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Rapid scale-up of negative emissions technologies: social barriers and social implications

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Abstract Negative emissions technologies have garnered increasing attention in the wake of the Paris target to curb global warming to 1.5 °C. However, much of the literature on carbon dioxide removal focuses on technical feasibility, and several significant social barriers to scale-up of these technologies have been glossed over. This paper reviews the existing literature on the social implications of rapidly ramping up carbon dioxide removal. It also explores the applicability of previous empirical social science research on intersecting topics, with examples drawn from research on first- and second-generation biofuels and forest carbon projects. Social science fieldwork and case studies of land use change, agricultural and energy system change, and technology adoption and diffusion can help in both anticipating the social implications of emerging negative emissions technologies and understanding the factors that shape trajectories of technological development. By integrating empirical research on public and producer perceptions, barriers to adoption, conditions driving new technologies, and social impacts, projections about negative emissions technologies can become more realistic and more useful to climate change policymaking.

Keywords Carbon dioxide removal · Negative emissions · Food systems · Direct air capture · BECCS

1 Introduction

Scenarios in the fifth Intergovernmental Panel on Climate Change (IPCC) report rely upon the use of "negative emissions" technologies to maintain less than 2 °C of warming; in particular, they anticipate widespread deployment of bioenergy with carbon capture and sequestration (BECCS) (IPCC 2014; Fuss et al. 2014; Gasser et al. 2015). Negative emissions technologies

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(NETs) are in varying, speculative stages of development. Yet they are implied in meeting the ambitious 1.5 °C target set in Paris. This critical role of negative emissions has alarmed scientists, provoking commentaries on the feasibility of these scenarios and calls for climate researchers to be candid to policymakers about the tight carbon budget (Anderson 2015; Geden 2015; Peters 2016; Williamson 2016).

What would a rapid scale-up of NETs entail? How would a successful scale-up transform society? There are few integrated analyses of the “technological, economic, social, and cultural pathways to get to 1.5°C, or about the implications of a massive expansion of negative emissions technologies”, observed Mike Hulme (2016). Of those few analyses, the social and cultural analysis is particularly limited (work in the special issue of this journal edited by Tavoni and Socolow 2013, is a notable exception). Many factors contribute to this lack of analysis: there are inherent uncertainties in the technologies and in the future that make declarative “results” difficult, and methods in the social sciences lend themselves to the study of currently-existing phenomena rather than future prospects. Social implications like changes in food security, concentration of land ownership, or resource access dynamics at community or household levels require difficult or expensive-to-gather data to understand in the present, and are even more challenging to anticipate in the future.

Thus far, the primary aim of studies on carbon dioxide removal is typically to calculate the potential that these methods can offer. Lines of inquiry begin from that starting point, bringing in social implications as difficult-to-quantify side issues later in the conclusion or discussion sections of the work. This work generates crucial insights and cautions about material issues that *will* have social implications, like fertilizer use and bioenergy crop yields (e.g. Creutzig et al. 2015, Smith et al. 2015). Yet a focused discussion of both social barriers and implications of the rapid scale-up of carbon dioxide removal is notably absent.

If the claims that NETs will be necessary to reduce climate damages are credible, the lack of social research is remarkable, since understanding the social dynamics is key to making these futures actually happen. A genuine evaluation of the social feasibility of large-scale carbon dioxide removal needs to be made if society is serious about comparing these technologies with other large-scale mitigation approaches, in order to make public and private decisions about what to invest in and design policy accordingly. On one hand, the research community could simply continue to acknowledge the vast social and political uncertainty around NETs. However, this may lead to “analysis paralysis”, which risks “losing valuable time and helping to self-fulfil the prophecy that GGR cannot be realized at scale”, as Lomax et al. (2015a) point out. Another course could be to use the already-existing body of empirical social science studies on related topics to understand the social implications and challenges to scaling up NETs. “Empirical” here simply means evidence-based: evidence from analogue case studies, from discourse, from commodity chain analysis, from the conventional suite of social science methods like interviews, surveys, focus groups, and other means of gathering social data. Evidence from the ground can indicate factors which biophysical and large-scale economic models may not be able to include, such as corruption, landowner preferences, not-in-my-backyard-ism, household and inter-community inequalities in land or food access, to name just a few. This paper aims to lay the groundwork for such an analysis by first reviewing the existing literature on the social implications of NETs. Then, selected examples from fields like environmental sociology, agricultural development, and science and technology studies are reviewed, to further understanding of what a rapid scale-up of NETs would entail.

2 Roles for social science research on NETs

Social science can contribute to discussing (1) public understanding and acceptability of NETs, including how NETs come to be understood and defined by society, (2) barriers to deploying or scaling up NETs, including what factors are shaping the technology as it develops, and (3) the social implications of a rapid scale-up of NETs, including changes in social relations. Within "social science", there are a range of relevant fields and sub-fields— environmental sociology, communications, anthropology, human geography, political ecology, science and technology studies, international development, each with a range of methods. Some methods, like scenario and foresight exercises, are better for understanding implications of the more speculative emerging technologies.

