



# Peculiarly pleasant weather for US maize

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Edited by Inez Fung, University of California, Berkeley, CA, and approved October 4, 2018 (received for review May 9, 2018)

Continuation of historical trends in crop yield are critical to meeting the demands of a growing and more affluent world population. Climate change may compromise our ability to meet these demands, but estimates vary widely, highlighting the importance of understanding historical interactions between yield and climate trends. The relationship between temperature and yield is nuanced, involving differential yield outcomes to warm (9–29 °C) and hot (> 29 °C) temperatures and differing sensitivity across growth phases. Here, we use a crop model that resolves temperature responses according to magnitude and growth phase to show that US maize has benefited from weather shifts since 1981. Improvements are related to lengthening of the growing season and cooling of the hottest temperatures. Furthermore, current farmer cropping schedules are more beneficial in the climate of the last decade than they would have been in earlier decades, indicating statistically significant adaptation to a changing climate of 13 kg·ha<sup>-1</sup>·decade<sup>-1</sup>. All together, the better weather experienced by US maize accounts for 28% of the yield trends since 1981. Sustaining positive trends in yield depends on whether improvements in agricultural climate continue and the degree to which farmers adapt to future climates.

agriculture | maize | climate | trends | adaptation

Increased agricultural production over the 20<sup>th</sup> century is a celebrated achievement of modern science (1). Continuation of these trends is essential to meeting future food and nutritional demands (2, 3), although our ability to do so may be compromised by climate change (4–6). To better understand how climate change will interact with future trends in crop yield, it is important to establish both how climate influenced historical crop yields and how farmers have responded to these changes. To explore these issues, we focus on maize, an important food, feed, and fuel crop in the US Midwest that is both highly productive and strongly influenced by temperature (7, 8).

Previous studies of US maize found that warming suppressed yield trends in Wisconsin (9) and that short-term cooling increased yield trends across the country (10, 11). These earlier studies did not, however, distinguish between moderate temperatures that are beneficial and hot temperatures that are damaging (7, 12), instead using growing-season temperature averages as explanatory variables. This distinction is especially relevant for the US Corn Belt because daily minimum temperatures have risen nearly ubiquitously (13, 14), whereas the hottest growing-season temperatures have cooled by ~1–2 °C over the last century (13, 15).

Recent work indicates that increasing yield trends are linked to earlier planting and longer maturing varieties (16–19). However, studies have found no evidence of US agricultural adaptation to historical changes in climate (7, 20). The combination of warming and absence of adaptation leads to alarming scenarios regarding climate-induced reductions in yield (7). However, the presumption of no adaptation seems at odds with the ingenuity of farmers, a characterization that is supported by evidence of regional adaptation to climate (8, 21) and patterns of insurance coverage that indicate careful apportionment of weather-related risks (22).

## Yield Trends from Changes in Climate and Crop Timing

Here, we use a recently developed statistical growth model (21) to analyze how changes in temperature distributions and crop phenology influence maize yield. Yield is modeled according to accumulated growing degree days (GDDs) and killing degree days (KDDs), the latter of which measure exposure to damagingly-high temperatures (8, 20, 23). To account for the fact that temperature sensitivity varies greatly over the course of crop development (24, 25), yield sensitivity to GDDs and KDDs varies across vegetative, early-, and late-grain-filling growth phases (Fig. 1 and *SI Appendix, Fig. S1*). The model accounts for 72% of the interannual variance in maize yield in the median county (*SI Appendix, Fig. S2*).

It is useful to distinguish between the influence of climate trends and timing trends associated with planting and crop development. We first isolate influences associated with climate trends by fixing planting and growth-phase dates to their average values between 1981 and 2017. Averaging across the Midwest, GDDs increase during every phase with a total increase of 14 °C days per decade (*SI Appendix, Fig. S3*). By contrast, KDDs decreased during every growth phase, for a net change of –10 °C days per decade (*SI Appendix, Fig. S4*). These remarkable improvements in weather combine to increase yields by 0.2 tonnes/ha per decade (95% CI 0–0.5; Figs. 2*A* and *B* and 3).

