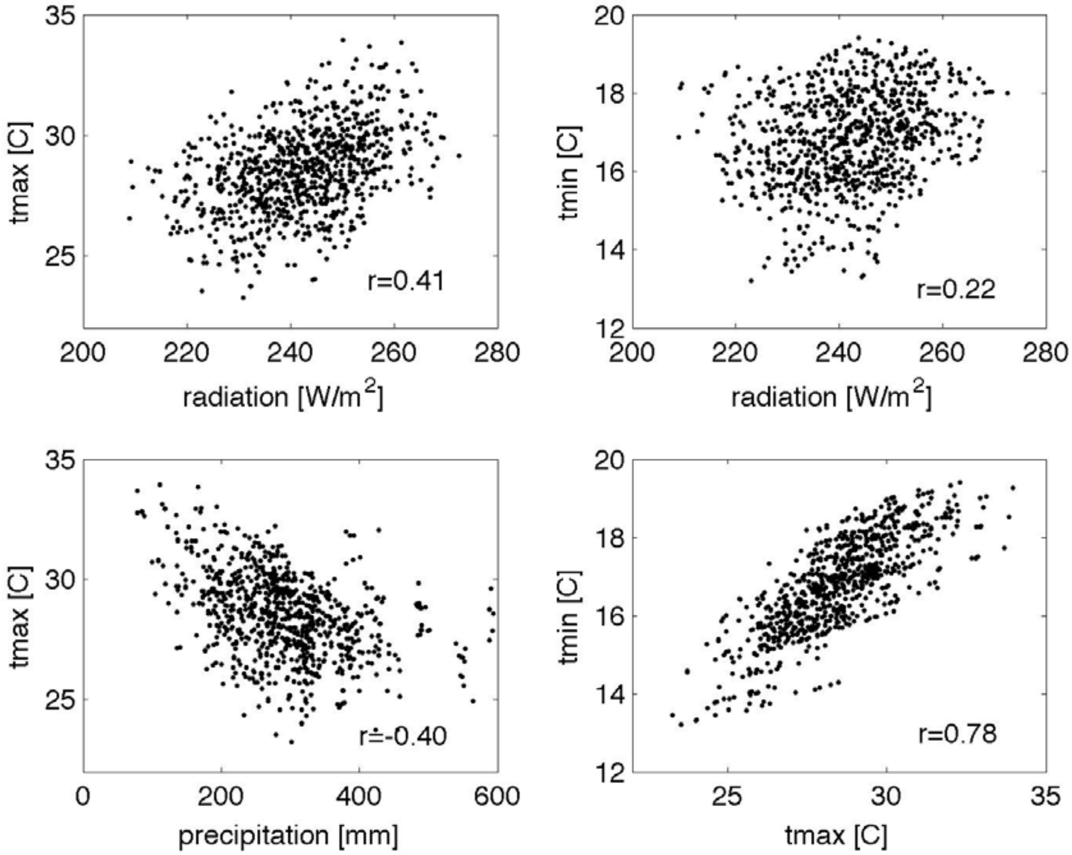

Figure 6. Correlations among different meteorological forcing variables used to drive the Agro-IBIS model. Data represent average conditions for all sites between June and August under nuclear war conditions. The Pearson correlation coefficient (r) is provided for reference.

