Title

Biomass enables the transition to a carbon-negative power system across western North America

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of adaptation. It is further essential to understand the interdependence of barriers within and across scales.

Importantly, and this may be where we truly differ in our thinking from Biesbroek and colleagues, the barriers concept does not imply a top-down or simplistic linear framing of adaptation decision-making. Some case studies, for example, show how grandfathered water-use rights can impede autonomous adaptation by local and private actors[4–6]. Such water rights might stem from governmental policies or might be old traditions of self-organized user communities. Adjustments of such social norms or institutions are messy, non-linear and complex. We think that comparative research would be worthwhile to explain under which actor- and context-specific conditions grandfathering rights systematically support or impede adaptations. Numerous further studies now analyse barriers with approaches that acknowledge complexity, unforeseen contingencies and dynamic processes[7–11].

Biesbroek *et al.* further suggest that focusing research on barriers implicitly entails the normative assumption that decision-making should result in adaptation. Quite to the contrary, we overtly decouple the definition of barriers from the discussion of adaptation success: "a 'barrier to adaptation' is (1) an impediment (2) to specified adaptations (3) for specified actors in their given context that (4) arise from a condition or set of conditions. A barrier can be (5) valued differently by different actors, and (6) can, in principle, be reduced or overcome"[1]. We thus explicitly state that barriers are in the eye of the beholder, and that some actors may well welcome perceived barriers. There is no claim that valuations are shared and conflict-free between actors. Thus, barrier research can deal with the issues raised by our colleagues in an analytically rigorous and practically relevant way without being tied to one particular normative view.

We appreciate the Correspondence from Biesbroek *et al.* for emphasizing three aspects for furthering the research agenda on barriers to adaptation. First, we wholeheartedly agree that a better understanding of real-world adaptation policy and decision-making processes is absolutely essential if science is to explain barriers adequately and — maybe more importantly — usefully inform these societal processes. Second, research on identifying, explaining, and thus helping to deal with barriers, is not the same as adopting a functionalistic black-box approach. The barriers concept is compatible with nuanced frameworks and theories of decision-making from different disciplinary perspectives, as many examples of published research have shown. Better use should be made of existing frameworks and theories in future adaptation research, for example from political, decision and cognitive sciences. Third, in our view, discarding the concept of barriers to climate change altogether would risk losing an important device for fruitful interaction: barriers serve as a 'boundary object', intuitively and widely understood by both practitioners and scholars from different disciplines. This fosters a key priority for the future: collaborative and comparative research that enhances trans-disciplinary learning across cases, about empirically proven ways in which particular actors can deal with particular barriers to adaptation. This promises to be real-world research of potentially high academic and societal value. ❐

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CORRESPONDENCE:

Emissions accounting for biomass energy with CCS

To the Editors — Sanchez *et al.*[1] provide a viable technological roadmap for using biomass energy with carbon capture and storage (BECCS) in the western United States[1]. However, they oversimplify emissions accounting by assuming a zero or negative carbon emissions factor. Accounting for total lifecycle emissions is perhaps the greatest challenge in deploying biomass (in solid, gaseous, or liquid form) to reduce carbon emissions[2,3].

When utilized to generate electricity, emissions sinks and sources for biomass occur in two different sectors. As plants grow, they take up CO_2 and store it. When combusted, the stored CO_2 is released and contributes to emissions. Accordingly, counting the emissions factor for biomass electricity generation as zero, or negative in the case of BECCS, causes double-counting of emissions on a cross-sectoral basis[4]. These accounting challenges persist when developing national or international carbon control 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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