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Global warming presents new challenges for maize pest management

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Abstract
It has been conjectured that global warming will increase the prevalence of insect pests in many agro-ecosystems. In this paper, we quantitatively assess four of the key pests of maize, one of the most important systems in North American grain production. Using empirically generated estimates of pest overwintering thresholds and degree-day requirements, along with climate change projections from a high-resolution climate model, we project potential future ranges for each of these pests in the United States. Our analysis suggests the possibility of increased winter survival and greater degree-day accumulations for each of the pests surveyed. We find that relaxed cold limitation could expand the range of all four pest taxa, including a substantial range expansion in the case of corn earworm (*H. zea*), a migratory, cold-intolerant pest. Because the corn earworm is a cosmopolitan pest that has shown resistance to insecticides, our results suggest that this expansion could also threaten other crops, including those in high-value areas of the western United States. Because managing significant additional pressure from this suite of established pests would require additional pest management inputs, the projected decreases in cold limitation and increases in heat accumulation have the potential to significantly alter the pest management landscape for North American maize production. Further, these range expansions could have substantial economic impacts through increased seed and insecticide costs, decreased yields, and the downstream effects of changes in crop yield variability.

Keywords: climate change, agricultural pests, maize, RegCM3, regional climate modeling

1. Introduction

It is now firmly established that global land and ocean temperatures have increased since the industrial revolution, and that rising greenhouse gas concentrations are the primary cause of this warming [1]. Even without further increases in greenhouse gas concentrations, mean global surface temperature is likely to continue to increase over the coming century [2]. Additionally, should greenhouse gas concentrations continue to rise, future warming is likely to be even more dramatic, with global surface temperatures likely to increase 1.1–6.2 °C by the end of this century [1]. However, there is likely to be substantial spatial heterogeneity in the

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response of climate to this global warming, both across the globe [3] and within individual regions (e.g., [4, 5]). Similarly, the response of daily-scale events is likely to be non-uniform across space and time [4, 6, 7], with the greatest climate change impacts likely resulting from threshold-exceedances associated with changes in climate extremes [6].

Quantifying the potential costs and benefits of these climatic changes requires assessment of the exposure of a suite of climatically sensitive natural and human systems. Exposure of agro-ecosystems to climatic changes is an important case in point. A review of climate impacts by Fuhrer [8] concludes that while there are expected to be some positive impacts of climate change upon agriculture, they will likely be offset by other negative consequences. One such potential consequence is the general expectation that climate warming will cause insect pests to become more abundant in mid- to high-latitude regions, a concern also reflected by other reviews [9–11].

Indeed, almost all insects will be affected to some degree by changes in temperature, and there may be a multitude of intertwined effects upon insect life histories. Porter *et al* [12] listed the effects of temperature upon insects, including limitation of: geographical range, overwintering, population growth rates, number of generations per annum, crop-pest synchronization, dispersal and migration, and availability of host plants and refugia. Laboratory and modeling experiments support the notion that the biology of agricultural pests is likely to respond to increased temperatures [13–15]. For example, warming could decrease the occurrence of severe cold events (e.g., [4]), which could in turn expand the overwintering area for insect pests [11]. In-season effects of warming include the potential for increased levels of feeding and growth, including the possibility of additional generations in a given year [9].

Uncertainty about the impact of pests on crop yield distributions has been a key limitation in assessing the potential impacts of climate change on agriculture [16], with the vulnerability of maize crops to increased pest pressure posing particular concern. Production of maize for both animal feed and human food is among the largest agricultural land uses in the world [17]. In North America, where approximately half of the world's maize is produced (275 million metric tons in 2006 [17]), there is also an increasing emphasis on using this grain for ethanol production, leading to soaring demand for maize in recent years [18].

