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On being and seeing red

The northern cardinal (*Cardinalis cardinalis*; pictured) owes its striking appearance to red ketocarotenoid pigments that are converted from yellow pigments in its diet. In *Current Biology*, Toomey *et al.* characterize the enzymatic pathway for this conversion in birds and fish (M. B. Toomey *et al. Curr. Biol.* https://doi.org/10.1016/j.cub.2022.08.013; 2022).

As well as being found in red feathers, ketocarotenoids are made in red 'cone' cells in the eye that detect red light. The gene encoding the enzyme CYP2J19 was the most highly expressed of the genes enriched in red cone cells compared with other cone-cell types. Mammalian cells engineered to express CYP2J19 converted yellow pigments into reaction intermediates, and other cells that were engineered to express an enzyme called BDH1L converted these intermediates into ketocarotenoids. Toomey *et al.* found both enzymes in feather follicles from domestic red canaries (*Serinus canaria* forma *domestica*).

The team eliminated ketocarotenoid production in *Danio albolineatus* fish by deleting genes that are closely related to those encoding CYP2J19 and BDH1L in birds. Thus, the pathway for ketocarotenoid synthesis is similar in fish and birds.

Natasha Bray

Climate change

Declining crop yields limit bioenergy potential

Gernot Wagner & Wolfram Schlenker

Global-warming projections that rely on bioenergy strategies to offset carbon dioxide emissions could be unduly optimistic, according to a study that accounts for how climate change affects crop yields. **See p.299**

Climate change is beset with unpleasant surprises[1]. Yields of maize (corn), wheat, rice and soya beans all fall precipitously when temperatures exceed certain thresholds – for example, 29 °C for maize[2]. These four staple crops together account for 75% of the calories consumed by humans[3], so the non-linear temperature dependence of their yields calls for rapid action to avoid the tipping points, either by limiting the carbon dioxide emissions that are warming the planet[4] or by relocating crop fields on a vast scale – probably both. But efforts to curb global warming rely increasingly on the use of plant biomass to reduce emissions, and introduce a feedback loop that endangers attempts to meet essential climate goals, as Xu *et al.*[5] report on page 299.

Plants absorb CO_2 from the atmosphere during photosynthesis, and this process can be used to capture and store CO_2 when fuels made from plant biomass are burnt without releasing the CO_2 back into the atmosphere; this results in a source of energy that has 'negative' emissions. Most models that estimate the costs associated with a changing climate assume that this technology, known as bioenergy with carbon capture and storage (BECCS), will be ramped up substantially over the coming decades[6,7]. And with good reason – an increase in the deployment of new, improved technologies is typically a safe assumption. However, Xu and colleagues' analysis shows that, as time goes by and the world warms, falling crop productivity rates will reduce the effectiveness of BECCS, highlighting limits of this new technology.

The authors describe the effect as a 'positive' feedback loop. There is, of course, nothing positive about this particular feedback in the conventional sense of the term: increased global average warming leads to reduced crop yields, which, in turn, decreases carbon capture through BECCS, inducing further increases in global average warming. In this scenario, two negative links combine to create one hot mess.

Climate–economy modelling has undergone a substantial shift over the past decade, as researchers have warmed to the idea that these models can include large quantities of bioenergy[5,6]. The Energy Modeling Forum (EMF) was established in 1976 at Stanford University in California to tackle issues associated with energy and the environment. In 2009, most of the 10 models used by the forum (then in its 22nd iteration) suggested that atmospheric CO_2 concentrations could not be kept below 450 parts per million[8] – a threshold that is expected to induce global average warming of around 2 °C above pre-industrial levels[9]. This prediction was all the more troubling because the models included ambitious assumptions, such as that the global price for CO_2 emissions would reach as much as US$1,000 in 2012. And, in spite of such assumptions, the world still seemed to lack the mitigation potential in mitigation efforts to cut CO_2 emissions to safe levels.

The 33rd iteration of the EMF in 2020 included these same models, albeit with some key changes. Crucial advances in technologies such as solar cells and battery storage had brought down the costs associated with reducing CO_2 emissions. This meant that many more cuts in emissions could be made than those previously planned – and sooner[4]. The EMF's updated models also assumed that there would be a higher potential for bioenergy around the globe than that predicted in 2009, especially in the latter half of the twenty-first century[10]. Xu and colleagues' study is a timely warning that this assumption should not be relied on to meet emissions targets.