Can social implications emerging technologies be anticipated? "Typically it is only as a technology is rolled out into society that one can get a firm grip on the timing and strength of side effects, the operation of countervailing forces, and the mobilization of direct opposition", writes Meadowcroft (2013), who cites biofuels and wind energy as examples. This is mainly true, yet there are numerous case studies of precedents and analogues to draw upon, and because most NETs have known component technologies, it should be feasible to get a handle on some "side effects". Because technologies are not simply forces that are rolled out— rather, they are shaped by human choices throughout their (often non-linear) development— doing such social inquiry at all stages of development is useful. Moreover, technologies develop along with societies: Meadowcroft helpfully points out that CDR approaches should not just be assessed from the perspective of their mitigation potential (tons removed over time), but also by "asking what sort of societal development trajectory they imply", noting that "a civilization that employed large scale afforestation and reforestation, for example, would look very different from one that declined this option; widespread BECCS implies an extensive bio-energy economy, and so on" (Meadowcroft 2013). Taking account of social contexts is crucial in anticipating technological development.

What social science research on NETs already exists, and how comprehensive is it? There is virtually no social science literature on the non-biological technologies (direct air capture, enhanced mineral weathering). This may be because non-biological methods are seen as distinct technologies to be rolled out, compared to biological carbon dioxide removal, which is more obviously embedded in socio-technical systems. However, the scale-up of an entirely new infrastructure or industry with either direct air capture (DAC) or enhanced weathering (EW) would warrant serious social research. Drawing down 50 ppm of atmospheric CO_2 with enhanced weathering could cost \$60–600 trillion for mining, grinding, and transporting rock, with further similar costs for distributing it (Taylor et al. 2016). A global enhanced weathering industry that sequesters 1Gt CO_2-C per year may have an energy demand equivalent to 0.7–19.4 % of global energy consumption (Hartmann et al. 2013). The governance and implementation barriers to distributing these amounts of rock are massive— some of the tropical lands signaled by models as geologically suitable for enhanced weathering are in places like the Democratic Republic of the Congo (Moosdorf et al. 2014), where institutional infrastructure for promoting adoption of new land use practices is limited. Direct air capture would also have high costs and substantial energy requirements (McLaren 2014); in some analyses, powering DAC with gas or coal would be pointless as more emissions would be generated than captured. The direct land footprint of DAC is low, but optimally emissions-free DAC implies large renewable energy resources, which may have been used for other purposes, and which may require large amounts of land. For example, for the U.S. to sequester ~13GtCO_2/

yr., roughly 100,000,000 acres of land in the Southwest United States would be required for the solar energy to make it emissions-free (NAS, 2015). Moreover, much of the current industrial infrastructure society enjoys was built in a time where infrastructure was valued as a source of national pride; today, in a fuller world, infrastructure has a new politics and is much more contestable. In sum, new industries of air capture or enhanced weathering would indeed be shaped by society, with opportunities but also considerable challenges. However, because literature on the social barriers, implications, or perception of DAC and EW has not yet emerged, we will turn to examining social research on the other technologies.

2.1 Research on biological NETs

Modeling studies on biological NETs (terrestrial or marine carbon sequestration) often point to the need for more social research. There is virtually no social science literature about microalgae biofuels or macroalgae sequestration, and just a few studies of “blue carbon” sequestration in coastal ecosystems (e.g. Wylie et al. 2016). Much attention has gone to terrestrial sequestration, particularly BECCS. Concerns identified with BECCS include land requirements, input requirements, freshwater requirements, and tradeoffs for food and fiber production (see e.g. Creutzig et al. 2015). For example, using dedicated high-energy crops (willow and poplar short rotation coppice and *Miscanthus*), Smith et al. found that achieving 3.3 Gt Ceq yr. − 1 of negative emissions would require a land area of approximately 380–700 Mha in 2100, which represents 7–25 % of agricultural land in 2000, and 25–46 % of arable plus permanent crop area (Smith et al. 2015). Both BECCS and afforestation and reforestation would have land demands 2–4 times larger than land identified as abandoned or marginal, and thus the use of these techniques on productive land would impact the amount available for food production and other ecosystem services (ibid). BECCS could increase groundwater reserve tapping, reduce access to clean water, and divert water from ecosystems. Moreover, BECCS would consume a significant portion of the world’s fertilizer supply: an estimated 17–79 Tg N y^{-1} applied per sequestered Pg C y^{-1} could represent up to 75 % of global annual nitrogen fertilizer production (Smith and Torn 2013). Phosphorous availability is another consideration, as this resource is limited and subject to price spikes, with reserves concentrated in just a few nations.

