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LETTER

# The benefits of recent warming for maize production in high latitude China

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**Abstract** Latitudes above 45°N have been characterized by rates of warming faster than the global average since 1980. However, the effects of this warming on crop production at these latitudes are still unclear. Using 30-years of weather and crop management data in Heilongjiang area of China (43.4° to 53.4°N), combined with the Hybrid-Maize model, we show that that maize yields would have stagnated in most areas and decreased in the southern part of Heilongjiang if varieties were assumed fixed since 1980. However, we show that through farmers' adaptation, warming has benefitted maize production for much of this region. Specifically, farmers gradually chose longer maturing varieties, resulting in a net 7–17 % yield increase per decade. Meanwhile, farmers also rapidly expanded maize area (from 1.88 million ha in 1980 to 4.01 million ha in 2009) and the northward limit of maize area shifted by more than 290 km from ~50.8°N to ~53.4°N. Overall, benefits from warming represented 35 % of the overall yield gains in the region over this period. The results indicate substantial ongoing adaptations and benefits at north high-latitudes, although they still represent a small fraction of global maize area. The sustainability of crop area expansion in these regions remains unclear and deserves further study.

## 1 Introduction

The north-high latitudes have experienced among the fastest warming trends in the world, with 0.29–0.57 °C warming per decade since 1980, compared with 0.13 °C increase per decade for

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global average temperatures in the past 50 years (IPCC 2007). In these areas, the pace of temperature increases is predicted to accelerate in the coming decades (Hansen et al. 2006). The effects of this significant warming on vegetation and biodiversity in non-agricultural systems have received attention recently (Lee et al. 2011; McManus et al. 2012). However, the response of various crops to this faster warming is less well understood.

In regions at low and middle latitudes (<45°), where the traditional agriculture areas are mainly located, the impacts of climate change have received wide attention (Peng et al. 2004; Lobell et al. 2011; Schlenker and Lobell 2010). Most results have indicated warming as a growing threat to agricultural yields and food security. However, at north high-latitudes, the limited studies have shown warming would predominantly bring benefits to crop yield while some other studies indicate adverse effects (Gregory and Marshall 2012; Liu et al. 2012). These contradictory results arise from uncertainty about how grain yield changes in response to warming in these regions.

For these northern regions, temperatures are not currently above the optimum level for maximum photosynthesis rates for many crops, so that warming could increase crop growth in these regions. Meanwhile, the gain in available growing degree days between frosts ($GDD_{available}$) implies opportunities for yield increases through adaptation such as using longer growth duration varieties. High temperatures could also open up new opportunities to expand areas of maize and other crops into regions currently constrained by cold (Olesen et al. 2007). However, despite these general expectations, little evidence exists on actual changes in crop management, yields, and area occurring in high latitude regions.

Here we focus on the Heilongjiang Province (121.2°–135.1° E, 43.4°–53.4° N) in Northeast China as a case study of north high-latitudes (Fig. 1). Maize in this region is mainly rainfed and contributed 13.0 % of the total maize production in China and 2.4 % of global production in 2009 (FAO 2013). The objectives of this study were to (1) quantify the effects of warming on maize yield and understand the underlying mechanism in Heilongjiang Province, and (2) investigate how local farmers have adapted to warming, such as by changing maize varieties and expanding maize area.

## 2 Methods

Heilongjiang Province is located in the northernmost part of China with a territory of 454,000 $km^2$ and a population of 38.2 million. The region has a continental-monsoon climate zone with a long, cold and dry winter, and warm and wet summer. Heilongjiang is generally divided into six zones traditionally based on the ≥0 °C accumulated temperature, which is the sum of mean daily temperature during the period from the first day of the first successive 5 days with air temperature ≥0 °C to the first frost day in 1 year. The ≥0 °C accumulated temperature in the six zones is >2,700 °C, 2,500–2,700 °C, 2,300–2,500 °C, 2,100–2,300 °C, 1,900–2,100 °C, and <1,900 °C, respectively, from south to north defined by Heilongjiang Institute of Agriculture Sciences in the 1980s. We used the historical temperature data in 1980s from 32 meteorological observation stations (see below) to delineate the six zones using an isoline method through a geographical information system (Yan et al. 2011) (Fig. 1, Figure S1). The area of these six zones is 4.93, 17.8, 5.73, 6.07, 2.05 and 4.98 million ha from south to north, respectively.

