CORRESPONDENCE:

CO_2 emissions from crop residue-derived biofuels

To the Editor — In the May issue of *Nature Climate Change*, Liska *et al.*[1] presented a comprehensive analysis of the soil organic carbon (SOC) loss due to harvest of corn residues for bioethanol production. We do not dispute the main findings that harvest of residues has a negative impact on SOC levels and that this impact should be addressed when evaluating the potential benefits of cellulosic biofuels. We do, however, find that the conclusion, that cellulosic biofuels increase CO_2 emissions, builds on an incomplete analysis and that the analysis could have reached the opposite conclusion had it been more complete.

Liska *et al.* refer to consequential life cycle assessment (LCA) as the reason why SOC loss must be incorporated in greenhouse-gas analyses of biofuels. Consequential LCA requires that mass balances are closed and if not, some impact allocation must take place. In cellulosic ethanol production based on agricultural residues 20–25% of the carbon in the biomass ends up in ethanol and half of that amount in CO_2. Approximately 40% is retained in the lignin residue and the rest (~20–30%) in molasses/vinasse[2,3]. Liska *et al.* surprisingly disregard a considerable part of that carbon mass and attribute all CO_2 interactions between the product system and the atmosphere to ethanol. The lignin fraction is not accounted for in the main comparison between cellulosic and fossil fuels (Fig. 3 in ref. 1). If the lignin fraction was used for electricity generation, the authors report a potential to save greenhouse-gas emissions worth 55 g CO_2 equivalent MJ^{-1}. Otherwise it can, due to its recalcitrance, constitute a valuable contribution to SOC if returned to the soil, as also noted, but not accounted for, by the authors. C5-molasses may be used to feed livestock or generate energy through anaerobic digestion, displacing in either case other production or energy use. This fraction is not accounted for at all. The feed fraction from corn residue ethanol is reported to make up ~17% of the total greenhouse-gas displacement potential from cellulosic ethanol production[4].

The analysis by Liska *et al.* shows that growing corn after corn, in itself, reduces SOC, and that the harvest of residues accelerates SOC loss. Owing to the exponential decay of carbon in soil (Supplementary Fig. 1 in ref. 1), time, so to speak, dilutes the average annual carbon emissions[5]. While Liska *et al.* chose a 5–10-year time perspective in their analysis, the IPCC recommends a 20-year perspective[6], the same as the European Union Renewable Energy Directive[7]. And much LCA work applies a 100-year time perspective[5]. Applying any of these time perspectives to the analysis of Liska *et al.* would reduce the greenhouse-gas impact of cellulosic biofuel and render cellulosic biofuels capable of reducing CO_2 emissions and perhaps even meeting the Renewable Fuel Standard reduction target.

Loss of SOC from biofuel production is a critical issue for greenhouse-gas emissions and soil quality, and it should be addressed in both science and management. But it is highly important that all biogenic carbon is included in greenhouse-gas analyses and that relevant time frames are applied, which is not the case for the analysis by Liska and co-authors. ❐

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To the Editor — The claim by Liska *et al.*[1] that corn stover-derived ethanol can be worse than gasoline has generated lots of media interest, but offers little value to the research community or to policymakers. They have merely demonstrated that if you model an irresponsible and unsustainable scenario, the results will look irresponsible and unsustainable. No one who has given serious thought to crop residues for biofuels would find their proposed across-the-board 6 Mg ha^{-1} collection rate in the US Corn Belt at all reasonable.

A decade ago, Sheehan *et al.*[2] used soil carbon and life cycle assessment (LCA) modelling to show that corn stover for ethanol would only make sense if farmers simultaneously adopted conservation tillage practices and constrained removal rates to account for local yield, soil, climate and topographical conditions. Numerous other field and modelling studies[3–6] have shown that soil carbon levels can be maintained with conservation tillage and moderate stover removal.

In contrast, Liska *et al.* applied a very simplistic soil carbon model that ignores important variables such as soil moisture and soil texture — making regional extrapolations highly questionable — and doesn't allow for varying management practices. This is an important shortcoming, as farmers can reduce their tillage intensity with stover harvest, saving money, without compromising yields[7]. Figure 1a illustrates these weaknesses when net changes in soil carbon emissions are modelled with DayCent[8] (the analysis was using the DayCent model version used in the most recent US national greenhouse-gas emissions inventory: www.epa.gov/climatechange/ghgemissions/usinventoryreport.html) for the Mead, Nebraska site in Liska *et al.*'s study.