Recognizing the effect of land-use changes on global warming is essential for effective mitigation strategies[11]. But the realization that BECCS and other negative-emissions technologies have a profound impact on the environment, and therefore on global warming, seems to have come only in the past few years[12]. The theoretical potential of a given technology is too often determined by its technical limits alone, with little regard for its political and socio-economic limits. In the case of BECCS, the many competing interests for limited land – with food chief among them – impose severe constraints on the likelihood that it can be scaled up as much as is sometimes assumed.

The political and socio-economic obstacles currently standing in the way of BECCS have often led climate modellers to assume that the mitigation potential will increase in the future, when the present constraints are lifted. But Xu and co-authors' analysis suggests that this optimism could be thwarted by the dependence of crop yields on temperature, and that of BECCS on biomass production, two relationships that together form a feedback loop set to exacerbate climate change. And timing is a crucial factor: the longer we wait before implementing BECCS on a large scale, the more negative will be the impact of climate on crop yields – worsening climate change still further (Fig. 1).

The interaction of timing with non-linear threshold effects is not limited to the relationship between BECCS, crop yields and temperature. Indeed, it is a broader phenomenon that highlights the need for prudence when dealing with climatic tipping points[13,14]. The danger of crossing uncertain tipping points raises the estimated cost of future damage caused by emitting CO_2 and other greenhouse gases into the atmosphere. Negative tipping points should thus prompt us to hasten the uptake of ambitious mitigation measures.

The existence of positive socio-economic tipping points, such as the rapid spread of charging stations for electric vehicles or deployment of heat pumps, could be just as crucial[15,16]. Mitigation technologies can seem both expensive and improbable until they are suddenly ubiquitous. Somewhat counter-intuitively, these positive non-linearities, too, provide an incentive for climate-mitigation action that is more ambitious and more rapid than that occurring without them[17,18]. One reason is that locking in existing 'dirty' technologies increases the cost of transitioning to cleaner alternatives later, whereas rapid changes incentivize further action.

Something similar could apply to BECCS. Increasing investments in BECCS sooner than currently planned will no doubt limit warming and boost crop productivity. But it could also lead to technological improvements that lessen the negative impacts of BECCS on food security and other competing land uses. This expectation should, however, be treated with caution. Although improvements to maize farming have been under way for decades, the rate of growth of US maize yields started to slow from exponential to linear in the 1980s, perhaps owing to binding biophysical constraints that are difficult to overcome[19].

Political constraints could be even more relevant than biophysical factors. Land and other natural resources are in limited supply, and land-use decisions can quickly prove to be unpopular with voters. Simply imagining that these political hurdles will be overcome in a distant future, well beyond current election cycles, will not make it so.

Much like the prospect of distant technological salvation from climate change, the expected future effectiveness of BECCS must not detract from the need to cut emissions now[20]. Xu *et al.* have offered further evidence that relying on technological breakthroughs down the line is a fraught endeavour. As their analysis demonstrates convincingly, waiting for salvation could well hasten our demise, because delays might restrict the technologies available to us now.

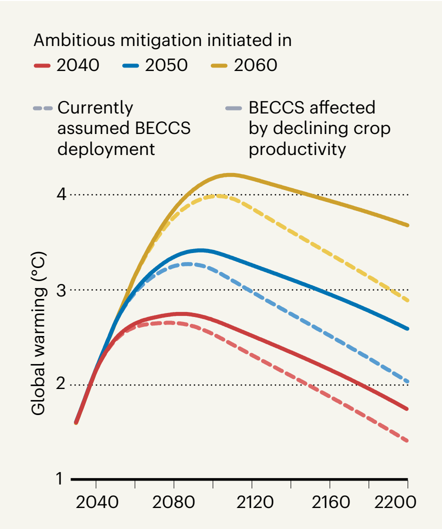

Figure 1 | Crop yields could affect global-warming mitigation. Climate–economy models assume that strategies for curbing global warming must involve increased deployment of technology known as bioenergy with carbon capture and storage (BECCS). However, Xu *et al.*[5] found that the effectiveness of BECCS is likely to be influenced by the temperature sensitivity of crop productivity rates, which is typically highly non-linear. The authors' analysis suggests that the timing of widespread implementation of BECCS will be key to its climate impact. (Adapted from Fig. S8 of ref. 5.)

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