At the 1st zone (the south part), the baseline temperature in 1980s was similar to middle latitude growing areas while the 2nd-6th zones represented the typical cold-temperate climate in north high-latitudes. Thus, the comparison of warming impacts on maize production between the 1st zone and other zones offers some insights into the unique features of impacts at high-latitudes.

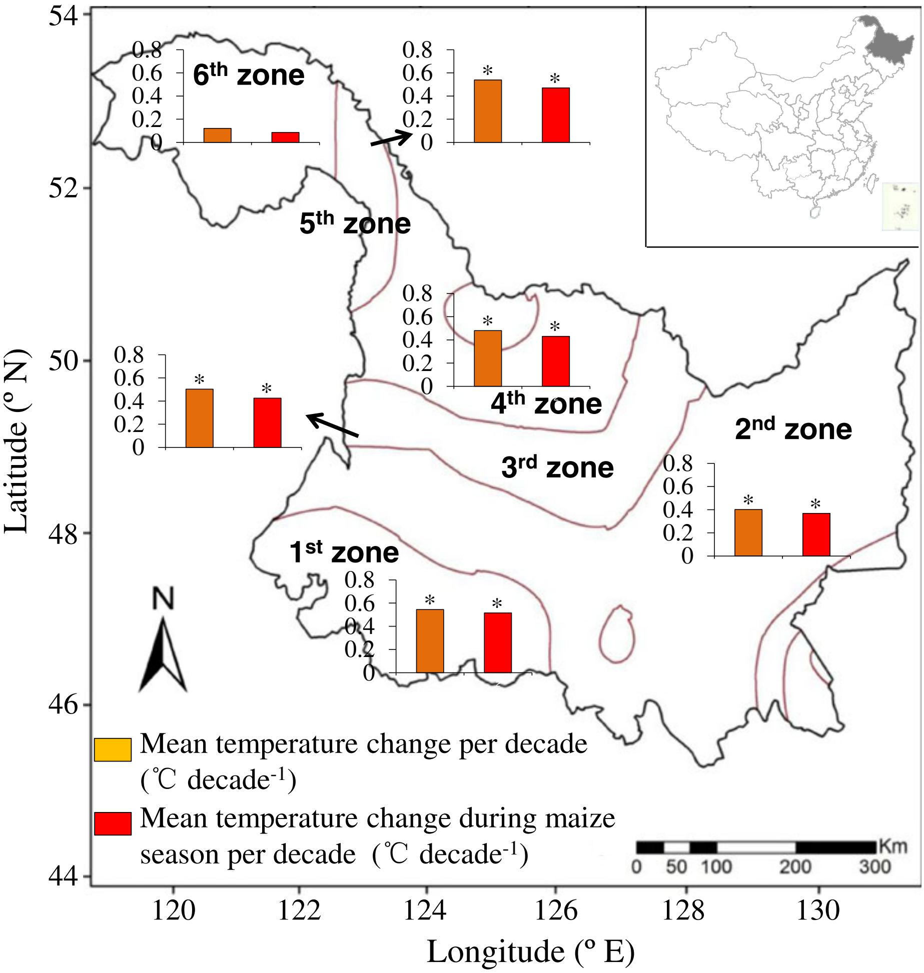


**Fig. 1** The study region and temperature change. *Significant at $P<0.05$

We collected the historical climate data from the Chinese Meteorological Administration across Heilongjiang Province from 1980 to 2009 (CMA archives 2013) (locations are shown in Figure S1). Daily records of sunshine hours, minimum, mean and maximum temperatures, precipitation and wind speed were available from 1980 to 2009. Daily solar radiation was estimated using the formulation from Jones (1992). To understand how farmers adapt to climate change, we investigated variety changes by farmers. Most information on varieties (planting, harvest dates and growth days) was from a combination of literature values (Jiang et al. 2000; Chang and Liu 2001; Jing et al. 2006) and local agricultural meteorological experiment stations since 1980s (CMA archives 2013). Meanwhile, we also interviewed local agronomists to verify the varieties information we collected. The names and growing degree-days (GDD) of the representative maize varieties adopted by farmers in the 1980s, 1990s and 2000s are presented in Table S1. GDD was calculated based on McMaster and Wilhelm (1997).