The results for 50% stover removal at this site are consistent with the 6 Mg ha^{-1}

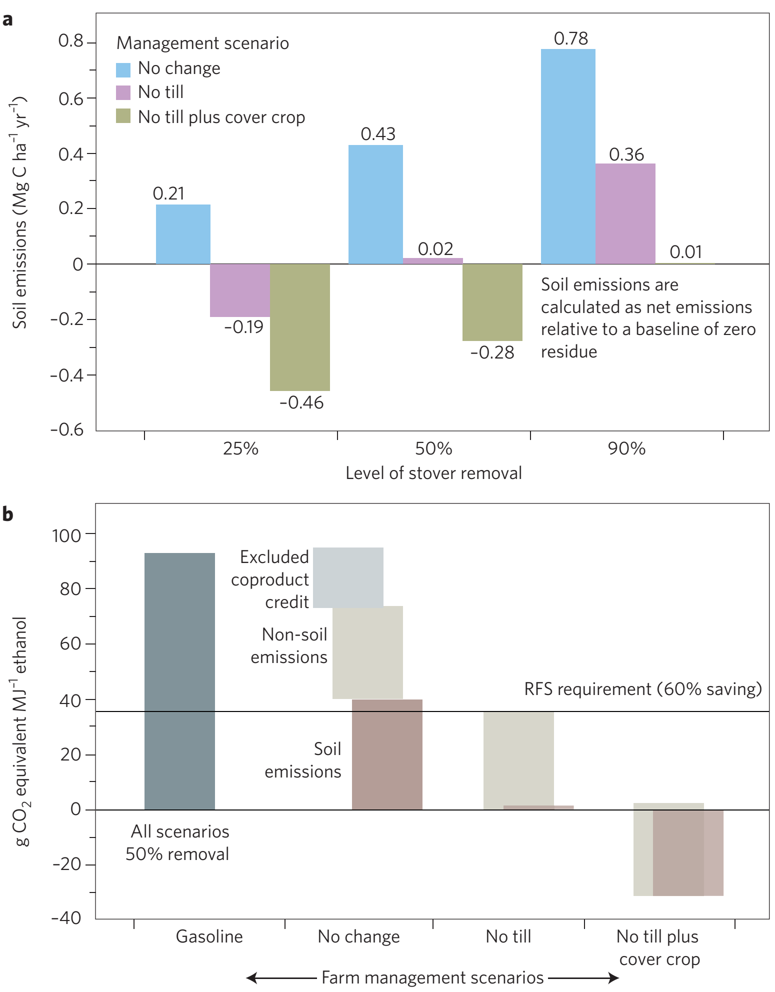

Figure 1 | Net soil carbon emissions and net life cycle greenhouse-gas emissions associated with crop residue removal and tillage practices. **a**, Net annual soil carbon emissions for three levels of stover removal and three management scenarios (that is, no change, adoption of no-tillage and no-tillage plus cover crop) simulated for the Mead, Nebraska site using the DayCent model[7]. Values are averaged over a 10-year period. **b**, Life cycle assessment results using soil carbon emissions from the 50% stover removal results for Mead, Nebraska combined with non-soil emissions (from ref. 8) and with and without taking lignin coproduct credit for electricity generation. RFS, renewable fuel standard.

collection scenario used by Liska and co-authors. With a continuation of existing tillage practices, soil carbon losses over the first 10 years average 0.43 Mg C ha^{-1} yr^{-1}, comparable to the value of 0.47 Mg C ha^{-1} yr^{-1} reported by Liska and co-workers. Adoption of conservation tillage reduces soil carbon losses to almost zero, while including a cover crop can yield net soil carbon increases.

The problems with the scenario of Liska *et al.* do not end at the farm. They took another extreme position by ignoring the carbon savings associated with coproduct electricity in the conversion facility. Figure 1b puts their assumptions for the farm and the biorefinery in an LCA context. Non-soil carbon emissions are taken from a recent LCA by the US Department of Energy's National Renewable Energy Laboratory[9]. Here, we focus on the 50% collection scenario in Fig. 1a. Combining the assumptions of unchanged tillage and no electricity credit made by Liska *et al.*, we too can generate a carbon footprint that is slightly worse than that of gasoline. Adoption of conservation tillage and proper accounting of the coproduct credit brings the footprint of ethanol below the Renewable Fuel Standard requirement for advanced biofuels. Adopting cover-crop strategies could make ethanol almost carbon neutral.

The study by Liska *et al.* is symptomatic of a broader problem in the realm of LCA. Had they followed International Organization for Standardization standards[10] and engaged stakeholders in the design of this study, instead of unilaterally making extreme and unsustainable assumptions, they might have ended up evaluating more useful scenarios. This is a mistake all too commonly found in the LCA literature. ❐

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To the Editor — Liska *et al.*[1] concluded that removing corn stover for cellulosic biofuel production is more CO_2 costly than gasoline by using a first-order kinetics soil organic carbon (SOC) model that uses residue age and temperature to predict SOC loss with changes in stover removal. The model was tested with data from a single site that is largely unrepresentative of other Corn Belt soils: a highly productive irrigated no-till corn experiment in Mead, Nebraska, where SOC even with very high yields and all residue retained lost 4.6% of its SOC stock over a four-year period (Supplementary Table 2 in ref. 1). The model was then used to extrapolate results across the US Midwest to conclude that stover removal in general reduces SOC in Midwest soils.