Losses due to insect pests, and the costs of controlling them, represent the largest allocation of resources in the production of maize worldwide [19]. Although there are over 90 insect species that are considered pests of maize [20], most of these can be considered minor and/or sporadic pests. However, there are several key pests of which all producers must be mindful each year. These include the corn rootworm complex of beetles (*Diabrotica* spp.), which have been estimated to cost producers in the US approximately $1 billion annually [21]. Other significant pests include the European corn borer, *Ostrinia nubilalis* Hubner, which is responsible for similar damage levels as the rootworm beetles [22]. Likewise, the corn earworm (*Helicoverpa zea* (Boddie)) is responsible for destroying about 2% of the maize crop annually [23], and is also a serious pest of several other major crops, including cotton, tomato, and grain sorghums [24]. The corn earworm is considered a migratory pest, moving into more northern latitudes during each growing season [25], while the other pest species listed above generally overwinter where maize is grown intensively.

The economic and social impacts of climate-induced changes in maize yield-distribution will depend on their impact on global supply relative to the global demand, the balance of which will determine the price of maize. Climate change is one factor amid several major long-term trends: the growth rate in the production of grains and oilseeds has been gradually slowing since the 1970s, and even though population growth is also slowing, increasing incomes—especially in developing countries—mean that global food demand is increasing [26]. For maize in particular, increasing incomes in developing countries have increased demand directly and indirectly through increased demand for animal protein [26]. The combination of slower production growth and increasing demand for both food and ethanol means that 2007/2008 global inventories of cereal grains other than wheat and rice (of which maize is estimated to be 79%) will be at their lowest levels in over 30 years [27]. Going forward, assuming no change in the United States and European Union policies toward biofuels, any impacts of climate change will likely occur in an environment of very tight maize supplies, where any reduction in supply will likely result in substantial economic and social consequences.

The quantitative relationships between temperature and physiology gleaned from decades of laboratory studies on key pest species provide an excellent opportunity to quantify how pest distributions may change in the future as climate continues to change. Insects are highly adaptable organisms in many ways. However, analysis of the fossil record suggests that some beetle species, and perhaps insect species in general, have kept similar climatic requirements over thousands of years of fluctuating temperatures [28], lending confidence to analyses using these climatic thresholds as a filter. Because insect physiology is sensitive to critical temperature thresholds, and because range shifts of hundreds of kilometers can have large economic consequences, fine-scale variations in the response of climate to elevated greenhouse gas concentrations could drive the net impact of climate change on agricultural pests. Thus, although there has been extensive laboratory work and some analysis of potential large-scale pest responses, there exists a need for analyses that consider daily-scale thresholds in fine spatial detail. Here we present such an analysis using previously published laboratory-based relationships in conjunction with high-resolution climate model simulations. This analysis attempts to quantify how the distribution of pest prevalence may respond to local warming associated with elevated greenhouse gas concentrations.

2. Methods

We calculate potential distributions for four key pests of maize production in North America: corn earworm (*H. zea*), European corn borer (*O. nubilalis*), northern corn rootworm (*Diabrotica barberi* Smith and Lawrence), and western

Table 1. Temperature screening criteria. (Minimum GDD must be met and cold limitation must not be exceeded in order for a given year to be considered suitable at a given grid point.)

	Cold Limitation				
	Chilling hours −10 °C	Annual minimum temperature (°C)	GDD season	GDD base (°C)	Minimum GDD
Corn earworm (*H. zea*)	120 [29]	—	January 1–May 31	12.5 [30]	150 [30]
European corn borer (*O. nubilalis*)	—	−28 [31]	January 1–June 30	10.0 [32]	284 [32]
Northern corn rootworm (*D. barberi*)	1008 [33]	—	January 1–June 30	10.0 [34]	340 [34]
Western corn rootworm (*D. v. virgifera*)	840 [33]	—	January 1–June 30	12.7 [35]	265 [36]

corn rootworm (*Diabrotica virgifera virgifera* LeConte). Temperature criteria are shown in table 1 and contain 3 components: the lower overwintering threshold (or cold limitation) of the appropriate life stage of each insect, and the threshold and cumulative growing degree days (GDD) required to initiate and complete in-season development, respectively.