Maize yield, production and area from 1980 to 2009 in Heilongjiang Province were obtained from China Agriculture Database (CAD 2013). Maize area in each zone was calculated from the statistical data based on country-level database in 1986 and 2009 in Heilongjiang Statistic Bureau.

To understand how temperature increase influenced maize yield since 1980s, and how yield was improved by adapted varieties, a process-based crop model (Hybrid-Maize model) was used for simulation in this study. The model was developed by the University of Nebraska in the United States (Yang et al. 2004, 2006) by combining the strengths of the existing specific models represented by CERES-Maize with organ growth and respiration functions from assimilate-driven generic crop models such as SUCROS and WOFOST. The model can simulate the yield potential under both optimum water and rainfed conditions. It can also simulate maize daily development and growth with minimal possible stress. Additionally, this model has been tested and widely used in the United States (Grassini et al. 2009), South Asia (Timsina et al. 2010), and China (Bai et al. 2010; Chen et al. 2011; Meng et al. 2013) to predict maize production. The previous studies showed that the model performed well in a variety of regions, including in Northeast China (Bai 2009). To further test the performance of this model at high-latitude area, three field experiments were conducted in 2009 in Heilongjiang Province (Figure S2). The results showed the simulations fit the measured data well. Thus, the Hybrid-Maize model can be used to simulate maize yield and growth dynamics in response to climate in this high-latitude area.

The Hybrid-Maize model requires daily total solar radiation, maximum and minimum temperature, and evapotranspiration to simulate grain yield. Other model inputs include variety's GDD (total GDD to maturity), date of planting, and plant population. In this study, the same sowing dates according to 1980s varieties and plant population (60,000 plants ha$^{-1}$ at all sites) were used in the simulation for rainfed maize with 1980s, 1990s and 2000s varieties, based on collected information that these factors have not changed significantly in the region (Figure S3). The change of $CO_2$ level was not taken into account in the simulation since 1980s, as Hybrid-Maize did not consider $CO_2$ changes. However, as a $C_4$ crop, maize responses to elevated $CO_2$ have been found to be very small in most field experiments (Leakey 2009; Markelz et al. 2011). Grain yield was calculated using 15.5 % water content.

## 3 Results and discussion

We found significant increases in the means of both annual and maize growing season temperatures during the 1980–2009 period (Fig. 1). The mean warming rate of 0.40 °C per decade is substantially higher than at middle and low-latitudes as well as the global scale (0.13 °C increase per decade) (IPCC 2007; Hansen et al. 2006), while the precipitation and solar radiation remained relatively constant (Table S2). During the maize season (May to September), trends of 0.37–0.52 °C increase per decade were observed for the 1st to 5th zones, while the only significant decrease in both solar radiation and precipitation were observed at 1st zone (Figure S4).

To investigate impacts of the above climate change on agricultural production, maize yields were first simulated with the Hybrid-Maize model from 1980 to 2009 under a scenario with constant 1980s varieties used by farmers (Fig. 2a). In 1980s, the 1st to 4th zones were the major maize area in Heilongjiang while $GDD_{available}$ was lower for maize growth and there were no appropriate varieties for other zones (5th and 6th zones). Simulations using constant varieties showed fairly constant maize yields in the 2nd-4th zones but significant yield decreases for the 1st zone.

To clarify the reasons for different yield trend at each zone, simulation results were aggregated by zone and changes in simulated photosynthetic and respiration rates, growth

