decline — and therefore potentially human influence — was playing a decisive role in this counterintuitive trend.

The debate about the recent cold spells followed the familiar pattern that characterises public reaction to surprising events such as disasters, aircraft accidents or crimes. A causal explanation is immediately called for, and experts are tempted (or forced) to speculate, even though little is known. The media happily runs the resulting stories, hypotheses further develop in the blogosphere and sometimes become accepted as facts despite a lack of evidence. It is natural to ask for explanations quickly after events happen. It is also valuable to publish hypotheses and propose causal mechanisms based on simple correlation and regression analyses. Thereafter, however, these hypotheses need to be scrutinized with observational evidence, confronted with the existing body of literature and rigorously quantified to test whether they play a dominant role in determining cold spells. Such a scientific debate can be stimulating and fruitful[12], but it takes time.

The proposed link between sea ice decline and enhanced meandering of the jet stream has been found to be sensitive to the analysis method used[13,14]. However, some of the proposed mechanisms linking Arctic amplification, declining sea ice or Pacific warm anomalies[15] to mid-latitudinal weather are indeed plausible. Nevertheless, it first needs to be demonstrated that their signature is strong enough to emerge from the noise of the ordinarily highly variable winter weather[16]. In the end, the most powerful argument is the observational evidence and our quantitative physical understanding. Screen demonstrates that despite recent cold winters, cold days have become less, rather than more, extreme.

This debate should remind both the public and the scientific community that drawing conclusions too quickly may not help, just as it does not help to prejudge suspects after a crime. It should be possible for scientists to say 'we do not know yet' — in fact, such a statement should increase, not decrease, their credibility. Sometimes explanations are not straightforward. It takes time to assemble the required data, study mechanisms, run model experiments and challenge each other on various hypotheses[12]. The final verdict on the linkage between Arctic amplification and mid-latitudinal winter weather is still out, but the explanation for the recent cold spells may indeed be quite straightforward, as Screen argues. Internal variability of cold weather is very high, and recent cold spells may just be a few excursions from a long-term trend to warmer winters. ❐

Erich M. Fischer and Reto Knutti are at the Institute for Atmospheric and Climate Science, ETH Zürich, Universitätstrasse 16, 8092 Zürich, Switzerland.
e-mail: erich.fischer@env.ethz.ch; reto.knutti@env.ethz.ch

References

1. Francis, J. A. & Vavrus, S. J. *Geophys. Res. Lett.* **39,** L06801 (2012).
2. Tang, Q., Zhang, X., Yang, X. & Francis, J. A. *Environ. Res. Lett.* **8,** 014036 (2013).
3. Liu, J., Curry, J. A., Wang, H., Song, M. & Horton, R. M. *Proc. Natl Acad. Sci. USA* **109,** 4074–4079 (2012).
4. Screen, J. *Nature Clim. Change* **4,** 577–582 (2014).
5. de Vries, H., Haarsma, R. J. & Hazeleger, W. *Geophys. Res. Lett.* **39,** L04706 (2012).
6. Fischer, E. M., Lawrence, D. M. & Sanderson, B. M. *Clim. Dynam.* **37,** 1381–1398 (2011).
7. Kharin, V. V., Zwiers, F. W., Zhang, X. & Hegerl, G. C. *J. Clim.* **20,** 1419–1444 (2007).
8. Collins, M. *et al.* 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* (eds Stocker, T. F. *et al.*) Ch. 12 (Cambridge Univ. Press, 2013).
9. Gregory, J. M. & Mitchell, J. F. B. *Q. J. R. Meteorol. Soc.* **121,** 1451–1476 (1995).
10. Della-Marta, P. M. *et al. J. Geophys. Res.* **112,** D15103 (2007).
11. Huntingford, C., Jones, P., Livina, V., Lenton, T. & Cox, P. *Nature* **500,** 327–330 (2013).
12. National Research Council *Linkages Between Arctic Warming and Mid-Latitude Weather Patterns: Summary of a Workshop* (The National Academies Press, 2014).
13. Screen, J. A. & Simmonds, I. *Geophys. Res. Lett.* **40,** 959–964 (2013).
14. Barnes, E. A. *Geophys. Res. Lett.* **40,** 4734–4739 (2013).
15. Palmer, T. *Science* **344,** 803–804 (2014).
16. Gerber, F., Sedlacek, J. & Knutti, R. *Geophys. Res. Lett.* **41,** 561–567 (2014).