In the case of the corn earworm, the pupal stage overwinters, with Eger *et al* [29] demonstrating that significant mortality occurs at 120 h of temperatures below −10 °C. Coop *et al* [30] combined several environmental chamber studies to generate a model of corn earworm development, and we use these parameters of a threshold of 12.5 °C and cumulative GDD of 150 in our calculations. Using environmental chambers to chill overwintering larvae of the European corn borer, Hanec and Beck [31] demonstrated that an annual minimum temperature of −28 °C was sufficient to cause mortality in the overwintering stage, while Got and Rodolphe [32] used these data and other controlled-environment studies to develop and validate a comprehensive model of temperature-dependent development for this insect. We use their model to set a base GDD of 10 °C and minimum cumulative GDD of 284.

In the case of the rootworm species we investigate (the western corn rootworm and the northern corn rootworm), the eggs are the overwintering stage and are highly cold-tolerant. Ellsbury and Lee [33] used chilling cabinets with thermocouples attached to groups of 3–5 eggs to determine mortality and super-cooling points for both species and demonstrated that northern corn rootworm eggs withstood 1008 h at −10 °C, while western corn rootworm eggs were able to withstand 840 h below this threshold. In-season development models for both species are based upon calculating GDD accumulations required until 50% egg hatch is reached. In the case of northern corn rootworm, this occurs at 340 GDD, with a base of 10 °C [34]. In the case of western corn rootworm, controlled-environment studies by Levine *et al* [35] found a threshold temperature of 12.7 °C, while Schaafsma *et al* [36] validated a model that predicts 50% egg hatch at 265 GDD.

We follow the approach of White *et al* [6] to calculate potential present and future temperature-based distributions of each of the pest taxa. This approach employs the 1 km observational Daymet dataset [37] (www.daymet.org) and the high-resolution climate change projections of Diffenbaugh *et al* (described in [4, 6, 7]). The Daymet dataset contains 24 years of observational temperature data (1980 through 2003). In calculating the present potential distribution of each pest, we first calculate whether the temperature screening criteria (table 1) are met at each grid point in a given year. After calculating those screening criteria at each grid point for each of the 24 years from 1980 through 2003, we then sum the number of years for which the screening criteria are met at each grid point. This summation yields the number of suitable years for each pest at each grid point, with a minimum of 0 and a maximum of 24.

We calculate projected future distributions in much the same way. However, instead of using the observational Daymet data directly, we first add the simulated future climate changes from [4]. This 'anomaly' approach helps to remove systematic biases in the climate model, and allows us to capture spatial variations in temperature that occur at the 1 km Daymet resolution. Thus, in calculating the potential future distribution of each pest, we first calculate the temperature variables (GDD, chilling hours, absolute minimum temperature) at each grid point in each year of the baseline (1961–1989) and future (2071–2099) simulations. We perform this initial calculation on the climate model's 25 km grid, and then interpolate those values to the Daymet 1 km grid. We next average the values of each variable for the 29 baseline model years and the 29 future model years, respectively. Calculating the difference between the mean annual values in the future simulation and the reference simulation yields the future mean annual change for each temperature variable at each grid point. We then add these simulated future mean annual changes to the respective Daymet values for each of the 24 years of the Daymet dataset, yielding a 'future' Daymet timeseries of 24 years in length. The difference between this future Daymet timeseries and the original Daymet timeseries is that the values of the temperature variables in the future Daymet timeseries are displaced from the original values by the magnitude of the mean annual change simulated by the climate model. We can then calculate the total number of years at each grid point in which the respective temperature criteria are met for each of the pests as described for the present potential distributions, but instead using the future Daymet timeseries, yielding the potential future distribution of each pest.

As in [6], our reference climate model simulation covers the period 1961–1989 and our future simulation covers the period 2071–2099 in the SRES A2 emissions scenario [38]. The high-resolution climate simulations are generated using the Abdus Salam ICTP regional climate model (RegCM3) [39] nested within the NASA finite volume general circulation model (FVGCM) [40]. The RegCM3 grid covers the continental United States and surrounding oceans with a