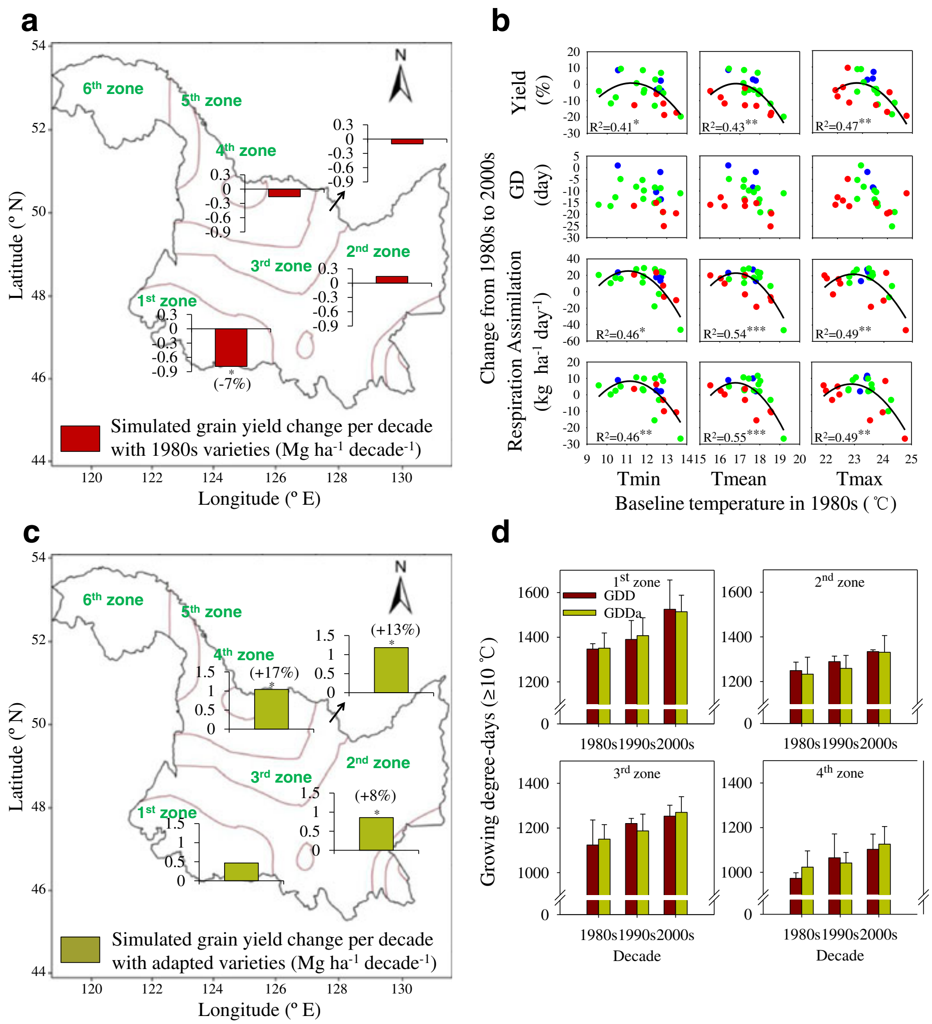


**Fig. 2** The mechanism of grain yield change for warming with 1980s varieties and yield performance with adapted varieties. **a** The change of grain yield from 1980 to 2000 with 1980s varieties. *Number in parenthesis* shows the percent of simulated grain yield change per decade from 1980s to 2000s. **b** Grain yield, growth days (GD), gross assimilation and total respiration change from 1980s to 2000s with baseline minimum, mean and maximum temperature change in 1980s. At the first column, the *blue*, *green* and *red dot* indicate minimum temperature (Tmin) increases <0.3 °C, 0.3–0.5 °C, and 0.5–1 °C per decade, respectively. At second and third columns, the *blue*, *green* and *red dot* indicate mean (Tmean) or maximum temperature (Tmax) increases <0.3 °C, 0.3–0.5 °C, and 0.5–0.7 °C per decade, respectively. **c** The change of grain yield from 1980 to 2000 with adapted varieties. *Number in parenthesis* shows the percent of simulated grain yield change per decade from 1980s to 2000s. **d** The change of GDD available between frosts ($GDD_{available}$) for maize growth and the growing degree-days (GDD) of varieties adopted by local farmers. $GDD_{available}$ was calculated according to the record weather data from May to September, and GDD was calculated according to local maize varieties in 1980s, 1990s and 2000s. *Significant at $P<0.05$

days, and final yields from 1980s to 2000s were compared to baseline temperatures in 1980s (Fig. 2b). We find that simulated yield changes were small or even slightly positive when the baseline minimum temperature in 1980s was less than 11.2 °C, mean temperature less than

16.8 °C, or maximum temperature less than 22.9 °C. In this process, both the assimilation from canopy photosynthesis and total respiration (maintenance and growth respiration) rates increase at a similar speed compared with the 1980s. Above these 1980s baseline temperature (11.2 °C for minimum temperature, 16.8 for mean temperature and 22.9 °C for maximum temperature), simulated grain yields changes show negative trends because of the faster decreasing trend in gross assimilation change ($a$=−1.83 in the quadratic regression) compared with total respiration change ($a$=−0.93 in the quadratic regression).

