CLIMATE CHANGE

Increase in crop losses to insect pests in a warming climate

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Insect pests substantially reduce yields of three staple grains—rice, maize, and wheat—but models assessing the agricultural impacts of global warming rarely consider crop losses to insects. We use established relationships between temperature and the population growth and metabolic rates of insects to estimate how and where climate warming will augment losses of rice, maize, and wheat to insects. Global yield losses of these grains are projected to increase by 10 to 25% per degree of global mean surface warming. Crop losses will be most acute in areas where warming increases both population growth and metabolic rates of insects. These conditions are centered primarily in temperate regions, where most grain is produced.

By 2050, growing-season temperatures will likely exceed those recorded during the past century and may substantially reduce crop yields (*1*–*4*). However, models assessing the effects of climate warming on crop yields rarely consider impacts on insect pests, despite the damages that result directly from pest infestations and indirectly from pesticides applied to reduce pest damage (*5*, *6*). In the future, pest species are likely to differ in their responses to warming, changing the relative impacts of pests geographically and among crops (*7*, *8*). Here we use well-established relationships between temperature and the physiology and demography of insects to project the future impact of insects on crop production globally and regionally. We estimate pest-related changes in yields of the major grain crops maize, rice, and wheat, which together account for 42% of direct calories consumed by humans worldwide (*9*).

A warmer climate will alter at least two agriculturally relevant characteristics of insect pests. First, an individual insect's metabolic rate (M) accelerates with temperature, and an insect's rate of food consumption must rise accordingly (*10*–*12*). Second, the number of insects (n) will change, because population growth rates of insects also vary with temperature. These growth rates are expected to decline as a result of warming in tropical regions while rising elsewhere (*8*) (fig. S1). The total energy consumption of a pest population (the "population metabolism") is proportional to the product of these two factors and directly relates to the crop yield loss (L) caused by insect herbivory. Fractional changes in pest-induced crop losses ($\Delta L/L$) can thus be partitioned into a metabolic component ($\Delta M/M$) and a demographic component ($\Delta n/n$) (*13*). The sum of these fractional changes approximates the total fractional change in yield loss

$$\frac{\Delta L}{L} = \frac{\Delta M}{M} + \frac{\Delta n}{n} \qquad (1)$$

To evaluate how warming changes the population metabolism of insect pests, we integrated established physiological responses of insects to temperature into a spatially explicit demographic model (*13*). The metabolic and population growth rates were derived from laboratory experiments across a wide range of temperatures and for diverse insect taxa including pest species. Relationships between temperature and insect population growth rates drive logistic population increases of insects during each crop's growing season, and they also scale the fractional survival rate of insects over the rest of the year (*14*), termed the diapause survival, ϕ_o. We calibrated key demographic model parameters—population size and carrying capacity—using contemporary crop yields (*15*) and their insect-related losses, measured for our three focal crops at sites around the world (*5*). To predict future changes in population growth and metabolic rates, we added projected monthly surface temperature anomalies from climate model simulations under a "business-as-usual" emissions scenario (RCP8.5) (*16*) to the observed daily and seasonally varying temperatures from the 20th century (1950 to 2000). Results are presented for several climate models that span a range of climate sensitivities and for a range of uncertainties in biological traits and assumptions (*13*). We report yield losses as a function of global mean surface temperature change, making the results comparable across emissions scenarios, time periods, and climate sensitivities.

Crop production losses to pests increase globally with rising temperatures in all climate models and across all biological parameters (Fig. 1). When average global surface temperatures increase by 2°C, the median increase in yield losses owing to pest pressure is 46, 19, and 31% for wheat, rice, and maize, respectively, bringing total estimated losses to 59, 92, and 62 metric megatons per year. These projected losses are similar across all climate models and are thus robust to uncertainties in both global and regional warming patterns, although the time at which such damage levels are reached depends on the emissions scenario and on each model's sensitivity to increasing atmospheric CO_2 (Fig. 1D)

The differences in global grain losses between crops and across model parameters (Fig. 1) reflect the distinct spatial patterns of demographic and metabolic impacts of warming on insect pests in the climates where these crops are grown. In temperate regions, warming increases both the size of insect populations and their per capita metabolic rate (Fig. 2, right). As a result, the increase in pest-related crop loss is consistently larger than in tropical regions, where the increasing metabolic rate is offset by declining population growth rates, resulting in a smaller overall rise in crop damages. This broad geographic pattern holds across all crops, climate models, and life history parameters considered (Fig. 2 and figs. S3 and S4).