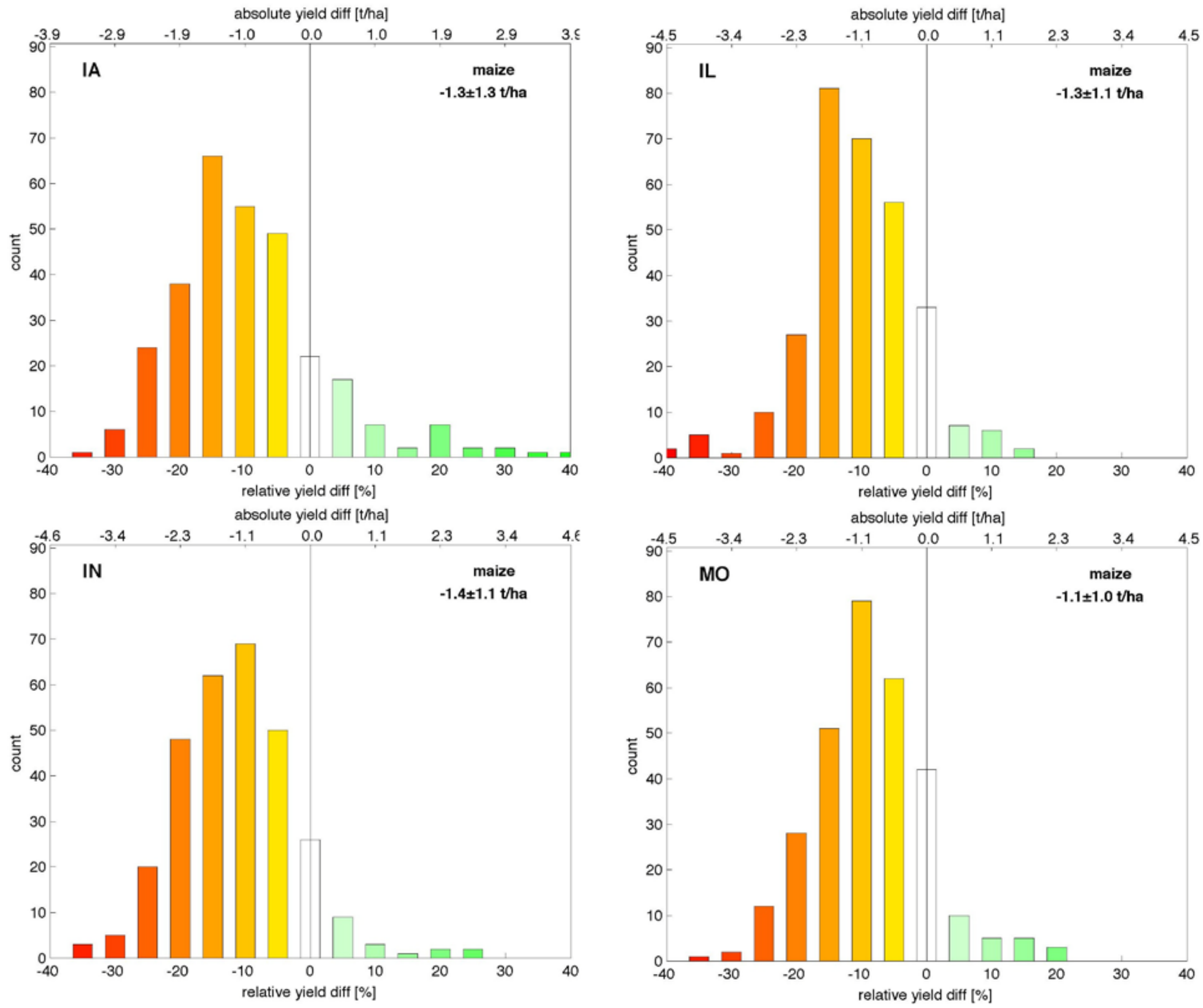

Figure 7. Histogram distribution of relative and absolute changes in modeled maize yields in four locations following the 5 Tg event. Small to nil yield changes are shown in white. Gradation of yellow to red colors depict reductions in yields while the hues of green indicate increases. The mean and variation of expected yield changes in absolute terms (t/ha) are also given.