The lack of simulated yield trends in the 2nd-4th zones despite warming reflects the fact that baseline temperatures in 1980s are close to optimum. The simulated gross assimilation and total respiration was constant from 1980 to 2009 (Figure S5). For the 1st zone, simulated grain yield decreased by roughly 7 % per decade (0.79 Mg $ha^{-1}$ $decade^{-1}$). The growing period of maize was shortened (Figure S4) and both gross assimilation and total respiration significantly decreased, with gross assimilation decreasing faster than total respiration (−0.31 Mg $CH_2O$ $ha^{-1}$ $yr^{-1}$ for gross assimilation and −0.20 Mg $CH_2O$ $ha^{-1}$ $yr^{-1}$ for total respiration) (Figure S5). At the 1st zone, a sensitivity analysis was also performed to identify which climatic factor contributed to grain yield change because temperature, solar radiation and precipitation all significantly changed during maize season (Figure S6). The results indicated temperatures were more important for yield than changes in precipitation and solar radiation, consistent with observations at the national, regional and even global scales (Figure S6) (Lobell and Burke 2008; Schlenker and Lobell 2010). Meanwhile, we estimate there would have been no significant yield change for the whole Heilongjiang area if temperature was constant since 1980 (Table S3).

To understand how farmers adapted to warming, we first consider changes in maize varieties since 1980s. The GDD for maize varieties adopted by farmers increased by 85–178 consistently in 1st to 4th zones, which agreed well with the $GDD_{available}$ in theoretically available in each zone (Fig. 2d). Using actual varieties farmers used in different decades, simulated maize yield increased 8–17 % per decade (0.86–1.18 Mg $ha^{-1}$ $decade^{-1}$) for 2nd to 4th zones, compared with using 1980s varieties (Fig. 2c). For the 1st zone, yield increase resulting from changing varieties was slower, but still 7 % higher than using the varieties in 1980s. This adaptation through cultivar selection was consistent with other areas (Liu et al. 2010). For the entire Heilongjiang area, the area-weighted average of grain yield across the first four zones increased by 8 % per decade through variety adaptation. During the same period, the observed maize yield increased 23 % per decade (Figure S7). This indicated that benefits from changing varieties represented 35 % of the overall yield gains in the region over this period.

As cold constraints to maize growth were diminished in this high-latitude region, the significant warming also led to a significant expansion of maize cultivated area. According to the lower limit (950~1,000 GDD) for maize cultivated in China, regions previously too cold, especially the 5th zone, became suitable for sowing maize since 2000s (Table S4). Statistical data on harvested area verified that farmers have responded to this change (Fig. 3). From 1980 to 2009, maize area increased from 1.88 million ha to 4.01 million ha, mainly through replacing other crops and expansion to new fields (Figure S7). For example, spring wheat area decreased from 2.11 million ha in 1980 to 0.29 million ha in 2009 (CAD 2013). For the 5th and 6th zones, maize area was to add to 4,000 ha in 2009. This was a significant northward expansion of maize cultivation, with a northward shift from ~50.8° N to ~53.4° N, equivalent to 290 km (Fig. 3), or 12 km per year. Aided by maize expansion and adoption of longer season varieties, total maize production in Heilongjiang area increased from 5.2 million tons in 1980 to 19.2 million tons in 2009 (CAD 2013), and the corresponding proportion of maize production to world total increased from 1.3 % to 2.3 % (CAD 2013; FAO 2013).