The contribution of per capita metabolic rates to the total pest-induced crop losses is projected to increase consistently across regions and over time. For each of the three crops examined here, increases in temperature vary only modestly across growing regions and seasons, causing a nearly uniform fractional rise in the metabolic rates of the insect pests (Fig. 1). The magnitude of the metabolic component (Eq. 1) is proportional to the temperature sensitivity of metabolic rates, E_{met}, which varies by <50% across insect species ($E_{met} = 0.65 \pm 0.15$; mean ± standard deviation) (*12*). As a result, the metabolic component of insect pest population metabolism can be estimated relatively robustly at both regional and global scales.

In contrast, the demographic component of future crop loss to insect pests is spatially variable and can either exacerbate or ameliorate the impact of rising metabolic rates (Fig. 1 and figs. S3 and S4). In the lowland tropics, pest populations are predicted to decline because current temperatures there are already near optimal, so warming should reduce population growth rates (*8*) (fig. S2). On the other hand, extratropical pest populations are generally projected to grow as temperatures become closer to optimal, with a small contribution from increasing diapause survival as winters warm (*14*) (fig. S6). Because temperate populations often reach carrying capacity only late in the growing season, if at all, they have the most potential for increases in population size as temperature rises (fig. S2). How much they increase depends on baseline survival rates

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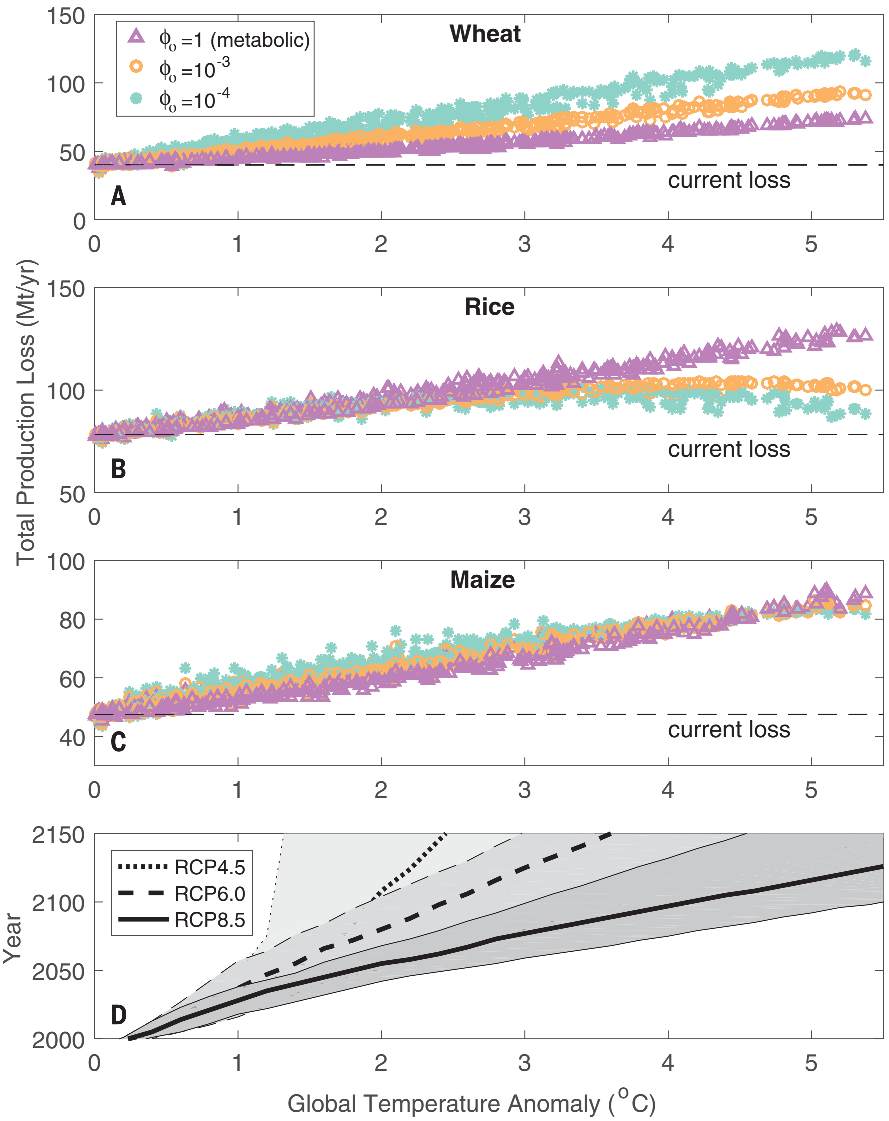