These findings diverge sharply from predictions made by process-based SOC models that also incorporate soil texture and water content to resolve SOC changes with crop management. These models[2–4], well constrained and broadly tested in a wide variety of soils, climates and cropping systems in the Midwest and elsewhere, almost universally predict stable or increasing SOC with full residue retention under no-till management in Midwest soils[5]. Soil inventory models[6] also show stable or increasing SOC across the Midwest, as do global inventories[7]. We are unprepared to explain the basis for the anomalous behaviour of the Mead, Nebraska site, but a very low root-shoot ratio of ~0.07 (Supplementary Table 3 in ref. 1), which likely underestimates root carbon inputs, may explain part of the difference, as might irrigation, which can accelerate decomposition.

Furthermore, under no-till management scenarios that remove a substantial proportion of corn residue, process-based models typically predict stable long-term SOC stocks on conversion from standard tillage. In one such study[8], for example, the DayCent model estimated that up to 70% of corn stover can be removed from a typical Iowa soil without SOC loss. These patterns can be explained in part by the disproportionate contribution of roots to stabilized SOC[9] and in part by a more realistic characterization of decomposition rates under different soil × climate conditions. While we agree with Liska *et al.* that full residue removal without cover crops will likely deplete SOC over the long term — although at a much lower rate than they estimate — this is an unrealistic scenario: we are not aware of any management practices for corn grain production that prescribe 100% stover removal.

Finally, while we agree with the motivation that underlies their analysis — there is a pressing need to understand the full climate impact of biofuels in general and stover removal in particular — we believe that this is best achieved with efforts that are based on our full understanding of carbon turnover in agricultural soils, and not on models that unduly simplify important relationships.

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Reply to 'CO$_2$ emissions from crop residue-derived biofuels'

Liska *et al.* reply — The soil organic carbon (SOC) model that we used[1] was parameterized with data from arable land under normal farming conditions in North America, Europe, Africa and Asia[2], but the equation is insensitive to changes in tillage, soil texture and moisture. The model has reasonable accuracy, however, in predicting changes in SOC, residue remaining and CO$_2$ emissions from initial SOC, carbon inputs from residue, and daily temperature[1,2]; the shoot-to-root ratio used in the geospatial simulation was 0.29 (that is, root carbon is 29% of total aboveground carbon), which did not underestimate carbon input to soil (Supplementary Fig. 2 in ref. 1). There is more theoretical confidence in the conserved nature of SOC oxidation due to temperature[1–5] relative to other factors such as tillage[6–8]. In a recent comparison of three SOC models (CENTURY, DAYCENT and DNDC), predictions were close to or within the range of uncertainty of estimates derived from soil measurements, showing that these models tend to produce similar results from residue removal[5]. (A range of soil measurements have also shown net SOC loss from residue removal[1,5].) The model also agreed well with CO$_2$ emissions measurements from an AmeriFlux field site[1], which since 2000 has been funded with $7,370,000 from the US Department of Energy, the US Department of Agriculture and NASA, leading to over 85 peer-reviewed publications.

The question for life cycle assessment (LCA)[1] is: what is the net change in SOC compared with a counterfactual situation where residue is not removed? It seems that the logic of this question has not been recognized by the US Department of Agriculture[9] or US Department of Energy[10]. Simulations with 2, 4 and 6 Mg ha^{-1} yr^{-1} residue removal in the Corn Belt, corresponding to ~25, ~50 and ~75–100% of corn residue produced in a single year, respectively, each resulted in a net SOC loss compared with no removal, which is difficult to measure in soil in less than 5 years but can be estimated confidently using models[1,3,5]. Importantly, when SOC losses are normalized for the energy in the biofuel derived from residue, roughly equivalent CO$_2$ intensities are estimated regardless of the amount of residue removed (Fig. 2c in ref. 1) — a central finding of our research.

The question for LCA is also not: how could these systems be in the future? The question is, however: how are these systems performing now, and how are they going to perform in the near term? The lignin coproduct is burned to provide energy for biofuel processing, and currently no electricity exports or other coproducts exist in the Poet's Liberty project (http://poet-dsm.com/liberty). Potential electricity output from burning lignin could also be 69% lower than the estimate previously provided (that is, −17 g CO$_2$ equivalent MJ^{-1} versus −55 g CO$_2$ equivalent MJ^{-1})[1,10]. The lignin oxidized in biofuel processing is the SOC that is lost, because that lignin would have oxidized more slowly in soil[1–4].