CLIMATE AND LAND USE

Forgive us our carbon debts

Sugar cane ethanol replaces fossil fuels, but changes in soil carbon could offset some of the benefit. Now, a study shows minor loss of soil carbon when pastures and croplands are converted to cane, but larger losses when converting native savannahs.

Marcia N. Macedo and Eric A. Davidson

As if growing enough food without clearing native forests and savannahs were not hard enough, an increasingly large land area is now being used to grow biofuel crops[1]. Brazil alone grew 98,000 km^2 of sugar cane in 2012, harvesting 721 million tonnes of cane, about half of which was destined for producing ethanol[2]. Burning biofuels in lieu of fossil fuels may increase energy security and mitigate climate change, but fully accounting for net greenhouse gas (GHG) savings has proved challenging. Among other things, limited data exist on potential soil carbon losses or gains when sugar cane replaces other land uses. As they report in *Nature Climate Change*, Mello and colleagues[3] use field measurements of soil carbon in Brazil to estimate the carbon debt and payback time associated with sugar cane expansion over a range of land covers.

Accounting for the GHG savings associated with sugar cane ethanol production requires reliable estimates of: (1) fossil fuels used during sugar cane production, transport and ethanol processing; (2) carbon and other GHG emissions when native forests or savannahs are cut down for cane production; (3) changes in soil carbon stocks during land conversion and crop production. These emissions add up to a 'carbon debt' that must be 'paid back' before a biofuel crop can be considered a net benefit for climate change mitigation. The paybacks include the sequestering of carbon in soils as biofuel crops grow and the fossil fuel emissions avoided through ethanol use.

Mello *et al.*[3] report field measurements of changes in soil carbon when cattle pastures, croplands or native savannahs were converted to sugar cane. Earlier studies[4,5] were based on broad-brush assumptions about how much soil carbon would be lost with tillage. The current study supports those conclusions, but provides greater confidence based on soil data from 75 pairwise comparisons of land conversion in Brazil. An average soil carbon loss of 10% was indicated by a comparison of 57 pasture-to-cane conversions. Combining these carbon losses with the gains from avoided fossil fuel emissions, the authors estimate a three-year payback time for ethanol production to compensate for the soil carbon debt and become a net benefit for climate mitigation.

All crops leave a portion of their biomass behind in the soil, but sugar cane is an especially prodigious biomass producer, building up soil carbon stocks compared with many other crops. Pairwise comparisons of thirteen cropland-to-cane conversions indicated an average increase of 16% in soil carbon stocks — a carbon surplus that requires no (or negative) payback time. In contrast, five pairwise comparisons of conversions from native Cerrado (woodland/savannah) to sugar cane indicated an average topsoil carbon loss of 25%. Carbon stocks in deep soils (deeper than 30 cm) also showed a declining trend after conversion, but there were too few data to establish statistical significance. Considering only topsoil carbon loss, the authors estimate that savannah-to-cane conversion incurs an eight-year payback time. Adding the carbon lost from aboveground woody vegetation means it would take 17 years for ethanol production to compensate the carbon lost due to converting Cerrado.

Sugar cane has been the star of first-generation biofuels, boasting greater carbon savings than corn, soy or palm oil[1]. With the world's largest fleet of flex-fuel vehicles (more than 20 million), Brazil has been a leader in ethanol use, making it an important part of its national commitment to reduce GHG emissions. Brazilian ethanol production is poised for continued growth as flex-fuel technology becomes more widespread and global demand for biofuels increases. But the potential climate mitigation benefits of expansion must be weighed against the consequences of land-use change. Given the significant carbon debt resulting from conversion of Cerrado to sugar cane and the importance of the remaining Cerrado for biodiversity and other ecosystem services[7], this land-use transition is unwise from both a climate and a conservation perspective. In contrast, the findings of Mello *et al.*[3] suggest that croplands and pastures can be converted to sugar cane without significant carbon debts.