Fig. 1. Global loss of crop production owing to the impact of climate warming on insect pests. Crop production losses for (**A**) wheat, (**B**) rice, and (**C**) maize are computed by multiplying the fractional change in population metabolism by the estimated current yield loss owing to insect pests, summed over worldwide crop locations. Results are plotted versus mean global surface temperature change, for four climate models (*13*), for two different values of the demographic parameter governing survival during diapause (ϕ_o = 0.0001, asterisks; ϕ_o = 0.001, circles), and for the metabolic effect alone (triangles). Mt/yr, metric megatons per year. The year in which a given global mean temperature anomaly is reached (**D**) depends on the greenhouse gas emissions scenario (RCP, representative concentration pathway) and varies across models (shading) owing to uncertainty in climate sensitivity to those emissions (*13*).

during the nongrowing season (ϕ_o), which can be highly variable. However, the pattern of weak demographic impacts in tropical regions and strong deleterious impacts in northern temperate regions is consistent across a wide range of plausible ϕ_o values, from 0.0001 to 0.01 (fig. S3).

Because our three focal crops are grown in different climates, where warming can induce opposite changes in insect population growth rates, diapause survival differentially affects losses of these three crops. For wheat, which is typically grown in relatively cool climates, warming will increase pest population growth and overwinter survival rates, leading to large population increases in the growing season (Fig. 1A). In rice, which is grown in relatively warm tropical environments, the same population dynamic has the opposite impact; warming there should reduce insect population growth rates and thus partly counteract the rising crop losses due to increased insect metabolism, allowing global rice production lost to insects to stabilize for warming exceeding ~3°C (Fig. 1B). For maize, the demographic effect has only a small net impact on global production losses, because this crop is grown in some regions where population rates will increase and in other regions where population rates will decline, in nearly equal measure (Fig. 1C).

The spatial patterns of modeled changes in insect population metabolism also predict differential impacts across major geopolitical boundaries (Fig. 3). The most substantial yield declines will occur in many of the world's most productive agricultural regions, thus reducing global grain availability (Fig. 3 and table S5). France, the United States, and China—countries that produce most of the world's maize—are also among the countries projected to experience the largest increases in pest-related crop losses (Figs. 1C and 3C). These countries have among the highest yields per hectare today (Fig. 3). In addition, France and China are responsible for a considerable fraction of global wheat and rice production, respectively, and are projected to suffer large increases in yield loss of these grains owing to climate impacts on pests (Figs. 1C and 3C and table S5).

Our analysis focuses on the changing impacts of insect pests on crop yields with an increase in global temperature, accounting for the most robust general responses of insect pests to temperature. The full scope of physiological and ecological impacts is likely to be complex and sensitive to particular crop-pest interactions for which more physiological data will be needed, especially among tropical pest species (fig. S1). These interactions will occur in conjunction with direct plant responses to warming and rising CO_2 levels, which, for the three major crops that we considered, are predominantly negative (*17*). However, scenarios with added or alternative biological dynamics, such as thermoregulation by insects (*18*) or increased diapause mortality with warming (*19*), suggest that the dominant patterns described here are robust (figs. S5 and S6), and species-specific predictions for pests that affect these three crops generally agree with our predictions (*13*).

