Table 1 | Predicted impact of 2 °C of warming using time-varying growing season.

	Impact among 1,829 counties					Weighted
	Mean	Min	Max	Loss	Gain	impact
Panel A: Model using log yields as dependent variable						
Reference model						
Constant effect of KDD	−16.5%	−67.6%	14.2%	1,610	219	−10.7%
Butler *et al.*						
Model without adaptation	−17.3%	−38.6%	14.8%	1,765	64	−14.9%
Model with adaptation	−8.7%	−20.4%	16.1%	1,665	164	−7.6%
Our model						
Costly adaptation	−12.5%	−28.8%	15.7%	1,717	112	−10.9%
Panel B: Model using yields as dependent variable						
Reference model						
Constant effect of KDD	−18.2%	−184.8%	15.9%	1,551	278	−7.4%
Butler *et al.*						
Model without adaptation	−16.0%	−147.7%	16.7%	1,773	56	−10.8%
Model with adaptation	−3.9%	−35.2%	63.2%	1,557	272	−3.7%
Our model						
Costly adaptation	−9.2%	−83.7%	40.7%	1,693	136	−6.8%

The first five columns summarize the distribution of impacts among the 1,829 counties. The Loss and Gain columns indicate the number of counties that will see an increase or decrease in yield, respectively. The final column gives the overall impact on yields, which is the production-weighted impact of all counties in the analysis.

model' that accounts for potential trade-offs, as well as a simpler model that uses a single value of KDD sensitivity for all counties (similar to the method used in ref. 3). We qualitatively reproduce the results of Butler and Huybers, although the numbers differ slightly as we do not weight counties by their individual regression fit or eliminate counties with insignificant fit (both of which can introduce bias into the estimates). Most importantly, we show that the costly adaptation model (see the Supplementary Information for more detail) predicts more severe impacts than Butler and Huybers, and almost identical results to the estimate that uses no interaction term.

In summary, a consistent interpretation of the current data requires that reduced sensitivity to extremes cannot be achieved without a reduction in average yields. When we account for this cost, the apparent adaptation benefits in this region are of second-order importance. ❒

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Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to W.S.

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Butler and Huybers reply — Schlenker *et al.*[1] assert that the data do not support our conclusions[2] but present an analysis whose results are quantitatively indistinguishable from our own.

According to Table 1 of Schlenker *et al.*, 2 °C of warming leads to a 15% decrease in yield without adaptation. When adaptation is included, their implementation of our model gives an 8% reduction in yield, whereas their model gives an 11% reduction. We also presented a model configuration that accounts for yield reduction when adapting to a warmer climate by modification of growing degree day sensitivity (see Fig. S7 in ref. 2), but did not focus on this result because the evidence for such a trade-off is weak both in our study and others[3]. Nonetheless, this extended model resulted in 30% greater losses, and factoring this increase into the result of the implementation of our method by Schlenker *et al.* gives 10% losses after adaptation. Our estimated 95% confidence interval was −2% to +3% around our best estimate, making a 10% loss indistinguishable from the estimate of Schlenker *et al.* of 11%.

Schlenker *et al.* note consistency between their adaptation model with spatially variable sensitivity to killing degree days (KDDs) and a reference model with spatially constant sensitivity to KDDs that does not include adaptation, but this is a misleading comparison. The comparisons that we provide in the previous paragraph are more appropriate because they are between models that are the same, excepting whether adaptation is included or not. Furthermore, our Letter shows — and Schlenker *et al.* confirm — significant spatial variability in the sensitivity to KDDs, indicating that a model with spatially constant sensitivity is a less adequate description of the data.

Schlenker *et al.* also raise two interesting questions as to whether relative humidity or a shorter growing season may instead account for a lower KDD sensitivity. We do not rule out the potential relevance of these factors, and note that the shorter time to maturation in the south may itself partly reflect adaptation[5]. However, our examination of relative humidity estimated from meteorological reanalysis[6,7] indicates that it has only a weak relationship with KDD sensitivity, linearly explaining just 3% of the variance. We focused on the logarithm of KDD climatology as this explains 31% of the variance in KDD sensitivity. We also note that support for our interpretation comes from a study by Ristic *et al.*[4] that showed US crop varieties growing in the south to be more heat tolerant than those grown further north.