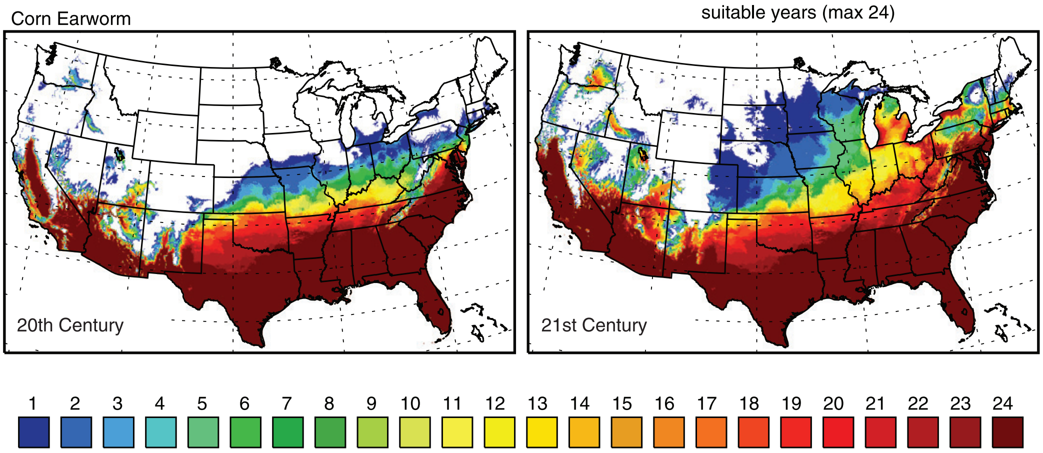

Figure 1. Current and future temperature envelop for a migratory, cosmopolitan taxon. 20th century distribution (left panel) and 21st century distribution (right panel) for corn earworm. Color contours show the number of years that are suitable (out of a maximum of 24).

horizontal resolution of 25 km, and 18 levels in the vertical. The FVGCM global grid has a horizontal resolution of 1° latitude by 1.25° longitude, and 18 levels in the vertical. Sea surface temperatures (SSTs) for the reference integration are taken from the observational dataset of [41]. SSTs for the future integration are calculated as described in [42].

Following [43], the chilling hours t for each hour hr are calculated from the daily maximum and minimum temperature as:

$$t = (mn + mx)/2 + (mx - mn) * \cos(0.2618 * (hr - 14))/2$$

where mn = daily minimum temp; mx = daily max temp; and hr ranges from 1 to 24.

3. Results

3.1. Modern potential distribution

The modern potential distribution of corn earworm prevalence stretches across the Gulf Coast and Atlantic Coast regions, as well as the Central Valley of California and the lowlands of the Desert Southwest (figure 1). The modern potential distributions of European corn borer, northern corn rootworm and western corn rootworm prevalence are more broad, covering much of the eastern two-thirds of the continental United States, as well as substantial areas of the western third (figure 2). These temperature-based potential distributions compare well with the actual distribution of these taxa at present (see Steffey *et al* [20] for pest distributions and range maps). For instance, the corn earworm is a migratory species that is the most sensitive to winter cold temperatures of the species in our study, thereby restricting its distribution to areas within migratory range of overwintering zones. Although it is an in-season pest wherever corn is grown, its overwintering range is much smaller. The other three taxa are more cold-hardy and therefore are able to overwinter in a broader climate envelope that includes most of the United States and small areas of Canada. However, the actual modern distributions of these 3 species are chiefly a reflection of areas where their host plants—primarily maize—are grown, namely the lower Great Plains and Midwestern states, extending into the southernmost regions of the Canadian provinces of Manitoba, Ontario and Quebec.

3.2. Future potential distribution

The potential range is larger in the future climate than in the baseline climate for all four pests (figures 1 and 2). Corn earworm prevalence expands into the Northeast and Upper Midwest, as well as coastal California and the Columbia Basin in eastern Washington. The potential range of European corn borer expands to cover most of the continental United States, excepting the high elevations of the Mountain West (figure 2). The potential ranges of northern corn rootworm and western corn rootworm also expand to cover the vast majority of the continental United States, with low occurrence in the upper Great Plains and absence that extends lower in elevation than the absence exhibited by European corn borer.