Agricultural practices will shift as the climate warms. Changes in planting dates, cultivar use, and planting locations are already under way (*20*) and will become more pronounced as the rate of climate warming increases (*21*). Our results suggest that farmers will need to make additional changes, such as introducing new crop rotations, to maintain yields in the face of rising insect pest pressure. In intensive agricultural environments, adaptation measures may involve greater pesticide use, at the cost of associated health and environmental damage and the elevated threat of pesticide resistance. Without wider attention to how climate warming will affect crop breeding and sustainable pest management strategies, insect-driven yield losses will result in reduced global grain supplies and higher staple food prices. Poor grain consumers and farming households, who account for a large share of the world's 800 million people living in chronic hunger (*9*), will suffer most.

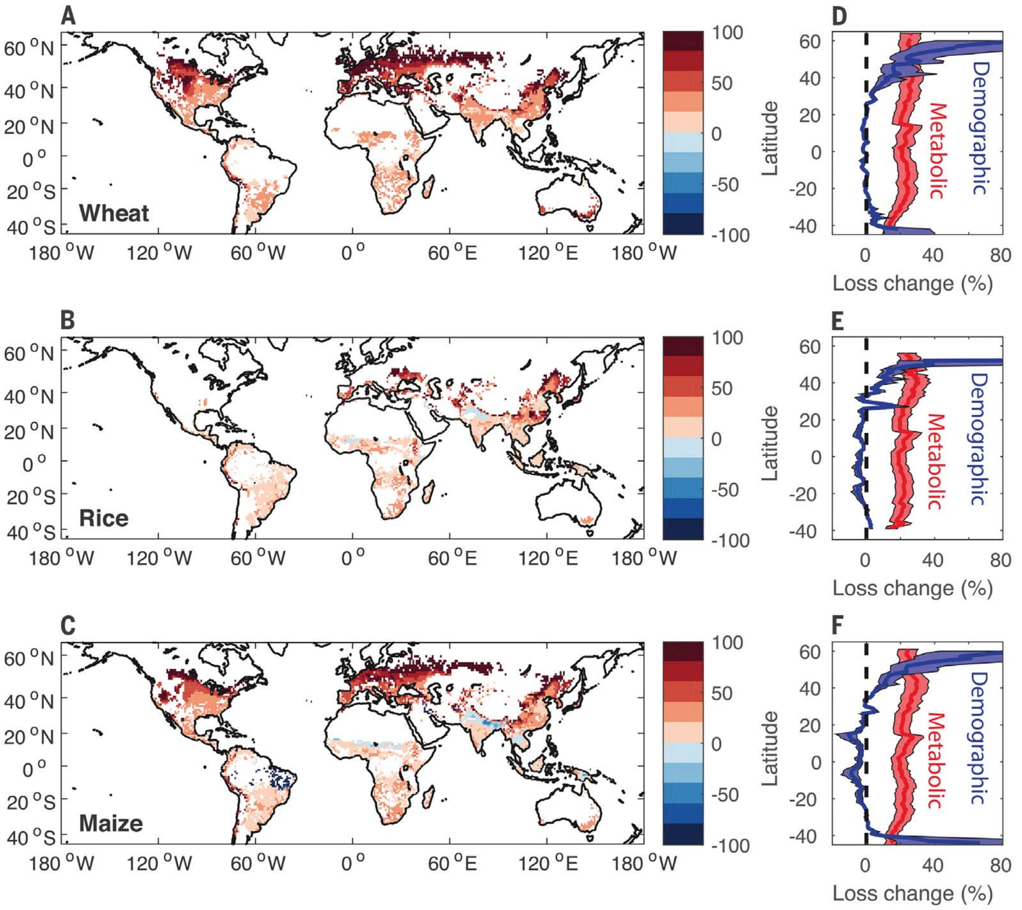

Fig. 2. Projected geographic pattern of change in crop yield losses to insect pests in a 2°C-warmer climate. Results are mapped for the fractional (percent) increase in crop yield loss owing to pests from both metabolic and demographic effects ($\Delta L/L$) for (**A**) wheat, (**B**) rice, and (**C**) maize. The zonal median change is plotted for the separate contribution of demographic effects ($\Delta n/n$, blue) and metabolic effects ($\Delta M/M$, red) for (**D**) wheat, (**E**) rice, and (**F**) maize. Results are shown for a range of life history traits in the longitudinal average curves (right panels). The metabolic effect uses activation energies (E_o) with a mean (0.65 eV) and standard deviation (±0.15 eV) for insects (*12*). The demographic effect assumes a range of ϕ_o values from 0.0001 to 0.01. All results are averaged over multiple climate models (*13*), in all years when the global mean surface temperature is 2 ± 0.1°C greater than in the late 20th century.

