address this concern, Lancaster performed a second analysis using only species with measurements on two populations, allowing her to test the prediction that a latitudinal increase in thermal tolerance breadth would be more likely near the poleward range boundary, where range expansions are most recent. In concordance with this prediction, tolerance breadths increased with latitude most often when both populations were in the poleward portion of their species range, consistent with the hypothesis that older equatorial populations are more likely to be locally adapted to their thermal environment. Fruitful avenues for future research would include improving sample sizes, latitudinal coverage, and information on range dynamics in this dataset, which would increase confidence in the findings and perhaps modify the precise shapes of the response of upper and lower thermal limits across latitudes.

These two independent analyses are consistent with the hypothesis that the increasing thermal breadth towards the poles is influenced by ongoing poleward range expansions. Lancaster's study highlights the role of biogeography and migration patterns in shaping global patterns of thermal physiology, and suggests that knowing the biogeographic history of populations could help predict their responses to climate change. The research does not refute the hypotheses that upper critical limits are constrained to some degree, nor that the selection on upper limits is relatively invariant across latitude, compared to selection on lower thermal limits. Laboratory selection experiments confirm that lower limits are less evolvable than upper limits[9], and it is undeniable that maximum temperatures change less than minimum temperature across latitude. However, this work suggests that these explanations, which are based around natural selection, may not be necessary to explain apparent invariance of upper thermal limits across latitude. An important implication is that stable, insular or endemic species, with narrower thermal breadths and less gene flow to provide heat adapted southern alleles, may be at greater risk than previously thought. Finer-scale and experimental approaches examining evolution of thermal tolerances during range expansion are required, and are already providing some support for the range-expansion hypothesis[10].

This work[2] has added a plausible and well-supported third hypothesis to the table regarding the causal mechanisms underlying increases in thermal tolerance breadth with latitude, and promises to stimulate research that may ultimately improve our ability to predict organismal responses to climate change. ❒

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AGRICULTURAL IMPACTS

Mapping future crop geographies

Modelled patterns of climate change impacts on sub-Saharan agriculture provide a detailed picture of the space- and timescales of change. They reveal hotspots where crop cultivation may disappear entirely, but also large areas where current or substitute crops will remain viable through this century.

William R. Travis

Climate change is sometimes illustrated as shifting geography. A future, warmer Vermont, for example, can be mapped as climatologically shuffling south-westwards across Ohio, down to present-day Alabama (http://go.nature.com/ePEBnn). Such animations can be quite effective at communicating climate trends. Geographical analogues and other spatiotemporal approaches, when applied technically with due attention to eco-climatological dynamics and spatial arrangements, can also yield insights into potential resource patterns of the Earth's climatic future. Rippke and colleagues[1], reporting in *Nature Climate Change*, apply spatiotemporal analysis to agricultural impact and adaptation assessment to provide a glimpse of how climatic changes might change crop production patterns in sub-Saharan Africa. The results are both encouraging and concerning. Some crops are geographically robust, shifting little over this century, so that they are able to maintain their role in regional food production even on a markedly warming planet. Others are squeezed from much of their current territory, signalling the need for proactive adaption planning to avoid serious production losses.

Geographical analogues were among the earliest approaches to assessing what climate change might mean for natural resource systems. Rough maps of shifting climate futures became iconic symbols of the climate change threat in the 1970s and 1980s. If the climate conditions at the time placed the American Corn Belt in the Upper Midwest, where might it shift in a climate affected by increasing concentrations of atmospheric carbon dioxide? With just 1 °C of warming, it would move about 100 miles north with an edge slipping into Canada, according to a frequently reproduced map from the 1980s[2]. Agro-ecological zonation was also applied as a tool for projecting changes in data-poor areas such as Africa[3], and for historical reconstructions of climate impacts[4]. The geographical approach has since been eclipsed by the more reliable statistical and process-based crop models, which have become available for most major crops in most regions. Meta-analysis on large suites of crop model runs has become the standard in agricultural impact assessments, including in the latest IPCC review of food security[5]. This type of model analysis has built on the tremendous foundation provided by the global crop modelling community and efforts such as the Agricultural Model Intercomparison and Improvement Project (AgMIP)[6].

But agronomic model projections falter as crops are pressed closer to the margins of viability; yield models struggle with large changes that presage shifts in crop type and location[7]. Increases in the quantity and quality of data covering larger geographies and at higher resolutions, coupled with the tools of spatial analytics and geographical information systems (GIS), have enhanced the power of spatiotemporal approaches and renewed their utility for climate change impact studies. In 2003, a large team of researchers mapped climate change impacts across the globe in four key sectors — water, agriculture, ecosystems and health — providing something of a global climate change risk assessment[8]. Their global impact 'hotspots' analysis — breath-taking in scope — also applied the techniques of model intercomparison to multi-sector impacts analysis.

Bringing this approach to focus at the sub-continental scale, Rippke *et al.*[1] simulate suitability across sub-Saharan Africa for nine major crops, constituting half of Africa's agricultural production. This allowed them to map areas of current crop viability that will become unsuitable over the course of this century. The largest shifts occur for beans, maize and bananas, whereas small grains such as millet and root crops such as cassava show up as much more robust, undergoing shifts in less than 15% of the currently suitable area over the century.

Emulating the impact hotspots approach taken by Piontek *et al.*[8], Rippke and colleagues[1] also search for areas of sub-Saharan Africa where suitable substitution crops do not present themselves — landscapes that are likely to transition entirely out of crop-based agriculture. Such high-risk areas are relatively small, but the potential for loss and dislocation in those zones looms large and worrisome for agricultural policymakers as well as for farmers. Though the state of spatiotemporal analysis in agricultural impacts may not yet tell us with great certainty where those hotspots will be, their likely emergence clearly demands forward-looking adaptation planning so that policies on insurance, extension and R&D can prepare people, technologies and food systems.


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Rippke *et al.*[1] also advance the study of adaptation processes, framing their analysis from incremental to transformative stages of adaptation, linked to rates of crop viability over time. In this way, their work offers an exemplar of climate risk assessment: crop viability is measured as the probability of crossing a suitability threshold. This risk-threshold framework, described recently by Dow *et al.*[9], offers a nuanced and quantitative approach to the abiding challenge of judging the necessary rates of adaptation[10]. For example, Rippke *et al.* find that 10% of bean-production areas in eastern Africa will need to adapt to crop failure rates approaching 1 out of 2 years by the 2050s, with 30% of the area needing transformative adaptation to alternative crops, or a shift out of cropping altogether, by the 2090s.

Future steps that build on the risk approach by Rippke *et al.*[1] include testing different adaptation rates that reflect underlying vulnerabilities of farmers and agricultural policy in different areas, such as where crop insurance is (or is not) available. Overlaying the spatial pattern of projected impacts with the geographies of socioeconomic sensitivity can help to ensure that early warning approaches are tuned to the risks identified. ❐

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