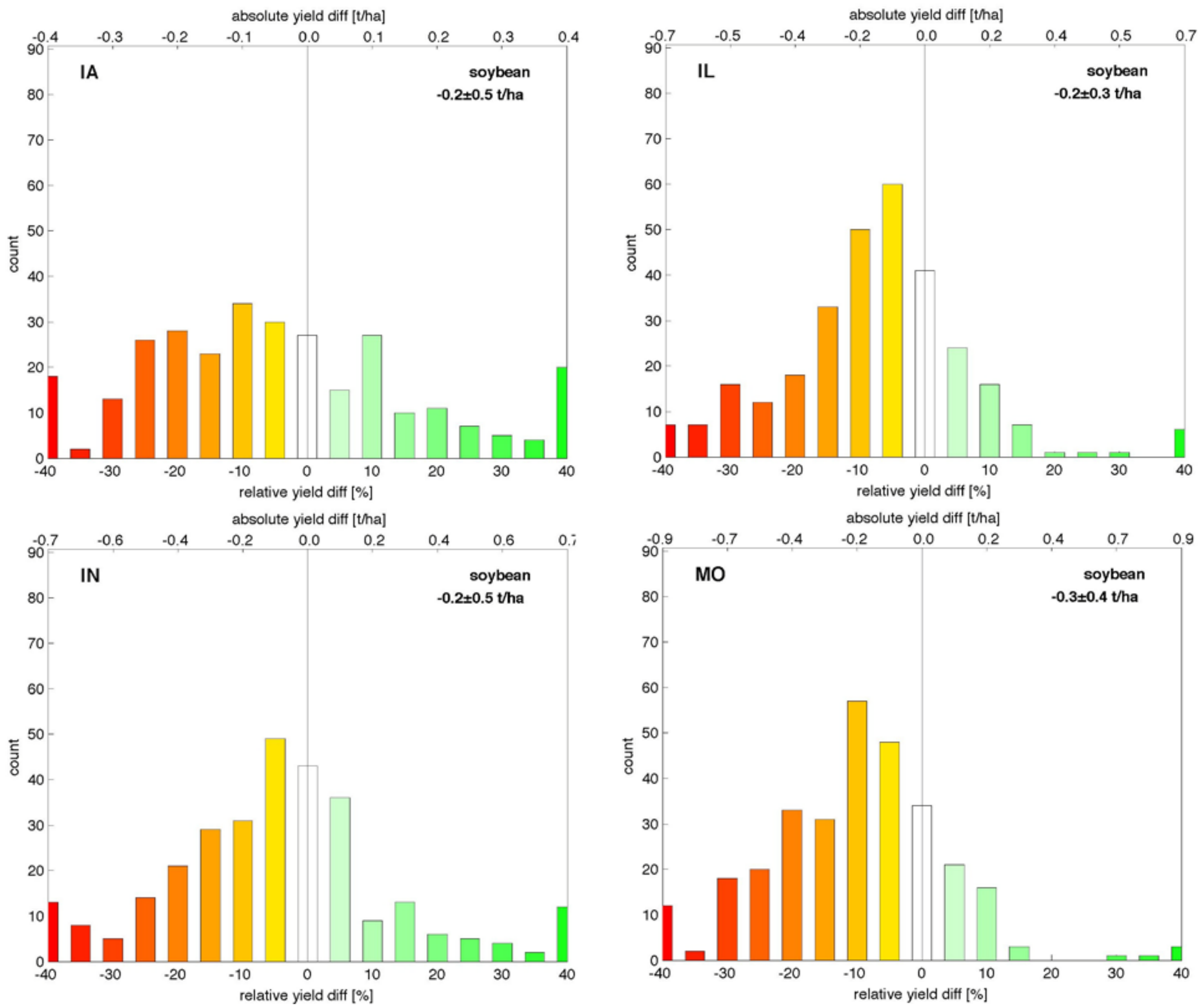

Figure 8. Histogram distribution of relative and absolute changes in modeled soybean yields in four locations following the 5 Tg event. Small to nil yield changes are shown in white. Gradation of yellow to red colors depict reductions in yields while the green hues indicate increases. Also provided are the mean and variation of expected yield changes in absolute terms (t/ha).