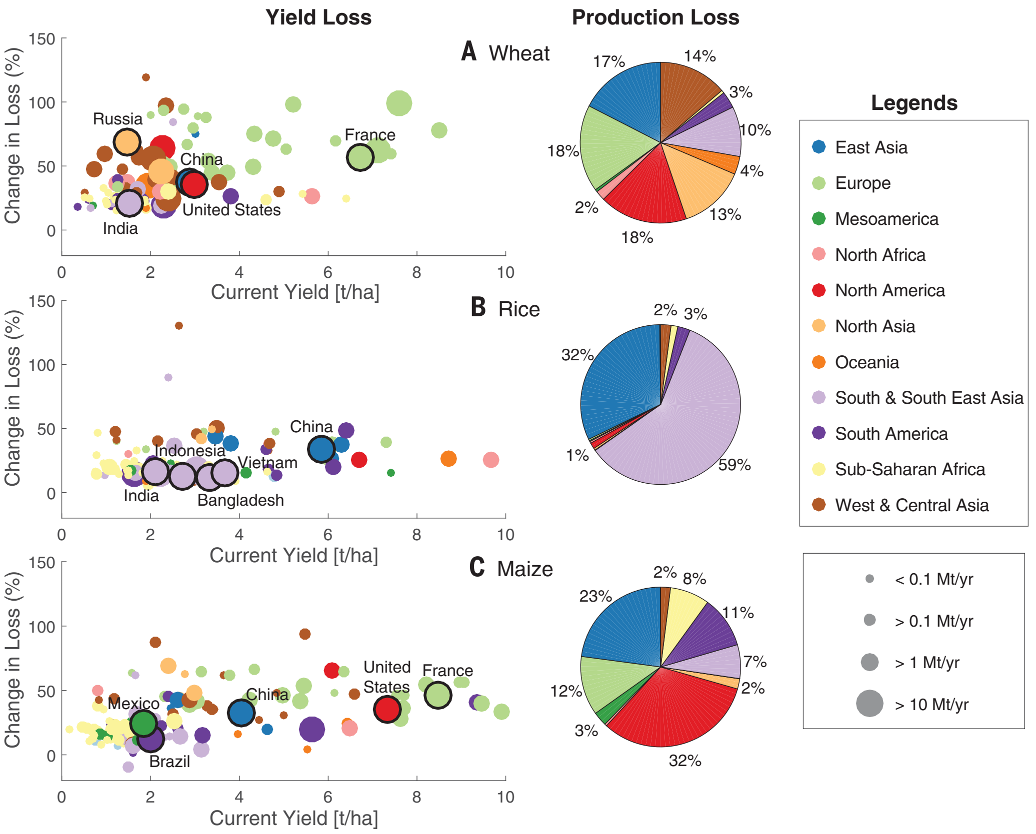

Fig. 3. Predicted regional increases in crop losses to insect pests in a 2°C-warmer climate. The change in future yield loss for each country is shown for the median grid cell within each country and plotted as a function of its median present-day crop yield per unit of planted area for (**A**) wheat, (**B**) rice, and (**C**) maize. The symbol size is scaled to total current production for each country, and color indicates the United Nations region. For each crop, the five countries with the highest current production are labeled and circled. The geographic burden of additional future production losses is shown in the pie charts. A full list of effects by region and country can be found in tables S1 to S5.

