regimes[5]. Further, in a carbon-constrained world, both biomass producers and electricity generators will have competing claims concerning monetization of their low-carbon attributes.

Sectoral accounting is further complicated by the timing of emissions in the biomass electricity lifecycle. Power generation releases CO_2 that was previously sequestered — and an implicit assumption made by Sanchez *et. al.* is that harvested biomass provides room for re-growth and sequestering of released emissions. This assumption, however, raises two problems.

First, if regrowth does not occur, net emissions will increase, even if CCS confines the majority of emissions. Measurement and verification are needed to ensure biomass is regrown and net negative emissions actually occur.

Second, the rate of CO_2 uptake from biomass fuel sources varies considerably. Trees — the dominant source of utility-scale biomass fuel today — grow over decades with different CO_2 uptake rates at different ages and across species. Ricke and Caldeira recently found that the climate impact of CO_2 emissions could occur in as few as 10 years[6]. The CO_2 released by uncontrolled biomass burning can thus contribute to short-term radiative forcing before CO_2 is sequestered by regrowth.

The concerns we raise suggest that additional, nuanced, and refined research is needed to improve our understanding of carbon flows in BECCS, develop efficacious legal regimes for CO_2 emissions reduction ownership, and design successful monitoring regimes for biomass regrowth. Only then can the future role of bioenergy and BECCS be more fully contextualized and appreciated. ❒

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Reply to 'Emissions accounting for biomass energy with CCS'

Sanchez *et al.* reply — Our Letter[1] assesses the impact on regional carbon emissions if biomass energy is used to replace fossil fuels in the electricity system, and carbon capture and storage (CCS) is used to sequester most of the emissions associated with electricity production. Our bioenergy assessment prioritizes, but does not rely solely on, bioenergy production from wastes and residues, which do not compete with food crops and would otherwise be burned or left to decompose, releasing their carbon into the atmosphere as CO_2. Most of these feed stocks minimize the impact of biomass regrowth and uptake rates. For feed stocks such as forest residues that may take many years to grow back, there will be some amount of short-term radiative forcing that was not accounted for in our analysis.

As Gilbert and Sovacool suggest[2], it is important not to count the same CO_2 emissions reductions in two separate sectors when quantifying economy-wide emissions. Our analysis avoids this accounting error by using a simplified methodology, ascribing all changes in atmospheric CO_2 — from plant growth to combustion in a bioenergy and CCS (BECCS) plant — to the electricity sector. Should BECCS be adopted widely, it will be important to allocate emissions credits among all relevant actors across sectors.

Several forms of complementary analyses inform roadmaps for sustainable bioenergy production. In addition to the bottom-up engineering-economic analysis performed in our Letter[1], our team at the Renewable and Appropriate Energy Laboratory at UC Berkeley, USA, and others, have engaged in commodity-chain theoretical bioenergy analysis, producing quantitative indirect land-use change estimates[3], and evaluations of previous efforts through meta-analysis[4]. Based on this work, we agree with Gilbert and Sovacool[2] that monitoring and verification should be a critical part of any long-term strategy for mitigating climate change. Of particular concern is whether the cultivation or extraction of biomass for energy will degrade or enhance the ecological productivity and related carbon flows of the land[5].

Each step of energy extraction, preparation, combustion, and disposal demands a rigorous assessment of carbon impacts. This statement applies not only to bioenergy, but also carbon capture technologies. In addition to oft-cited concerns about sustainable bioenergy production, risks of CO_2 leakage from long-term geologic sequestration raises additional uncertainties about BECCS and other CCS strategies[6]. However, the choice of counterfactual is critical to any bioenergy analysis, including assumptions of population, future diet, and crop productivity[7]. Recent research shows that biofuel production can provide emissions benefits over non-bioenergy land-use decisions, including forest recovery on marginal land[8]. Geologic storage of carbon through CCS can proceed for decades and potentially millennia if properly managed, which may be more stable than other carbon sequestration options from biomass. The emissions benefits of BECCS — encompassing displaced fossil-fuel CO_2 emissions from energy production and geologic CO_2 sequestration — may improve the desirability of biomass production for bioenergy over other land-use decisions, but more research is needed to directly compare it with other sequestration strategies. Moving forward, supportive policy should incentivize land-use decisions that are beneficial for the climate[9]. ❒

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