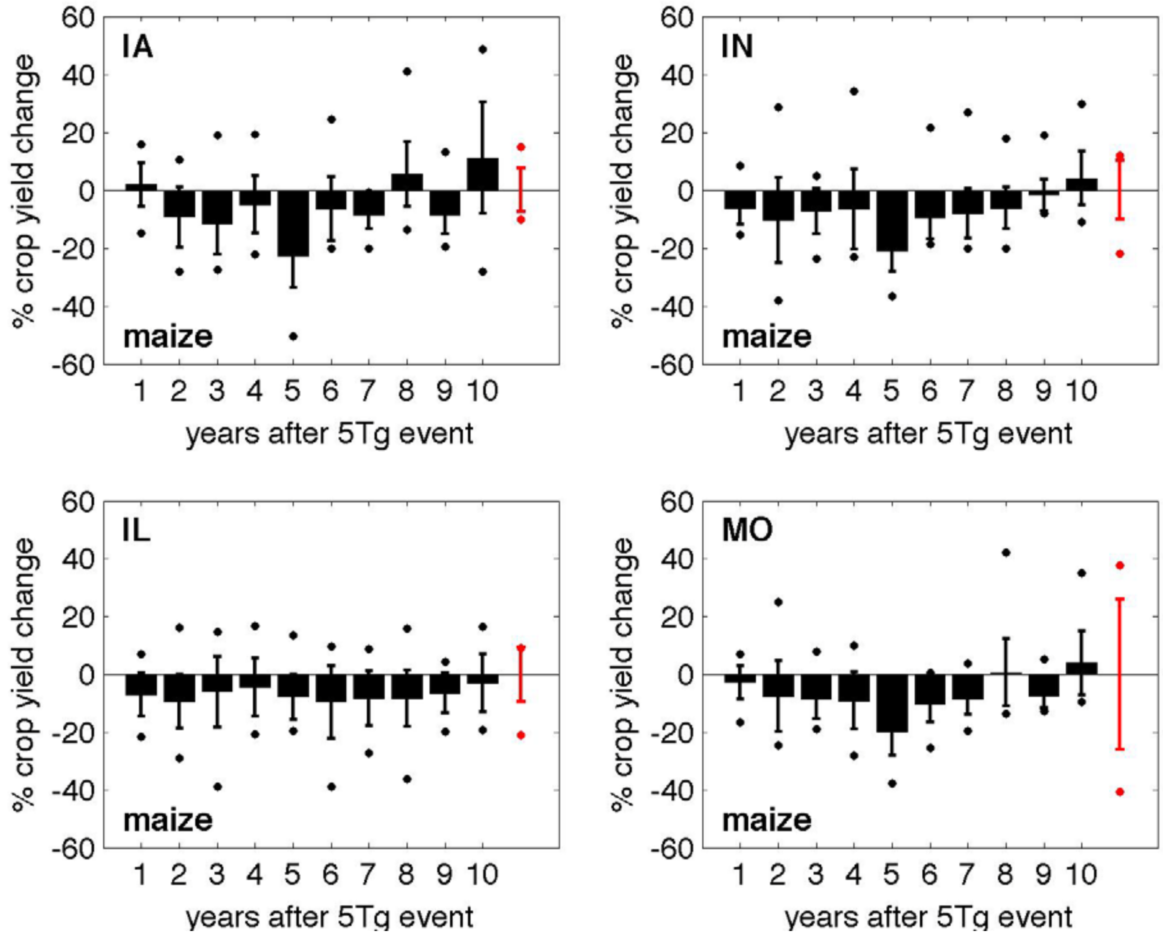

Figure 9. Mean relative changes in maize yields across four sites over a decade following the 5 Tg nuclear event. Negative values indicate a decrease from the control run. Each black bar represents the average of 30 realizations of the model run for a given year while the whiskers indicate +/- one standard deviation across experiments. The minimum and maximum yield changes across 30 model runs are shown as black dots. A missing black dot means it was outside of the range of Y-axis limits. The natural variation of maize yield over a 10-year period in each location is shown in red. The mean of natural variation is set to zero and the spread is given in the form of percent deviation from this natural mean.