We stand by the viability and correctness of the two main points of our Letter: that higher KDD climatologies are related to lower KDD sensitivity and that this relationship provides an empirical basis for estimating adaptability. We also stand by our conclusion that "losses are almost certainly overestimated if adaptation is not accounted for" — adaptation yielding a non-zero benefit is a rather low bar, and one that both our model and that of Schlenker *et al.* clears[1,2]. That said, the degree to which adaptation will reduce damage from a warming climate remains uncertain, and we look forward to further discussion and inquiry into this topic. ❐

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COMMENTARY:
Triple transformation

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A new business plan that enables policy transformation and resource mobilization at the national and international level, while improving access to resources, will allow the Green Climate Fund to integrate development goals and action on climate change.

In 2009, the developed world collectively pledged to mobilize US$100 billion per year by 2020 to help developing countries reduce greenhouse gas (GHG) emissions and adapt to climate change[1]. In 2010, the Green Climate Fund (GCF) was established to channel this sum to support low-emission and climate-resilient development, and its board is now designing the fund's policy and institutional framework. Here we draw on lessons learned from existing multilateral financing mechanisms, discuss the need to mainstream climate finance into development and propose a business plan for the GCF that aims to combat climate change and create development opportunities in unison.

There are several existing international climate financing instruments, the most prominent of which are hosted by or linked to the World Bank. Launched in 2008, Climate Investment Funds (CIFs), for example, focus on technology, resilience, mitigation and forest preservation. Their governance structure — comprising donors and selected recipient developing countries — is limited. CIFs pushed concessional loans towards adaptation and thus saddled recipient countries with extra debt rather than facilitating development. Nevertheless, they have piloted private sector engagement and tested risk-management tools and instruments.

Operationalized in 2007 under the Kyoto Protocol, the Adaptation Fund provides grants for adaptation through the UN Development Programme, World Bank, UN Environment Programme and other multilateral entities and accredited national implementing institutions. Its funds are derived from a 2% levy on carbon credits generated through mitigation projects that are conducted under the Kyoto Protocol's Clean Development Mechanism. Although it takes voluntary donor contributions, there is no defined annual replenishment mechanism. Owing to a drop in the carbon price, resources have dwindled and delivery mechanisms have not been reformed or adjusted to address adaptation needs. Thus, despite handling roughly US$170 million so far, the Adaptation Fund has not spurred widespread integration of resilience into the economic planning of recipient countries, many of which remain vulnerable to climate change. Although financed projects have benefitted local communities, they have had negligible effect on a large scale. However, by strengthening national adaptive capacity and promoting national implementing entities, these schemes have reduced the long-term dependence of developing countries on international assistance.

The Least Developed Countries Fund (LDCF) has received more than US$500 million, of which US$326 million has been approved for specific projects, although only US$133 million has so far been disbursed. The LDCF supports adaptation in poor countries with the highest vulnerability to climate change. Its sole responsibility is to finance National Adaptation Programmes of Action. Criteria used to identify priorities include 'poverty reduction to enhance adaptive capacity'[2]. Indeed, a distinguishing feature of the LDCF is that — unlike the Adaptation Fund — it is mandated to not only provide resources to undertake adaptation, but also to invest in building the institutional capacity of these countries to manage climate risks. Nevertheless, both institutions have failed to address tensions between development and climate action and to achieve the necessary large-scale shift towards low-emission and climate-resilient development.

As opposed to the climate financing architecture, two successful non-climate funds show how taking the links between environment, health and economic development into account can lead to successful win-win strategies and tangible co-benefits.

The Montreal Protocol Trust Fund is concerned with protecting the ozone layer in the upper atmosphere. The phase-out of ozone-depleting substances, which are