CORRESPONDENCE:

Transformation is adaptation

To the Editor — Transformational change is an essential part of society's adaptive and mitigative response to climate change. Existing structures, institutions, habits and priorities need to be critically re-evaluated in light of the risks that climate change poses. Although some transformation will be forced on society as a last resort, some will be more voluntary, positive and anticipatory[1,2].

The latter sort of adaptation is neglected in the recent Commentary by Dow *et al.*[3] on limits to adaptation. Implicitly and explicitly, they present transformational change as outside rather than part of the scope of successful adaptation. Focused on determining where individual or group adaptation limits lie, they present a transformation in behaviour as a response to an 'absence of new adaptation options or resources' and a discontinuity that is 'symptomatic of an adaptation limit being reached'. But rather than a shift from adaptation to non-adaptation, the above represents a move from one major adaptation strategy to another. For example, Dow *et al.* present a farmer's decision to exit farming as a negative situation of 'abandonment'. But such a move may be highly rational and desirable from a personal, familial and ecological point of view, as examples in Australia suggest[1,4,5]. This is especially the case if it fosters public goods, such as revegetation for carbon sequestration and emissions reductions. Mitigation is a crucial part of successful adaption, and it requires transformational responses.

As is argued about other aspects of climate change[6], uncertain system dynamics mean that the prediction of adaptation limits — as Dow *et al.* call for — is unfeasible. Adaptation is necessarily experimental. Strategic shifts are frequently going to be needed in response to new conditions and information. They will also emerge as we reassess existing trajectories and goals. Adaptation cannot simply be a conservative project of protecting things we value, at least in the developed world. Our existing values and norms need to be thoroughly re-evaluated as part of the adaptation project.

As others' have pointed out[7,8], how we frame climate change adaptation strongly influences the way that people approach the issue. It is imperative that the potential for positive transformational change is included in the scope of planned adaptation options and policies. ❐

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CORRESPONDENCE:

US maize adaptability

To the Editor — Butler and Huybers[1] argue that without adaptation a 2 °C increase in temperature would decrease maize yields in the US by 14%, but that with adaptation the same temperature increase would decrease yields by only 6%. Butler and Huybers modelled adaptation as decreasing sensitivity to extreme heat (degree days above 29 °C, which they call killing degree days; KDD). Here we show that their conclusions are based on an unjustified interpretation of the data, and that when properly analysed, the data do not support their statement that "losses are almost certainly overestimated if adaptation is not accounted for."

We agree with Butler and Huybers that sensitivity to KDD is, on average, lower in hotter counties. However, this does not necessarily "demonstrate how maize is locally adapted to hot temperatures." It may be that southern counties — because of higher average humidity levels — have a weaker relationship between KDD and vapour pressure deficits (VPD), with high VPD the more direct cause of yield loss[2]. It may also be that southern counties grow shorter-season or hardier varieties, in which case they could be considered adapted, in exchange for lower yields in good conditions. Regardless of the specific reason, it is misleading and unwarranted to simply assume that some counties could benefit from the lower KDD sensitivity observed in other counties.

Consider how the method used by Butler and Huybers would deal with an extreme scenario where yields were exactly zero every year in hot southern counties. This would result in a coefficient of zero on KDD, as well as a zero intercept. By their method, 'adaptation' would apply the zero coefficient on KDD to northern counties as they warm, but preserve the positive intercept in northern counties, suggesting that average yields will remain the same irrespective of any warming. (Supplementary Figure S7 of Butler and Huybers considers only changes in the KDD coefficient, but not the intercept.) A method that fails on this simple example should not, in our view, be trusted.

A more appropriate approach to modelling adaptation would account not only for the change in KDD coefficient in hotter counties, but also for the changes in all other regression parameters. The predicted impacts of a 2 °C warming is given in Table 1, both for models from Butler and Huybers and a 'costly adaptation

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. ❐

References

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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