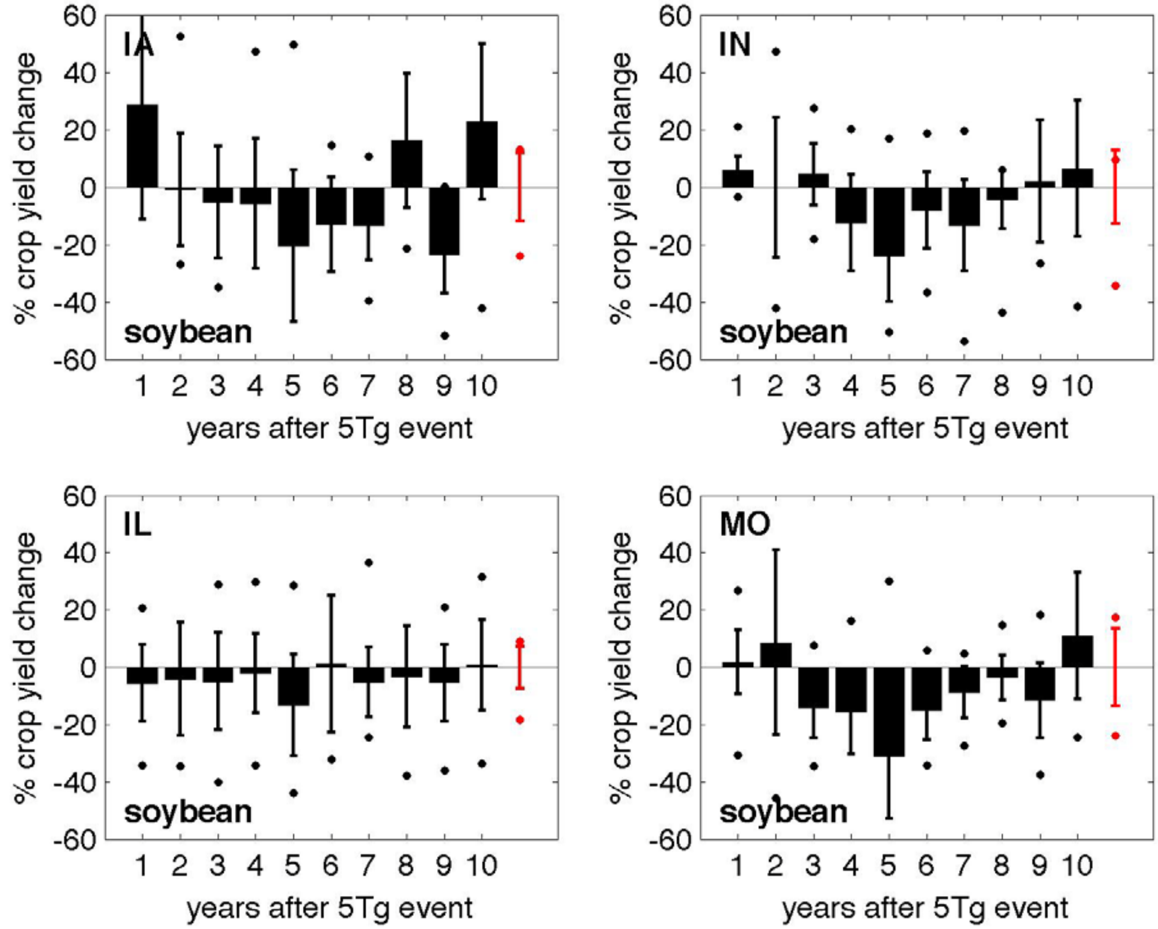

Figure 10. Mean relative changes in soybean yields across four sites over a decade following a 5Tg nuclear event. Negative values indicate a decrease from the control run. Each black bar represents the average of 30 realizations of the model run for a given year while the whiskers indicate +/- one standard deviation across experiments. The minimum and maximum yield changes across 30 model runs are shown as black dots. A missing black dot means it was outside of the range of Y-axis limits. The natural variation of soybean yield over a 10 year period in each location is shown in red. The mean of natural variation is set to zero and the spread is given in the form of percent deviation from this natural mean.