Cold limitation decreases in the future climate relative to the baseline climate (figure 3). Absolute minimum temperatures increase (future minus present) throughout the domain, with peak increases of up to 12 °C over the Midwest. Similarly, chilling hours below −10 °C decrease throughout the domain, with peak decreases (up to −1000 h) occurring over the northeast of the domain. Conversely, heat accumulation increases throughout the domain in the future climate relative to the baseline climate (figure 4). Peak increases in $GDD_{10.0}$ and $GDD_{12.7}$ (of over 500° days/year) occur over the Desert Southwest, southern Great Plains, and Gulf Coast regions. Increases in $GDD_{12.5}$ are smaller throughout the domain, with peak increases of over 400° days per year also occurring over the Desert Southwest, southern Great Plains, and Gulf Coast regions.

4. Discussion

The largest change in potential range is seen in the corn earworm, a cosmopolitan pest. We project substantial

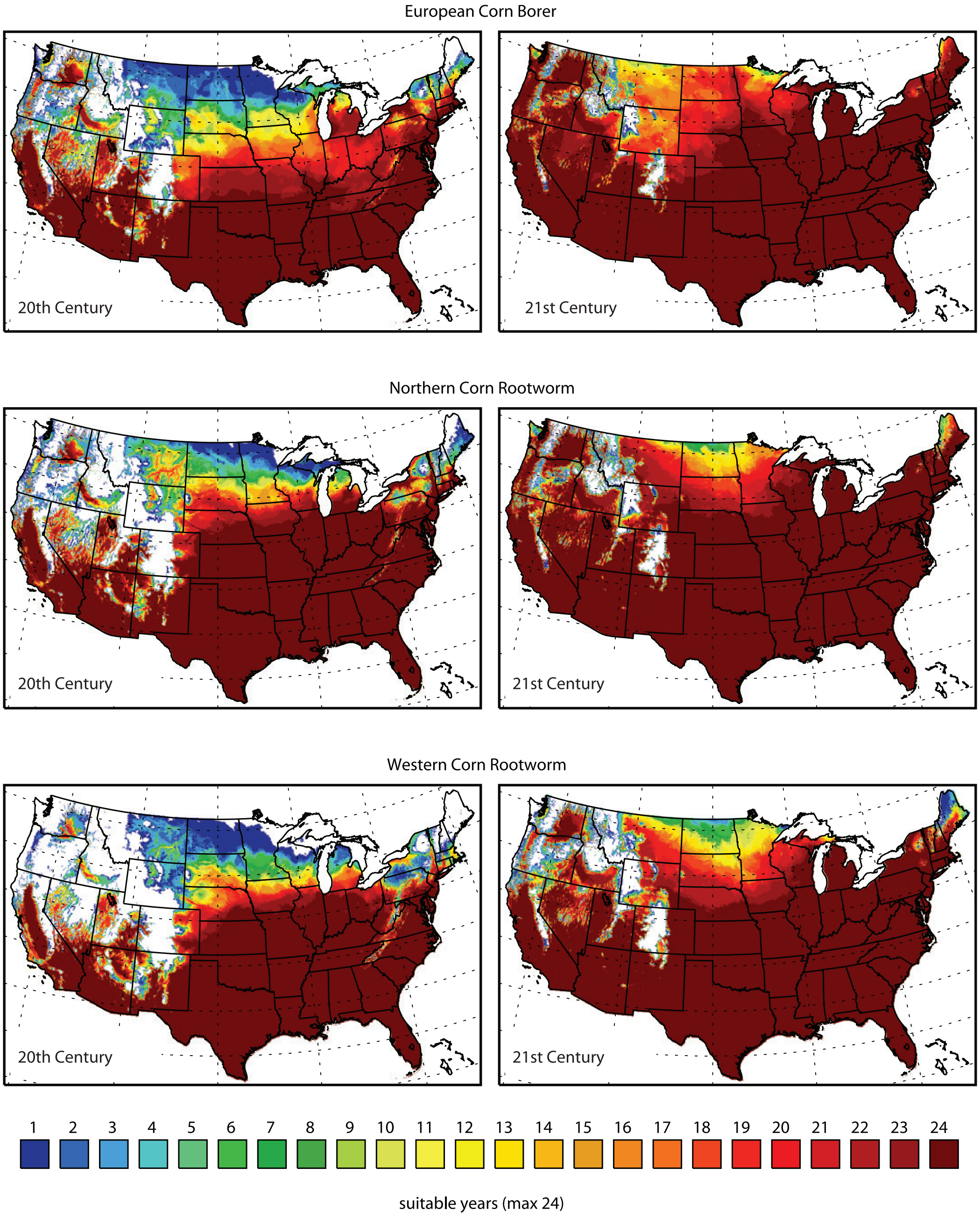

Figure 2. Current and future temperature envelopes for non-migratory, corn-specific taxa. As in figure 1, but for European corn borer (top panels), northern corn rootworm (middle panels), and western corn rootworm (bottom panels).

northward range expansions into the upper Midwestern United States, a key region of global maize production. This is particularly noteworthy because female corn earworm moths are capable of flying long distances and infesting a wide variety of annually sown crops during the season [25, 44]. Corn earworm is an established significant pest in the southern United States, and expansion of overwintering range would allow this pest to more readily colonize maize and other potential host plants (e.g. soybeans, tomato) grown in the upper Midwest and southern parts of Canada [45]. Likewise, the simulated range expansion in coastal California, the Willamette Valley in Oregon, and the