Brazil has a large supply of under-used, low-productivity pasturelands that are suitable for crop production[8,9], but sugar cane is just one of many potential uses for these lands. Competition for land

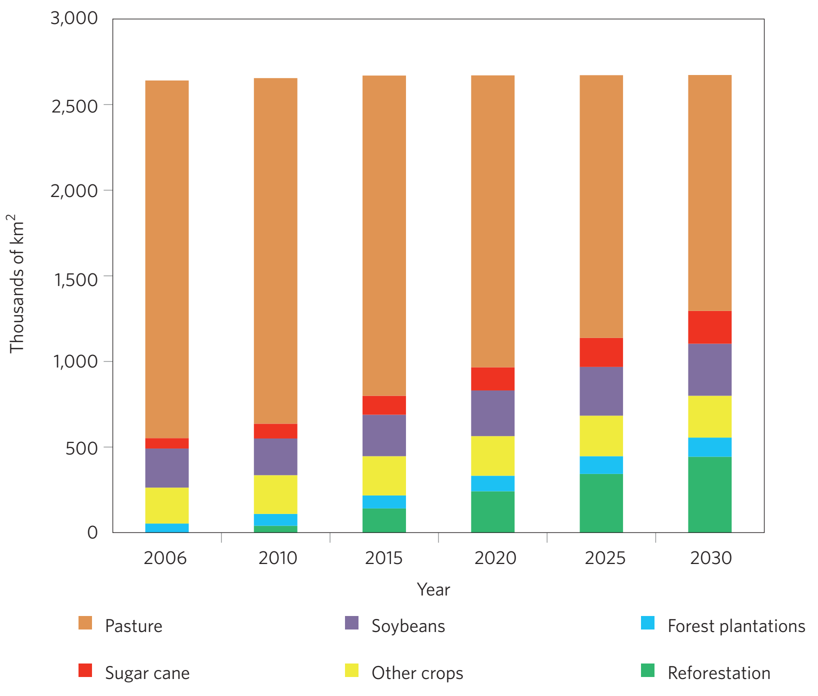

Figure 1 | Potential allocation of existing cleared lands in Brazil. Future land uses are based on a low-carbon modelling scenario that greatly reduces deforestation after 2006, the reference year[9]. The land-use model reallocates the large pool of low-productivity pastures to sugar cane, forest regrowth and other competing land uses, while intensifying cattle production on remaining pastures. Results from Mello *et al.*[3] confirm that such pasture-to-cane and cropland-to-cane transitions result in little or no carbon debt. Figure adapted from ref. 9.

among food, fuel and beef production greatly complicates the application of the new findings presented by Mello *et al.* (Fig. 1). Converting large areas of existing pastures to sugar cane could preclude expansion of other crops and would restrict beef production to a shrinking area of pasturelands. Barring large-scale intensification of cattle production, there is a risk that such pasture-to-cane transitions could push the expansion of pasturelands and other croplands into new regions, spurring new deforestation. Such 'leakage' (as it is called in policy circles) is notoriously difficult to document, as it may occur across state and national boundaries, is subject to varying time lags, and is technically difficult to establish causality[10].

Not all degraded pasturelands are suitable for crops, but they could provide wildlife habitat and improve water quality if allowed to regenerate as forests. Fortunately, Brazil's pool of pastureland is huge, so it is probable that there is room for an 'all of the above' strategy that allows expansion of reforestation, sugar cane and other crops, while still allocating more than half of the current pastureland for intensified beef production (Fig. 1). As Mello *et al.*[3] demonstrate, knowing how soil carbon stocks are distributed and how they change with land use is an important step in developing smart, low-carbon emission approaches that balance land demands for food and energy, while providing vital ecosystem services. ❒

Marcia N. Macedo and Eric A. Davidson are at Woods Hole Research Center, 149 Woods Hole Road, Falmouth, Massachusetts 02540, USA.
e-mail: mmacedo@whrc.org

References

1. Gibbs, H. *et al. Environ. Res. Lett.* **3,** 1–10 (2008).
2. Brazilian Institute of Geography and Statistics (IBGE) http://www.sidra.ibge.gov.br/ (2014).
3. Mello, F. C. *et al. Nature Clim. Change* **4,** 605–609 (2014).
4. Fargione, J. *et al. Science* **319,** 1235–1238 (2008).
5. Searchinger, T. *et al. Science*, **319,** 1238–1240 (2008).
6. Brazilian Sugarcane Industry Association (UNICA) http://www.unicadata.com.br/ (2014).
7. Turner, W. *et al. Bioscience* **57,** 868–873 (2007).
8. Soares-Filho, B. *et al. Science* **344,** 363–364 (2014).
9. Gouvello, C. *Brazil Low-carbon Country Case Study* (The World Bank and Brazilian Institute for International Trade Negotiations, 2010).
10. Meyfroidt, P. *et al. Curr. Opin. Environ. Sust.* **5,** 438–444 (2013).