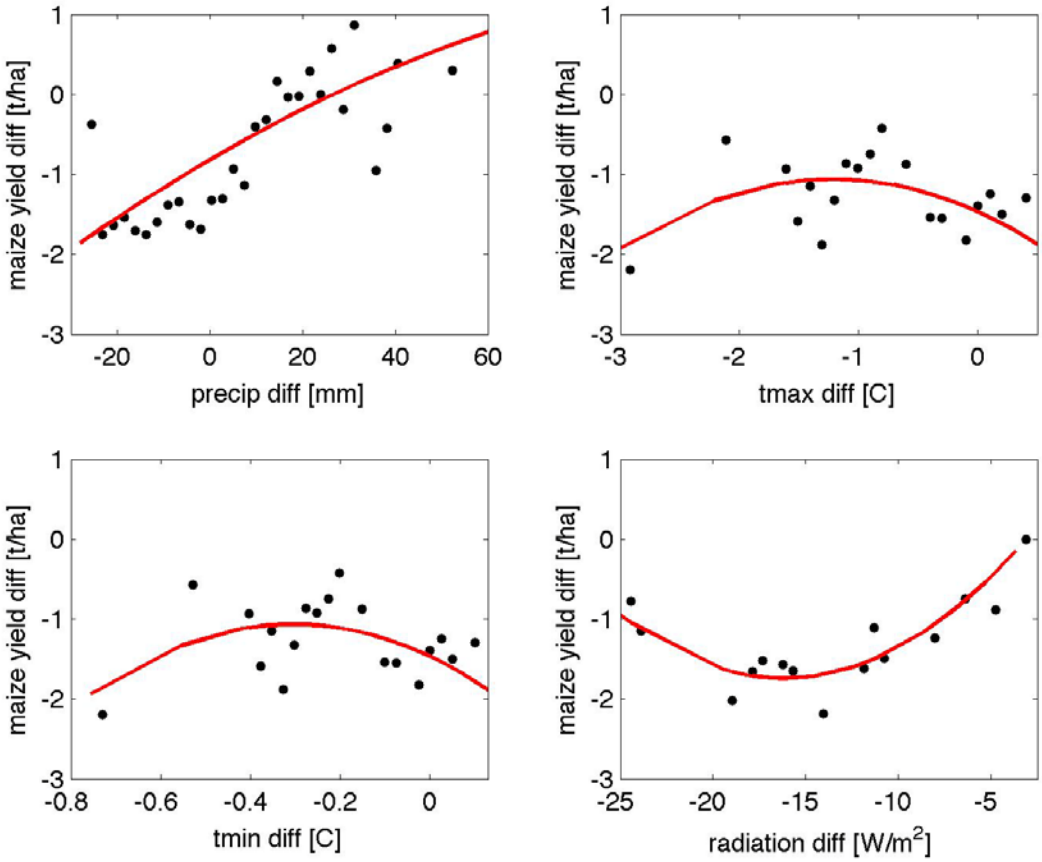

Figure 11. Climatic controls of modeled yield changes between the control and nuclear scenario for maize. For each panel, the climate data (X-axis) represent the averaged binned difference (calculated as nuclear – control) in growing season conditions between the scenarios while yield differences on the Y-axis depict the binned yield difference between the nuclear and control runs.