Increasing GDDs is consistent with general warming driven by increasing greenhouse gases, whereas suppression of the high-temperature extremes that produce KDDs appears to be a fortuitous by-product of more productive row-crop agriculture and corresponding increases in evapotranspiration (15, 26). Strong associations between increasing summer crop productivity and cooler extreme temperatures are found in the Midwest (15) as well as other major cropping regions (27–29). Increased irrigation also cools surface air temperature (30, 31), but we

## Significance

Over the course of the 20th century, US maize yields have improved by more than a factor of five. Whereas this trend is often attributed exclusively to technological improvements, here, we also identify contributions from improved temperatures during the growing season. More than one-quarter of the increase in crop yield since 1981 is estimated to result from trends toward overall warmer conditions, but with cooling of the hottest growing-season temperatures, and from adjustments in crop timing toward earlier planting and longer maturation varieties.

Author contributions: E.E.B., N.D.M., and P.H. designed research; E.E.B. performed research; E.E.B. analyzed data; and E.E.B., N.D.M., and P.H. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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Data deposition: Code to download and organize the data as well as perform analyses and produce the figures are available from [https://github.com/eebutler/us\\_maize\\_trends](https://github.com/eebutler/us_maize_trends).

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This article contains supporting information online at [www.pnas.org/lookup/suppl/doi:10.1073/pnas.1808035115/-DCSupplemental](http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1808035115/-DCSupplemental).

Published online November 5, 2018.









Lack of explicitly resolving silking and tasseling may therefore account for underestimation of damage. Further, despite covariance between drought and extreme heat (57), our model does not explicitly resolve crop stress from low soil moisture.

Bootstrap CIs are constructed to assess the uncertainty associated with each of the statistical models by using 1,000 samples that account for contributions from errors in trend estimates, sensitivity parameters, as well as  $D'$  and therefore KDD\* and GDD\* terms. County-years are used as the unit of replication. To be more conservative with respect to regional estimates, we also explore the implication of spatial autocorrelation using a  $K$ -means clustering algorithm on longitude, latitude, and mean yield to generate 108 clusters. This number of clusters reflects numbers of agricultural districts that average nine per state (SI Appendix, Fig. S9). The 95% CI of the adaptation trend is 13–20 kg/ha per decade when resampling on county-years,

4–21 kg/ha per decade when resampling on spatial clusters and years, and –3 to 32 when resampling on yearly regional averages. We view the final estimate involving regional averages as overly conservative on account of ignoring within-season independence amongst different parts of the Midwest, but include it to illustrate how the associated reduction in spatial degrees of freedom influences the results (SI Appendix, Table S3).

All regional trends that aggregate individual county trends reported in the work are computed as a weighted average according to average area planted. Individual country areas are computed as the average planted area across years.

**ACKNOWLEDGMENTS.** E.E.B. was supported by Packard Foundation Award 2009-34709; P.H. was supported by National Science Foundation Award 1521210; and N.D.M. was supported by USDA Grant 2016-67012-25208.