Standards for LCA are under development and in a state of flux. Owing to the complexity of LCA, a wide range of values can be produced in these assessments due to arbitrary variability in spatial and temporal parameter values, modelling assumptions, timeframes and system boundaries[11,12]. Consequently, our analysis focused on quantifying uncertainty in one primary variable: net SOC loss to CO_2 from residue removal[1]. The 30-year time interval precedent set by Searchinger *et al.* is arbitrary and biases results in favour of biofuel producers[12,13]. Precedents used by the US Environmental Protection Agency may not favour near-term emissions reductions, and existing precedents will probably be revised. To accurately represent current climatic conditions and SOC dynamics, temperature measurements from 2001 to 2010 were used[1], because older data do not represent increased temperatures and future projections are more uncertain. The model[1], however, was also used to estimate SOC changes from 2010 to 2060 with estimated increases in crop yields and temperatures from the IPCC's Fifth Assessment Report climate simulations (representative concentration pathway 8.5 emissions scenario)[14]. When compared with no residue removal, removal of 3 Mg ha^{-1} yr^{-1} of residue from continuous corn was estimated to lose ~0.22 Mg C ha^{-1} yr^{-1} on average in the first 10 years in three counties in Nebraska and Iowa; for the first 30 years, this value was reduced by ~52% on average to ~0.11 Mg C ha^{-1} yr^{-1} (ref. 14).

Yet, to dilute SOC emissions over 30 years or more does not represent actual CO_2 emissions over the first 10 years, and presenting longer-term lower values can be deceptive. Sanchez *et al.* noted, "Policymakers may find it appropriate to focus on more certain, near-term climate impacts, in which case a short horizon for fuel warming potential is sufficient."[12] If residue is removed for biofuel, these systems could produce more CO_2 emissions than gasoline for more than 10 years (ref. 1) and then possibly reduce emissions in 20 to 30 years, after agricultural SOC stocks have significantly decreased and crop yields have probably declined. Alternatively, SOC loss from residue removal can be widely recognized, and appropriate management can be used to compensate for lost carbon and increased CO_2 emissions[1]. ❐

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CORRESPONDENCE:

Lessons learned from geoengineering freshwater systems

To the Editor — Our ecosystems and the services they provide are increasingly being degraded by multiple and interacting pressures. Humans are using geoengineering to mitigate their effects, even though it commonly addresses acute symptoms of single pressures. Barrett *et al.*[1] discuss the benefits, problems and geopolitical consequences of proposed geoengineering to alleviate the effects of climate change by injecting sulphate into the stratosphere. This is an untried, global measure, the efficacy of which is difficult to predict[2]. However, geoengineering is already being applied in fresh waters, at smaller scales, using additives to alleviate the effects of either local nutrient enrichment or regional acid deposition[3]. Lessons from these and other freshwater management experiences provide empirical evidence to reinforce the conclusions of Barrett *et al.* Here, we highlight the need to consider feedbacks between ecosystems and the pressures acting on them beyond the potential interactions in their Fig. 1.

Barrett *et al.*[1] discuss various environmental problems that stratospheric sulphate injection cannot solve, such as Antarctic ice loss and indirect effects on precipitation. Similarly, in fresh waters, phosphorus reduction using geoengineering will not alter the widespread effects of nitrogen enrichment[4]. Barrett *et al.*[1] point out that geoengineering will not return the climate to past conditions. The same is also true in lakes for phosphorus removal, and for natural or artificial recovery from acidification, where multiple pressures produce novel ecosystems[5]. Mitigation of climate change by sulphate injection could reduce the pressure on politicians to lessen carbon emissions. In fresh waters, there is a similar concern that geoengineering will reduce the pressure on regulators to manage nutrient loss from the catchment[3].

These limitations seem to be common across scales, but there are also positive and negative feedbacks of geoengineering that are difficult to predict. For example, a cooled climate may alleviate eutrophication symptoms in fresh waters, such as cyanobacterial blooms or the effects of rapid expansion of non-native species from warmer areas[6]. A decrease in phosphorus following rapid phosphorus control using geoengineering in fresh waters is likely to favour a decrease in methane ebullition from lakes to the atmosphere[7]. Altering weather may change catchment productivity, which is also linked to carbon dioxide losses to the atmosphere from lakes[8]. Both climate mitigation and phosphorus control are likely to reduce coastal fish stocks, compounding the negative socioeconomic effects of overfishing[9].

Management of climate systems may cause geopolitical problems that benefit