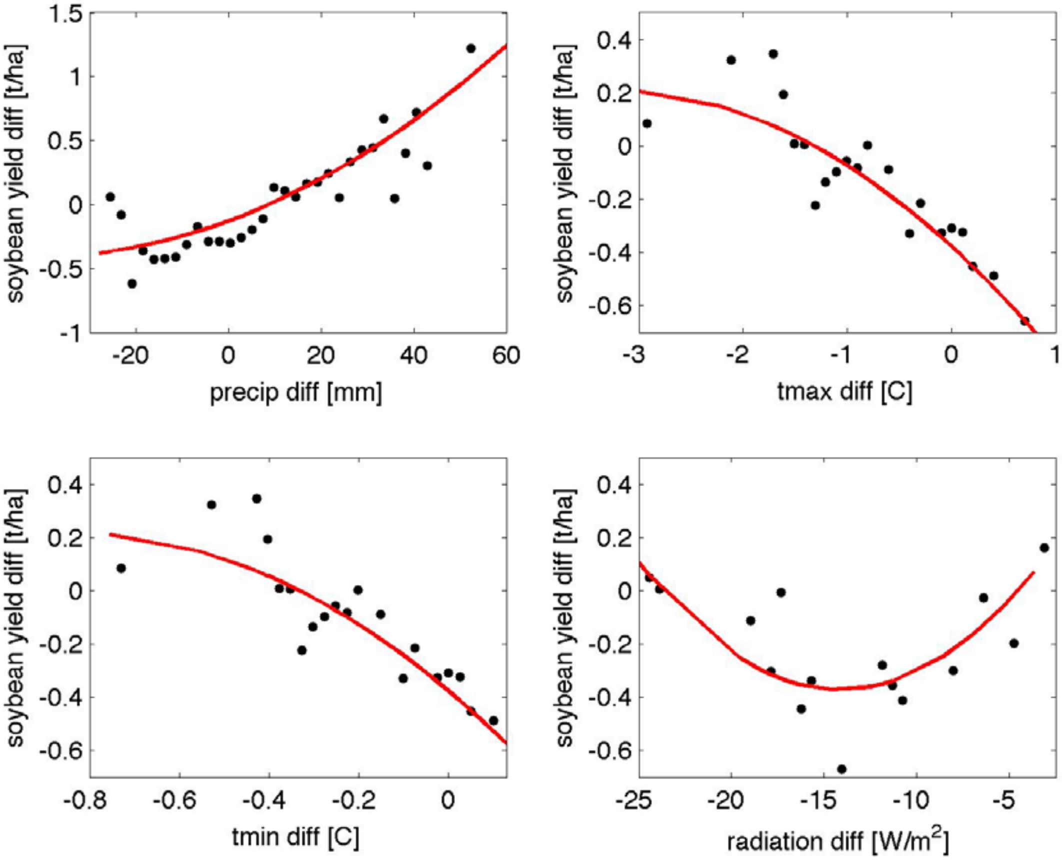

Figure 12. Climatic controls of modeled yield changes between the control and nuclear scenario for soybeans. For each panel, the climate data (X-axis) represent the averaged binned difference (calculated as nuclear – control) in growing season conditions between the scenarios while yield differences on the Y-axis depict the binned yield difference between the nuclear and control runs.