- Evans LT (1993) *Crop Evolution, Adaptation, and Yield* (Cambridge Univ Press, Cambridge, UK).
- Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci USA* 108:20260–20264.
- Ray DK, Mueller ND, West PC, Foley JA (2013) Yield trends are insufficient to double global crop production by 2050. *PLoS One* 8:e66428.
- Rosenzweig C, et al. (2013) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc Natl Acad Sci USA* 111:3268–3273.
- Battisti DS, Naylor RL (2009) Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* 323:240–244.
- Myers S, et al. (2017) Climate change and global food systems: Potential impacts on food security and undernutrition. *Annu Rev Public Health* 38:259–277.
- Schlenker W, Roberts MJ (2009) Nonlinear temperature effects indicate severe damage to U.S. crop yields under climate change. *Proc Natl Acad Sci USA* 106:15594–15598.
- Butler EE, Huybers P (2013) Adaptation of US maize to temperature variations. *Nat Clim Change* 3:68–72.
- Kucharik CJ, Serbin SP (2008) Impacts of recent climate change on Wisconsin corn and soybean yield trends. *Environ Res Lett* 3:034003.
- Lobell DB, Asner GP (2003) Climate and management contributions to recent trends in U.S. agricultural yields. *Science* 299:1032.
- Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production since 1980. *Science* 333:616–620.
- Carlson RE (1990) Heat stress, plant-available soil moisture, and corn yields in Iowa: A short- and long-term view. *J Prod Agric* 3:293–297.
- McKinnon KA, Rhines A, Tingley MP, Huybers P (2016) The changing shape of Northern Hemisphere summer temperature distributions. *J Geophys Res Atmos* 121:8849–8868.
- Rhines A, McKinnon KA, Martin PT, Huybers P (2017) Seasonally resolved distributional trends of North American temperatures show contraction of winter variability. *J Clim* 30:1139–1157.
- Mueller ND, et al. (2016) Cooling of US Midwest summer temperature extremes from cropland intensification. *Nat Clim Change* 6:317–322.
- Kucharik CJ (2006) A multidecadal trend of earlier corn planting in the Central USA. *Agron J* 98:1544–1550.
- Kucharik CJ (2008) Contribution of planting date trends to increased maize yields in the Central United States. *Agron J* 100:328–336.
- Sacks WJ, Kucharik CJ (2011) Crop management and phenology trends in the U.S. Corn Belt: Impacts on yields, evapotranspiration and energy balance. *Agric For Meteorol* 151:882–894.
- Zhu P, et al. (2018) The important but weakening maize yield benefit of grain filling prolongation in the US Midwest. *Glob Change Biol* 24:4718–4730.
- Burke M, Emerick K (2016) Adaptation to climate change: Evidence from US agriculture. *Am Econ J Econ Pol* 8:106–140.
- Butler EE, Huybers P (2015) Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase. *Environ Res Lett* 10:034009.
- Annan F, Schlenker W (2015) Federal crop insurance and the disincentive to adapt to extreme heat. *Am Econ Rev Pap Proc* 105:262–266.
- Lobell DB, Bänziger M, Magorokosho C, Vivek B (2011) Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nat Clim Change* 1:42–45.
- Rattalino Edreira JI, Otegui ME (2012) Heat stress in temperate and tropical maize hybrids: Differences in crop growth biomass partitioning and reserves use. *Field Crops Res* 130:97–98.
- Sánchez B, Rasmussen A, Porter JR (2014) Temperature and the growth and development of maize and rice: A review. *Glob Change Biol* 20:408–417.
- Ross EA, Douglas HC, Winter JM, Eltahir EAB (2018) Twentieth century regional climate change during the summer in the Central United States attributed to agricultural intensification. *Geophys Res Lett* 45:1586–1594.
- Betts AK, Desjardins R, Worth D, Cerkowniak D (2013) Impact of land use change on the diurnal cycle climate of the Canadian prairies. *J Geophys Res Atmos* 118:11996–12011.
- Zhao N, Han S, Xu D, Wang J, Yu H (2016) Cooling and wetting effects of agricultural development on near-surface atmosphere over Northeast China. *Adv Meteorol* 2016:6439276.
- Mueller ND, et al. (2017) Global relationships between cropland intensification and summer temperature extremes over the last 50 years. *J Clim* 30:7505–7528.