Columbia Basin in Washington could increase pest pressure on the wide variety of economically important crops currently grown in those areas. Adding significant pressure from the corn earworm could pose problems for pest management, as this species has shown documented resistance to a wide range of insecticides (see [24] for a review), including products belonging to the widely used pyrethroid class of insecticides.

Conversely, simulated European corn borer ranges expand primarily into regions of the northern Great Plains that currently exhibit relatively low production of maize or other hosts, so it is unlikely that this insect would create a completely novel pest problem. However, the increase in GDD over the course of the growing season could provide an increased opportunity for damage. In the area of primary maize

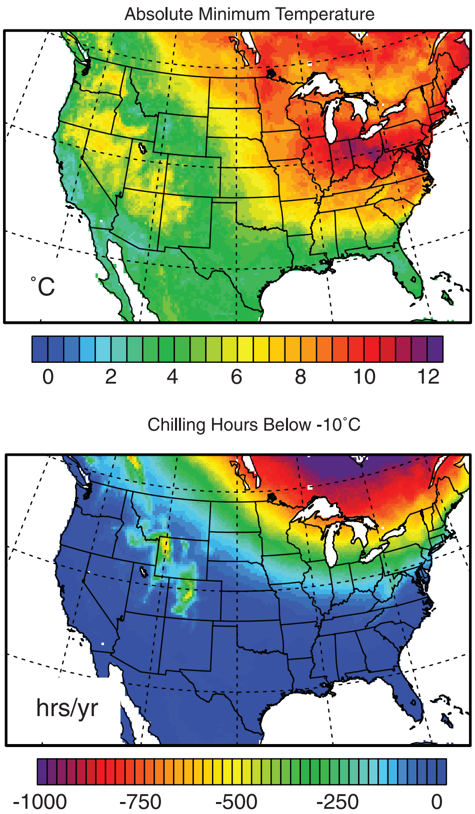

Figure 3. Simulated changes in cold limitation in the 21st century. Annual absolute minimum temperature (°C; top panel) and chilling hours below $-10\,^{\circ}$C (hours per year; bottom panel). See table 1 for references supporting respective cold limitation formulations.

production in North America—the Midwest—corn borers are generally restricted to two generations per year because of GDD requirements. The addition of heat units would help to increase the likelihood of a third generation development [15], which both causes damage to the crop late in the season, and could significantly increase the overwintering population [46].

The corn rootworm species we analyzed both demonstrate nominal range expansions into the upper Midwest and the northern Great Plains. Of the two, the western corn rootworm is the more damaging pest, and is less cold-tolerant than the northern corn rootworm [33]. Relaxed cold limitation would reduce overwintering mortality and could allow this species to become dominant in new areas, such as northern Minnesota and the Dakotas.