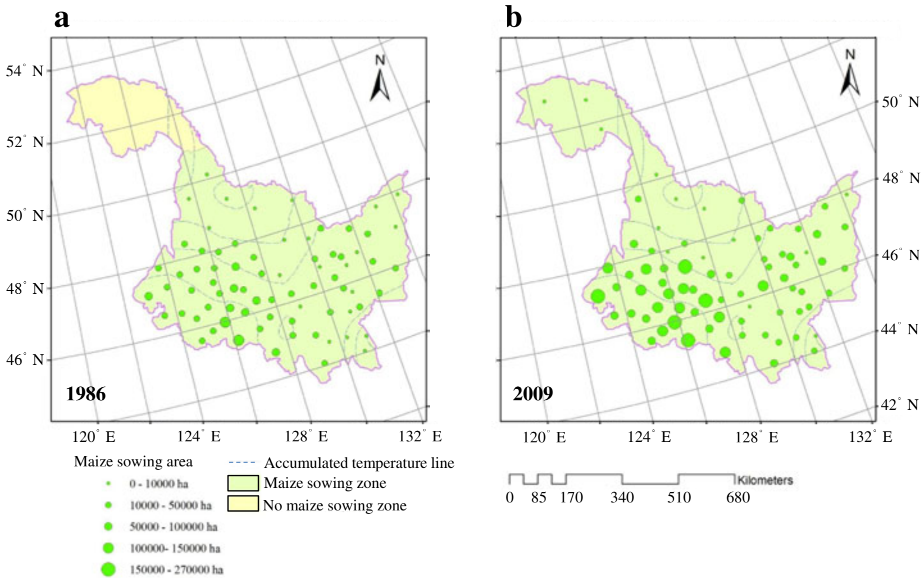


**Fig. 3** Maize sowing area in 1986 and 2010 in Heilongjiang area. The *green area* show maize sowing zone and the *yellow area* show no maize sowing zone. The *circles* show locations of maize sowing zone, with the size of the circle indicating the area of maize sowing per site. The *blue dashed lines* show the line of accumulated temperature zone

As a likely response to warming, northward expansion of maize is also occurring in other high latitude areas such as Denmark, Canada, and Russia (Figure S8). The expansion of cultivated areas has resulted in a steady increase in crop production. However, the ultimate importance of increasing crop area in high latitudes for ensuring global food security remains unclear, given the relatively small current proportion of total production and questions about soil resources (Euskirchen et al. 2006) and infrastructure in these regions. Meanwhile, warming also provides the chance to replace other crops by high-yielding maize, where lower yielding crops such as wheat are currently sown.

Globally, the largest agricultural land expansion has occurred in the low latitudes, where between 1980 and 2000 83 % of new land expansion came from a combination of intact or disturbed forests (Rosenzweig and Parry 1994; Gibbs et al. 2010; Foley et al. 2011). Yet, with the exception of parts of Brazil, this expansion has done relatively little to add global food supplies (DeFries and Rosenzweig 2010; Foley et al. 2011) and has resulted in various environmental damages such as greenhouse gas emissions and biodiversity and ecosystem services losses (Friedlingstein et al. 2010; Foley et al. 2011). For example, deforestation from 2000 to 2005 added a maximum of only 2.5 % of agricultural area relative to 2000 for the tropics as a whole while contributing 39 % of $CO_2$ emissions (DeFries and Rosenzweig 2010). Our results indicate high latitude expansion may offer a new possibility to crop area expansion. However, the sustainability and environment footprint of this expansion is not clear and should be taken into account cautiously.

In Heilongjiang and other high latitudes, maize area expansion can be mainly attributed to replacing other crops (e.g. soy and wheat) as well as natural systems (e.g. 5–6th zones). Maize, with $C_4$ photosynthesis, can be taken as a benchmark for other current and future crops because it achieves remarkably high and stable grain yields, high efficiencies in use of solar radiation, N, and water (Grassini and Cassman 2012), with similar or even decreased environmental footprint

(Linquist et al. 2012). Meanwhile, the warming trend makes it suitable to sow varieties with longer maturing times together with higher grain yield potential than before (Fig. 2).

## 4 Conclusions

In contrast with many middle and low-latitude regions, warming trends have not led to maize yield decreases in most of Heilongjiang, because temperatures were previously below the optimal level in much of this region. We estimate that farmer adaptations have been significant, both in replacing older varieties and expanding areas. Specifically, maize planting area expanded rapidly in global high latitudes in recent years. The impacts of ongoing crop expansion in high latitude regions on greenhouse gas emissions, biodiversity loss, and other valued outcomes are still not clear and need further evaluation.

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