REFERENCES AND NOTES

1. J. R. Porter, L. Xie, A. J. Challinor, K. Cochrane, S. M. Howden, M. M. Iqbal, D. B. Lobell, M. I. Travasso, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, 2014), pp. 485–533.
2. D. S. Battisti, R. L. Naylor, *Science* **323**, 240–244 (2009).
3. J. Liu *et al.*, *PLOS ONE* **8**, e57750 (2013).
4. C. Rosenzweig *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **111**, 3268–3273 (2014).
5. E.-C. Oerke, *J. Agric. Sci.* **144**, 31–43 (2006).
6. P. J. Gregory, S. N. Johnson, A. C. Newton, J. S. I. Ingram, *J. Exp. Bot.* **60**, 2827–2838 (2009).
7. E. L. Zvereva, M. V. Kozlov, *Glob. Change Biol.* **12**, 27–41 (2006).
8. C. A. Deutsch *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 6668–6672 (2008).
9. Food and Agriculture Organization of the United Nations, FAOSTAT database collections; www.fao.org/faostat/en/.
10. M. E. Dillon, G. Wang, R. B. Huey, *Nature* **467**, 704–706 (2010).
11. C. Petersen, H. A. Woods, J. G. Kingsolver, *Physiol. Entomol.* **25**, 35–40 (2000).
12. U. M. Irlich, J. S. Terblanche, T. M. Blackburn, S. L. Chown, *Am. Nat.* **174**, 819–835 (2009).
13. See the supplementary materials.
14. C. Lesk, E. Coffel, A. W. D'Amato, K. Dodds, R. Horton, *Nat. Clim. Chang.* **7**, 713–717 (2017).
15. C. Monfreda, N. Ramankutty, J. A. Foley, *Global Biogeochem. Cycles* **22**, GB1022 (2008).
16. M. R. Collins, R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W. J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A. J. Weaver, M. Wehner, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge Univ. Press, 2013), pp. 1029–1136.
17. C. Zhao *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 9326–9331 (2017).
18. K. A. Potter, H. Arthur Woods, S. Pincebourde, *Glob. Change Biol.* **19**, 2932–2939 (2013).
19. C. M. Williams, H. A. L. Henry, B. J. Sinclair, *Biol. Rev. Camb. Philos. Soc.* **90**, 214–235 (2015).
20. Z. Liu, K. G. Hubbard, X. Lin, X. Yang, *Glob. Change Biol.* **19**, 3481–3492 (2013).
21. D. Deryng, W. J. Sacks, C. C. Barford, N. Ramankutty, *Global Biogeochem. Cycles* **25**, GB2006 (2011).
22. C. Deutsch, J. J. Tewksbury, M. Tigchelaar, D. S. Battisti, S. Merrill, R. B. Huey, R. L. Naylor, Dataset for "Increase in crop losses to insect pests in a warming climate." Dryad (2018); https://dx.doi.org/10.5061/dryad.b7q3g2q.

ACKNOWLEDGMENTS

We gratefully acknowledge H. Frenzel for technical support, the World Climate Research Programme for producing and making available the CMIP5 (Coupled Model Intercomparison Project Phase 5) model output, and the editorial suggestions of three anonymous reviewers. **Funding:** This work was made possible by grants to C.A.D. from the Gordon and Betty Moore Foundation (GBMF#3775) and the National Science Foundation (OCE-1419323, OCE-1458967, and OCE-1542240). **Author contributions:** C.A.D. and J.J.T. conceived of the study. C.A.D. constructed the model with input from J.J.T. and S.C.M. R.B.H. contributed data. C.A.D. and J.J.T. analyzed model results with input from all authors. All authors contributed to writing the manuscript. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** All data used in this study are described in the supplementary materials, and gridded model output is available in the Dryad repository (*22*).

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/361/6405/916/suppl/DC1
Materials and Methods
Figs. S1 to S7
Tables S1 to S5
References (*23–36*)

16 February 2018; accepted 18 July 2018
10.1126/science.aat3466

Science

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Science **361** (6405), 916-919.
DOI: 10.1126/science.aat3466

Warming, crops, and insect pests

Crop responses to climate warming suggest that yields will decrease as growing-season temperatures increase. Deutsch *et al.* show that this effect may be exacerbated by insect pests (see the Perspective by Riegler). Insects already consume 5 to 20% of major grain crops. The authors' models show that for the three most important grain crops ––wheat, rice, and maize––yield lost to insects will increase by 10 to 25% per degree Celsius of warming, hitting hardest in the temperate zone. These findings provide an estimate of further potential climate impacts on global food supply and a benchmark for future regional and field-specific studies of crop-pest-climate interactions.

Science, this issue p. 916; see also p. 846

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005.