Management of all of the pests discussed here is currently achieved both through the use of insecticides applied at planting and, increasingly, through the use of maize hybrids expressing insect-resistance traits (or 'Bt corn'), which represented 49% of US acreage in 2007 [47]. The average costs of managing these pests currently range from \$22 to \$68/ha. If the producer uses insecticides, then the costs of managing these pests in 2008 range from \$22 to \$40/ha [48, 49]. If the producer uses genetically modified seed (i.e. Bt corn) to control these pests, then the average additional seed cost in 2008 is \$60/ha, with an additional cost of \$4.40 to \$8/ha to treat the 20% refuge [49]. Further, in addition to these short-term costs, increased use of any insecticidal product (including Bt corn) as a response to elevated pest pressure and/or range expansions provides enhanced opportunities for the evolution of resistance to these products [50].

Therefore, one possible impact of pest response to climate change is an increased cost of producing maize via increased seed and insecticide costs, which would increase the price of maize in the long term. In addition, increased insect damage could lower maize yields, further increasing prices. The magnitude of the maize price increases due to climate change will depend on global supply relative to demand, but they could have substantial economic and social impacts via higher food prices and reduced food supply. The maize price increases that occurred in 2007 and early 2008 clearly illustrate the potential negative economic and social impacts of higher maize prices. For example, the UN's Food and Agriculture Organization (FAO) Food Price Index increased by 47% between January 2007 and January 2008, with cereal prices increasing 62% [51].

A second potential economic impact is through changes in maize yield variability. As noted by Chen *et al* [52], there are several economic implications of increased yield variability, potentially leading to higher costs of insurance and disaster-relief, as well as pressure to maintain larger grain stocks in order to ensure food security. However, the potential impacts of changes in pest prevalence on crop yield variability remain unexplored in a quantitative framework (e.g., [52, 53]).

Although our data suggest range expansions for each of the four major pests that we selected, there are some limitations to our analyses. First, it is important to note that the complexities in the interactions between these insects and their environment (such as those we noted earlier) make it difficult to make statements about future populations and ranges based only upon the temperature parameters included in our analyses. Second, although there is substantial evidence for temperature controls on insect prevalence, other environmental variables such as drought and atmospheric transport could also play a role in determining future ranges [8, 10]. Likewise, our work does not address the possibility of interaction between future changes in temperature and the effects of simultaneously elevated levels of atmospheric CO_2, which has been shown to indirectly increase susceptibility to insect pest feeding in other agricultural systems [54, 55]. Such multi-factorial experiments are required to fully understand the impacts of changing climate upon insects, caveats which have also been noted by other researchers studying the problem [46, 56]. However, the use of quantitative, empirically generated insect life history parameters in our calculations increases confidence in our interpretations of the effects of temperature on this suite of maize pests.

There are also limitations to the climate model projections. First, although we use climate model experiments of unprecedented spatial and temporal detail, computational restrictions have limited us to single realizations of the baseline and future periods. Although the general results of relaxed cold limitation and enhanced heat accumulation are likely to be robust, the actual magnitude and spatial heterogeneity of those responses could vary in the future. Ongoing work is focused on quantifying the physical uncertainty in highly detailed future climate projections.

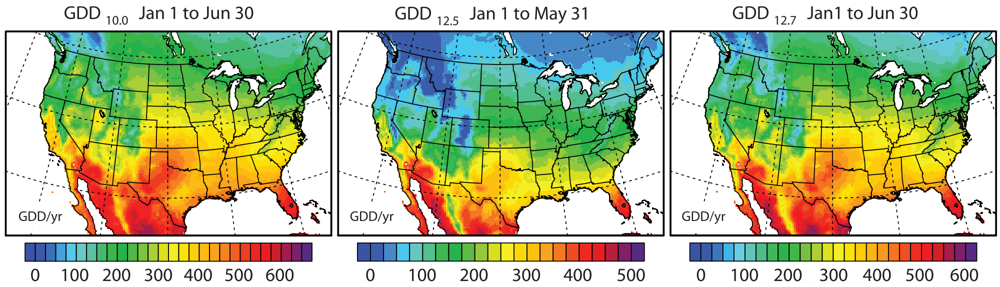

Figure 4. Simulated changes in heat accumulation in the 21st century. Seasonal growing degree days (GDD per year) above 10.0 °C (left panel), 12.5 °C (center panel), and 12.7 °C (right panel). See table 1 for references supporting respective heat accumulation formulations.

