Consequences of a Regional Nuclear Conflict for Crop Production in the Midwestern United States

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ABSTRACT

Crop production would decline in the Midwestern U.S. from climate change following a regional nuclear conflict between India and Pakistan. Using Agro-IBIS, a dynamic crop growth model, we simulated the response of maize and soybeans to cooler, drier, darker conditions from war-related smoke. We combined observed climate conditions for Iowa, Illinois, Indiana and Missouri with output from a general circulation simulation that injected 5 Tg of elemental carbon into the upper troposphere. Both maize and soybeans show notable reductions for a decade after the event. Maize yields would decline 10-40 percent while soybeans would drop 2-20 percent. Temporal variation in magnitude of yield for both crops generally follows the variation in climatic anomalies; greatest decline is in the five years following the 5 Tg event, then gradually levels out. Yield decline for both crops appears linked to changes in growing period duration and, less markedly, to reduced precipitation and altered maximum daily temperature during growth. Seasonal average of daily maximum temperature difference between the control and nuclear scenarios has a quadratic relationship to yield differences; extreme changes create increased yield loss, but mean changes are neutral.
1. Introduction

In an event of nuclear war, targets in cities and industrial areas would release light-absorbing particles (e.g. 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, 1983; Harrington, 1992; Oppenheimer, 2003). Less known, however, is whether similar crop failure might be caused by a regional nuclear conflict.

Consequences of a nuclear war were recognized in the 1980s when studies investigated expected agricultural production changes. For example, Sinclair (1986) used a physiologically-based model to simulate potential soya bean production during slow climatic recovery following a nuclear winter in Midwestern US. This study showed that temperature reductions of 2-4°C throughout the growing season substantially reduced soya yields. Unfortunately, since then, there has been little study of 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. Its 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., 2007).

Consequences of a 5 Tg nuclear war

The resulting climatic anomalies were extracted from Robock (supra), in which temperature, precipitation and radiation effects of 5 Tg of elemental carbon were 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 quickly reaches the stratosphere after a nuclear conflict. Because of lack of rain — an important stratospheric feature — some elemental carbon lingers there for over a decade.

When averaged globally and annually, temperatures fell 1.25°C and precipitation decreased 9% for years 2-4 following smoke injection; after 10 years, temperature was still -0.5°C and precipitation still down 1%. Temperature reductions exceeded the global average in summer in the middle of continents, and precipitation anomalies varied highly in space and time. These changes are less dramatic than those in “nuclear winter” simulations of a massive nuclear exchange between superpowers involving 50 to 150 Tg of elemental carbon. However, the changes 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 represent the stratospheric plume rise.

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, and spring and winter wheat, and management choices into IBIS, simulating both managed and natural ecosystems (Kucharik, 2003; Kucharik and Twine, 2007). 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). Thus 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). Soil moisture and leaf-nitrogen stress functions
reduce the maximum photosynthetic capacity \( (V_{\text{max}}) \) of the plant.

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, ET, and energy balance across the Midwest.

**Perturbation of contemporary climate data**

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, approximations 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. 2007). 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, 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 .25° grid cells centered at four locations in the Midwest (Table 1, Figure 1). The sites are located in the “Corn Belt,” an arc-shaped region with tremendous agricultural productivity, and are located across an east to west precipitation gradient during summer, but with similar mean annual temperature. We modeled the yield of maize and soybeans, which are the most abundant types grown there, while keeping ambient CO₂ concentrations at the 2000 level. In each case, all management practices including nitrogen-based fertilizer use (150 kg/ha for maize, 25 kg/ha for soybeans) 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; these thresholds 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 a soil biogeochemistry model was artificially activated more frequently than the model time step to bring soils into equilibrium (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 when available water content of the soil fell below 50% of the maximum in any location; water was added to reach 100% available water. Thus the irrigation module was only activated at the drier sites. 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; a discussion is provided later for the amount of change in sowing and harvest dates as well as changes in weather conditions during the growing period (Sacks and Kucharik, 2011).

To assess the accuracy of crop yield predictions from the Agro-IBIS model, 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 closest to the simulation site. 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), 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

\[ \text{yield change (\%)} = \frac{nuclear - control}{control} \times 100. \]

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 (2007), 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 reduction of solar radiation. For the last five years the precipitation anomalies are small. Temperature displays more negative than positive anomalies, indicating significant cooling through the decade, but returns to pre-war conditions soon after. 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 (Robock et al., 2007). The precipitation anomaly varies greatest across sites, followed by temperature and radiation. Solar radiation does not exhibit a very strong variation. Robock et al (2007) show that when averaged globally and annually, the temperature anomaly trends to
–0.5°C in year 10, but anomalies in the Midwest don't 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 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.

**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 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-existant. Available insolation seems to be correlated with yields although there seems to be better correlation with soybeans than maize. 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. The observed correlation between solar radiation, maximum temperature, and precipitation provides evidence for this (Figure 6).

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 percent 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 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 percent 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 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 (PDF). 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 normal distribution but with greater variable mean rate, ranging from 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, soybeans 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 soybeans for the sites.
considered here. For maize, mean relative change is predicted to be <20% decline in year five, with all years showing production loss 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.

What are the drivers of yield change in the nuclear scenario?

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 one to three tons/hectare 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 change, 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 changes simultaneously (precipitation + temperature + radiation) produces the yield reduction.