- Bonfils C, Lobell D (2007) Empirical evidence for a recent slowdown in irrigation-induced cooling. *Proc Natl Acad Sci USA* 104:13582–13587.
- Lobell DB, et al. (2008) Irrigation cooling effect on temperature and heat index extremes. *Geophys Res Lett* 35:L09705.
- Abendroth LJ, Elmore RW, Boyer MJ, Marlay MJ (2011) *Corn Growth and Development* (Iowa State Univ Extension, Ames, IA), PMR 1009.
- Lauer J (2001) Earlier planting dates for corn: Real progress or an effect of global warming. *Wis Crop Manager* 8:83–85.
- Gesch RW, Archer DW (2005) Influence of sowing date on emergence characteristics of maize seed coated with a temperature-activated polymer. *Agron J* 97:1543–1550.
- Lobell DB (2014) Climate change adaptation in crop production: Beware of illusions. *Glob Food Secur.* 3:72–76.
- Liu Z, Hubbard KG, Lin X, Yang X (2013) Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. *Glob Change Biol* 19:3481–3492.
- Parmesan C, Gary Y (2003) A global coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37–42.
- Miller-Rushing AJ, Primack RB (2008) Global warming and flowering times in Thoreau's Concord: A community perspective. *Ecology* 89:332–341.
- Ellwood ER, Temple SA, Primack RB, Bradley NL, Davis CC (2013) Record-breaking early flowering in the Eastern United States. *PLoS One* 8:e53788.
- Bradley NL, Carl Leopold A, Ross J, Huffaker W (1999) Phenological changes reflect climate change in Wisconsin. *Proc Natl Acad Sci USA* 96:9701–9704.
- Cassman KG, Dobermann A, Walters DT, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. *Annu Rev Environ Resour* 28:315–358.
- Ray DK, Ramankutty N, Mueller ND, West PC, Foley J (2012) Recent patterns of crop yield growth and stagnation. *Nat Commun* 3:1293.
- Grassini P, Eskridge KM, Cassman KG (2013) Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nat Commun* 4:2918.
- Leakey ADB, et al. (2009) Elevated CO<sub>2</sub> effects on plant carbon, nitrogen, and water relations: Six important lessons from FACE. *J Exp Bot* 60:2859–2876.
- Long SP, Ainsworth EA, Leakey ADB, Nösberger J, Ort DR (2006) Food for thought: Lower-than-expected crop yield stimulation with rising CO<sub>2</sub> concentrations. *Science* 312:1918–1921.
- Porter JR, et al. (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, chapter Food Security and Food Production Systems (Cambridge Univ Press, Cambridge, UK) pp 485–533.
- Ainsworth EA, McGrath JM (2010) *Direct Effects of Rising Atmospheric Carbon Dioxide and Ozone on Crop Yields* (Springer, Dordrecht, The Netherlands), pp 109–130.
- Tollenaar M, Fridgen J, Tyagi P, Stackhouse PW, Jr, Kumudini S (2017) The contribution of solar brightening to the US maize yield trend. *Nature Clim. Change* 7:275–278.
- Natural Agricultural Statistics Service, US Department of Agriculture (2014) Quick stats 2.0. Retrieved from quickstats.nass.usda.gov/. Accessed March 22, 2018.
- Menne MJ, Jr, Williams CN, United RSV (2014) States historical climatology network daily temperature, precipitation, and snow data. (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN), Technical report.
- Barber CB, Dobkin DP, Huhdanpaa HT (1996) The Quickhull algorithm for convex hulls. *ACM Trans Math Softw* 22:469–483.
- Cornes RC, Jones PD (2013) How well does the era-interim reanalysis replicate trends in extremes of surface temperature across Europe? *J Geophys Res* 118:262–276.
- Troy TJ, Kipgen C, Pal I (2015) The impact of climate extremes and irrigation on US crop yields. *Environ Res Lett* 10:054013.
- Lauer J (2005) Optimum relative maturity for yield and profitability in corn. *Agron Advice* 28:39.
- Diffenbaugh NS, Hertel TW, Scherer M, Verma M (2012) Response of corn markets to climate volatility under alternative energy futures. *Nat Clim Change* 2:514–518.
- Tigchelaar M, Battisti DS, Naylor RL, Ray DK (2018) Future warming increases global maize yield variability with implications for food security. *Proc Natl Acad Sci USA* 115:6644–6649.
- Huybers P, McKinnon KA, Rhines A, Tingley M (2014) U.S. daily temperatures: The meaning of extremes in the context of non-normality. *J Clim* 27:7368–7384.