Likewise, uncertainties in the human dimension yield a range of possible future greenhouse concentrations [38]. The actual concentration trajectory will ultimately determine the magnitude and spatial pattern of climate change that is actually experienced, with the tails of the temperature distribution particularly sensitive to varying greenhouse gas concentrations (e.g., [57]). Although at present we cannot analyze a suite of high-resolution simulations for the full continental United States that tests multiple emissions pathways, we can take advantage of the multi-model suite of lower-resolution global climate model simulations used in the IPCC Fourth Assessment Report [1]. This is a rich dataset containing multiple simulations from multiple global models for multiple emissions pathways. Unfortunately, data storage limitations have precluded the archiving of the sub-daily-scale temperature data required for our temperature screening criteria. However, the international modeling groups have archived simulated annual-scale occurrence of a number of extreme climate variables, including freeze days. While freeze days cannot be used to directly assess the sensitivity of our calculations to varying emissions pathways, they can help to provide some indication of the sensitivity of cold limitation. We find that the ensemble mean of the 7 climate models archiving results for both the A2 and B1 emissions scenarios shows substantial reductions in projected freeze day changes in the B1 scenario, with a maximum 'deceleration effect' [57] of almost 50% occurring in the Upper Midwest (figure 5). The A2 scenario (which we used in our high-resolution simulations) is a 'high-end' emissions scenario, with atmospheric carbon dioxide concentrations exceeding 800 ppm by the end of the 21st century, while the B1 scenario results in concentrations of less than 540 ppm in the year 2100. The magnitude of the deceleration effect in freeze days thus indicates that substantial greenhouse gas mitigation could reduce climate change challenges to agricultural pest management.

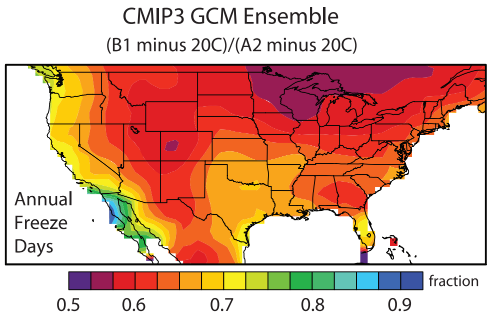

Figure 5. Deceleration effect for annual freeze days. Differences in simulated climate change between the B1 and A2 emissions are calculated from the 7 global climate models archiving freeze days results for both scenarios in the Coupled Model Intercomparison Project (CMIP3) archive. Differences are shown as (B1 minus 20th century) divided by (A2 minus 20th century) for the periods 1971–2000 and 2071–2100.

5. Conclusions

We find that elevated greenhouse gas concentrations could lead to an expansion in the ranges of four major pests of maize, the dominant crop in the United States. In our analyses, the corn earworm experiences the largest expansion, with temperature suitability growing north and west in the central and eastern United States, and in prime agricultural areas of the western United States. It is significant that the corn earworm shows the largest expansion, as it is a migratory pest that both infests a broad suite of agricultural commodities and has demonstrated resistance to a wide range of insecticides. We also find that temperature suitability expands for the three maize-specific taxa that we analyze, particularly in the upper Great Plains. Warming could increase pest pressures in these areas both by increasing cold-season survival and by increasing the number of pest generations in a single warm season. Because managing significant additional pressure from this suite of established pests would require additional pest management inputs (including possible costs of monitoring/scouting, applying pesticides and/or use of transgenic hybrids), the projected decreases in cold limitation and increases in heat accumulation have the potential to significantly alter the pest management landscape for North American maize production. Further, these range expansions could have substantial economic impacts through increased seed and insecticide costs, decreased yields, and the downstream effects of changes in crop yield variability.

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