The climatic response of soybean yield differences parallels 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 increases in yield, albeit small. The responses 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 experiments were conducted under the no adaptation scenario. 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 sowing dates and length of growing period, we investigated the relationship of two variables: (a) the difference in planting dates between the control and the nuclear scenario, and (b) the difference in yields between the two scenarios (Figure 14). The results show that the event is always accompanied either with no change or later planting for both crops. The later dates also have 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 difference in yields and difference in growing period, we find that the strength of the correlation for growing periods is much larger for both crops (Figure 14). Thus maize yields experience little or no change when the growing season is constant or increases. However, as it becomes shorter (negative numbers), maize yield drops precipitously; the largest reduction occurs when the growing period is reduced 40 days. This also applies to soybeans, although the rate of yield decline increases as the number of days in the growing period is reduced.

Based on observational evidence, recent work by Kucharik (2006, 2008) has shown the opposite trend; 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. While there are some subtleties in Agro-IBIS pertaining to optimum planting date (determined by running mean temperatures in spring) and an optimum hybrid (determined by GDD) for a grid cell, the analysis above emphasizes the impact
of cooler spring conditions on delayed planting, shorter growing period and lower yields. This indicates the importance of changes expected to timing and duration of maize and soybean growth.

4. Discussion and conclusions

The results of this research suggest that both crops may experience significant yield reductions with 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 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 a region 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 with ample time to develop and apply 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. Warming during spring or fall could lengthen the growth period for summer crops, particularly in more northern locations of the Corn Belt (see Kucharik, 2008). This would support increased yields. Cooler conditions during the seasonal transition periods associated with a nuclear conflict likely condense the available growth period, and lead to fewer calendar days for crops to intercept radiation and perform photosynthesis. Moreover, temperature increases create an accelerated rate of GDD accumulation that can contribute to crops progressing through their phenological stages more quickly, with fewer calendar days to accumulate biomass. Extreme heat can lead to stress, a higher rate of evapotranspiration (ET), and may contribute to late season water deficits as ET exceeds precipitation for longer periods of time. Thus, temperature 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.

Increases in rainfall as a result of a nuclear conflict have the ability to increase yields. However, this is not true of temperature where both decreases and increases have negative effect, though with different contributions. The primary effect of temperature on yields is through shortening or lengthening the growing season. 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. One needs to consider that later planting would
reduce chances of early freeze and crop loss, but at the risk of encountering killing temperatures before physiological maturity occurs (Sacks and Kucharik, 2011).

Given present uncertainty about location-specific environmental effects of a regional nuclear conflict, one contribution of this study is to localize these effects; this may 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 planting in the US (e.g., Kucharik, 2006) is supported by development of temperature-activated polymers applied to seeds. Moreover, planting densities have increased; 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 (2007) 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. An additional limitation of this study is the less-than-ideal fit between modeled and observed crop yields and the larger variation in modeled yields in the study sites. There are two reasons for this. First, the model is sensitive to year-to-year weather variations in part because Agro-IBIS, like most crop models, is a production efficiency model designed to respond effectively to environmental conditions.
Second, county-level yield values are integrated over a large region containing farms that are both above and below the mean. Thus, when scaling up to county level, over long time periods some extremes are smoothed. In contrast, when Agro-IBIS is run in a point type mode, only one set of weather conditions is selected that effectively shows up as increased variability in the long term. More precisely, if fine-scale weather data existed for all the farms that comprise the NASS county yield data, repeated Agro-IBIS runs across many years of weather, would be expected to show less variability in simulated yields when averaged over all farm points.

The lack of fit between modeled and observed yields can be attributed to other limiting factors that are not considered by this model. For example, the number of acres harvested in each county generally has an impact on how well the model performs; the IA and IL sites have the best correlation between model and observations, and IN/MO the least. Kucharik (2003) found that yield observations in counties with a large planted area of a crop often had the closest agreement to Agro-IBIS simulations. This may be attributable to large areas representing a more accurate yield average. Moreover, the model automatically decides the optimum planting date and hybrid (GDD) for each location, when in fact these could differ significantly from reality due to human decision-making. Finally, pests and disease may decrease the yields but this factor is not considered in Agro-IBIS.

Finally, this research focused on only the U.S. Midwest and on only two crop types. While the region covered is small compared to the global effects of aerosol forcing generated by a nuclear war, it represents an area with significant crop production connected to global food and feed supplies. Maize is an important ingredient in many food products, is used as feed for livestock, and in recent years, is increasingly used to make ethanol for fuel.
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References


Table 1. Location of sites tested.

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<th>location</th>
<th>latitude/longitude</th>
<th>description</th>
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<tr>
<td>IA</td>
<td>Southwest Iowa</td>
<td>42.0°N - 95.0°W</td>
<td>mixture of cropland, prairie and savanna</td>
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<td>IL</td>
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<td>40.0°N - 89.0°W</td>
<td>mixture of cropland and prairie</td>
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<td>Northern Indiana</td>
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<td>drift plains, croplands, and sandy areas</td>
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<td>MO</td>
<td>N Central Missouri</td>
<td>40.5°N - 92.0°W</td>
<td>mixture of forests and croplands</td>
</tr>
</tbody>
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Figure 1. Locations of experiment sites, depicted as black triangles on a generalized land cover map. The dark brown color represents the corn belt.
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. (2007).
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 USA 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.
Figure 5. Climatic controls of modeled soybean yields in Midwestern USA 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.
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.
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.
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.