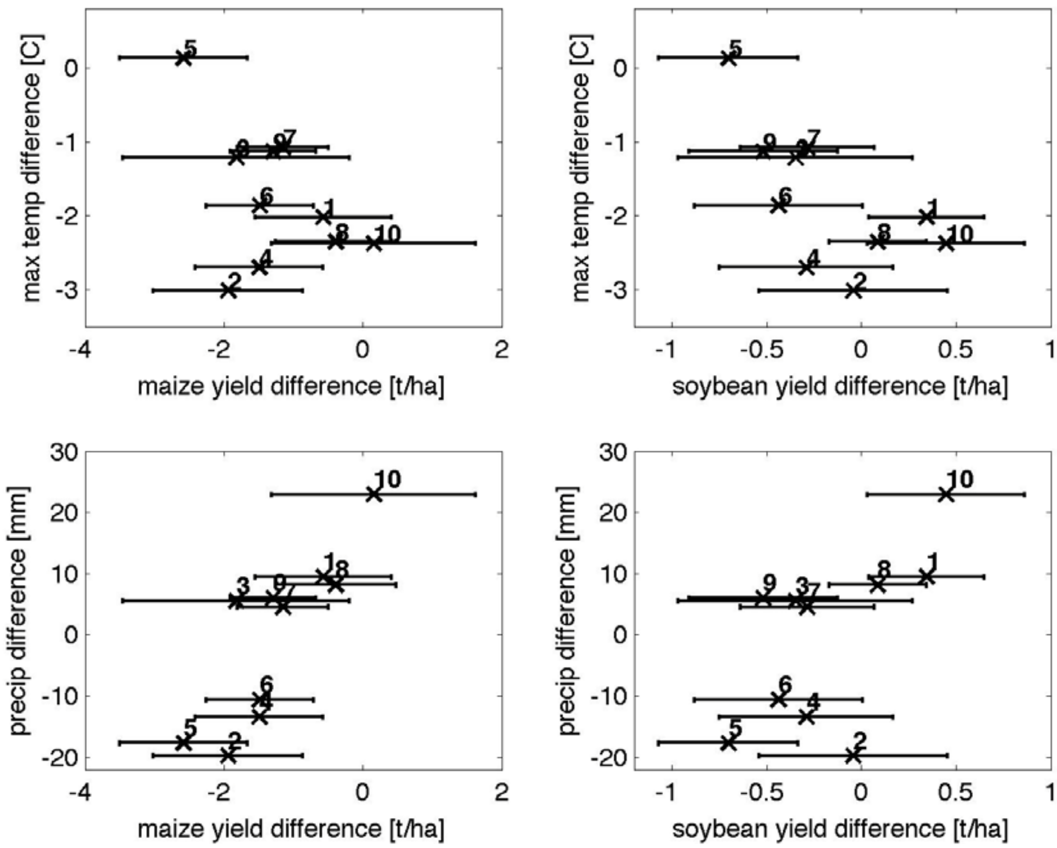

Figure 13. The effects of growing season maximum temperature (top) and precipitation (bottom) differences between the control and nuclear scenario on maize and soybean yields. Each marker (x) represents the average value of the 30 experiments per year while the length of the bar shows its variation. The numbers on the figure represent the years following the 5 Tg nuclear event where 5 means the 5th year following the event. The growing season is defined as June through August.

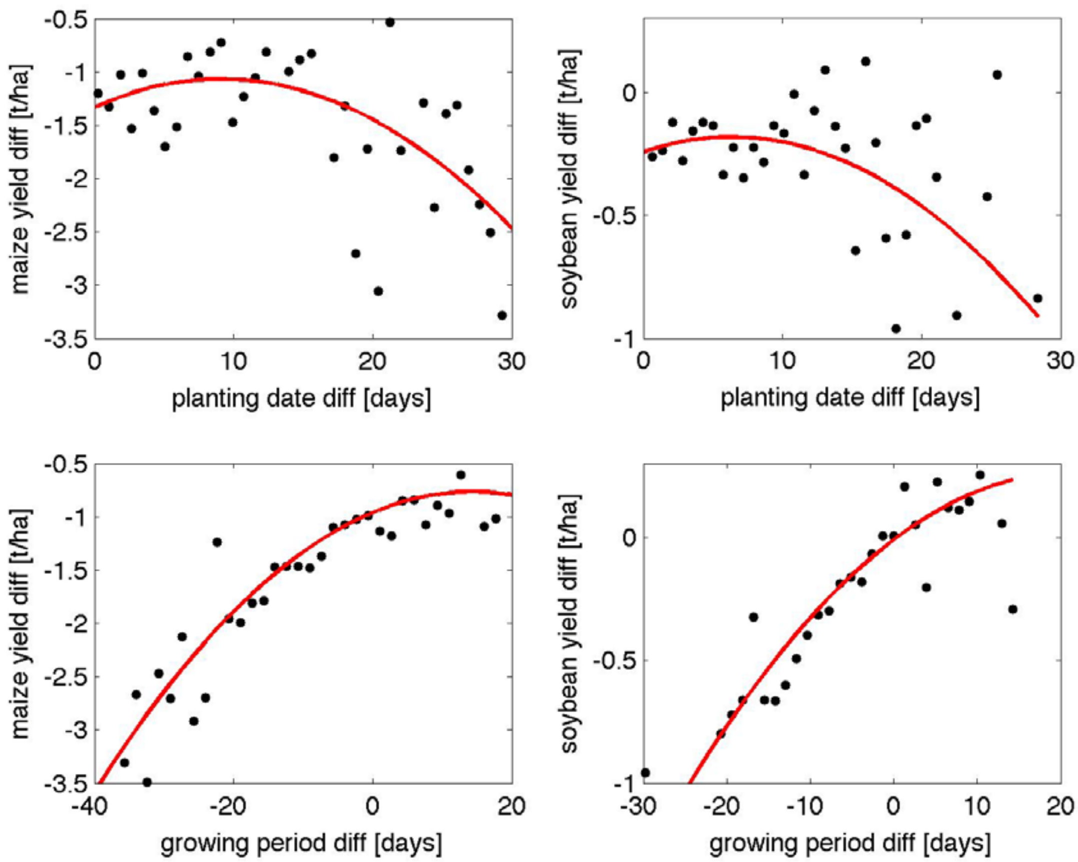

Figure 14. Relationship between changes in planting date (upper panels) and growing period (lower panels) and crop yield differences between the nuclear and control scenario for maize (left panels) and soybean (right panels). The planting date difference was calculated as the difference between the nuclear and control case predicted planting date so the positive values indicate later sowing dates. The growing period length is defined as the number of days between predicted planting and harvest dates. The positive values in the planting date difference indicate later sowing while negative values in the growing period indicate a shorter growing season.