How do these biophysical projections “translate” into social impacts? Writing about bioenergy broadly, Creutzig et al. (2013) point out that modeling studies of bioenergy potential are deficient in two ways: firstly, social impacts are measured in terms of economic efficiency, economic growth, and occasionally food prices, which leaves out important dimensions of human wellbeing like change in socio-economic and health conditions; secondly, the high level of spatial aggregation makes place-specific drivers and distribution of impacts among social groups and regions invisible (Creutzig et al. 2013). The translation from model results to social impacts is not straightforward, which is where empirical social science research could be helpful. A handful of studies address expert and public perceptions of BECCS. Lomax et al. (2015b) conducted twelve semi-structured interviews with experts, who caution about systemic technology “lock-out” due to reasons of technology choice, infrastructure development, resource supply (for biomass and biochar), and capacity and skills. Vaughan and Gough report on a deliberative workshop about BECCS feasibility, finding that social acceptability was likely to be a barrier, though there was little consensus on the magnitude (Vaughan and Gough 2015). Dowd et al. (2015) review the public opinion research on bioCCS and discuss social license to operate, with the key question of whether or not the public opinion challenges of

CCS will apply to BECCS, noting that BECCS might receive more public support than its component technologies do individually. While social research on BECCS is limited, CCS has been well investigated.

2.2 CCS research

Underpinning both BECCS and DAC is carbon capture and storage, which has been the focus of a relatively large body of social science research since 2005; see for example the edited collection *The Social Dynamics of Carbon Capture and Storage* by Markusson et al. (2012a), or the special issue on the politics and policy of CCS in *Global Environmental Change* edited by Bäckstrand et al. (2011). Two foci in this literature are 1) public acceptance and 2) economic modeling of deployment options (Markusson et al. 2012b). This is largely still the case at the time of writing this article. Markusson et al. also point to a small literature on CCS innovation and technology development, such as learning curve analysis, which tends to borrow from cost trends in other technologies (Markusson et al. 2012b). Why has carbon capture and storage, a technology considered necessary in climate assessments, had so much difficulty in getting off the ground? Barriers include the lack of government action, public concerns about storage, low carbon prices and advances in alternative renewable technologies (De Coninck and Benson 2014). Other key questions revolve around whether CCS will be an “add-on” technology, or a broader part of a hydrogen economy (Shackley and Thompson 2012), or whether it creates fossil fuel “lock-in” (Vergragt et al. 2011). These types of questions are relevant to the scale up of DAC and BECCS as well. Areas for further research identified by Bäckstrand et al. (2011) were the synergies and tensions between CCS and renewable options; public dialogue and choice; and work in developing countries, including technology transfer and risks in the context of fragile political institutions. These are all crucial areas for further inquiry within the contexts of DAC and BECCS.

3 Bringing in insights from empirical studies of intersecting topics

This paper will examine two cases of relevant literature from other fields: empirical studies of the recent biofuel boom, and studies of forest carbon projects. These are clearly more relevant to biological NETs, and were chosen to illustrate the depth and breadth of work being done here. Equally interesting to bring in would be studies of biochar projects (Leach et al. 2012) and agricultural sequestration efforts (e.g. Swallow and Goddard 2013). There are also case studies of energy system transitions and infrastructure scale-ups that could help analysts understand a scale-up of a DAC industry. For example, with regards to the CCS part of DAC, Rai et al. (2010) studied analogue technologies of nuclear power, SO_2 scrubbing, and global liquefied natural gas, observing the decisive role of government, the credibility of incentives for investment in commercial-scale projects, and the weakness of the truism that experience with technologies inevitably reduces cost. Literature on the scale-up of renewables would also be particularly useful: for example, Iyer et al. (2015) examined constraints on diffusion of low-carbon technologies and review the historical diffusion rates of energy technologies. Here, though, the focus is on bioenergy and forest carbon, in order to illuminate: What social factors identified in the existing literature on bioenergy and forest carbon could shed light on the social dynamics of a rapid NET scale-up?

3.1 Biofuel booms and busts

Most, if not all, projections regarding BECCS assume second-generation biofuels: switchgrass, *Miscanthus*, poplar, crop or forestry residues, etc. Advanced biofuels would theoretically be free of the social concerns that first-generation biofuels came under fire for. Nevertheless, empirical studies of the most recent first-generation biofuel crop boom (late 1990s ~ 2010) are useful to understand future biofuel scale-up for two reasons. Firstly, the *speed* of land use change and infrastructure and policy development is an object of study. This wave of interest in ethanol and biodiesel produced from sugar, starch, and oilseed crops mirrors earlier waves of interest in the late nineteenth century and in the 1970s; however, the twenty-first century boom was also driven by concerns about agricultural stagnation and climate change (Kuchler 2014). Secondly, the failure of this earlier biofuel boom is still affecting prospects for a second. Advanced biofuels still have not received the breakthroughs they would need to be competitive, and while part of this is technological— cell walls in woody biomass evolved to be difficult to break down— part is certainly economical. Despite the cleanly demarcated terminology of "first" and "second", these are interrelated technologies.

There is no shortage of high-level assessment of first-generation biofuels. Much of this is framed in terms of sustainability and addresses various aspects: e.g. the UK's Gallagher Review of the indirect effects of biofuel production (Gallagher 2008); there are also numerous studies of livelihood impacts. Because this literature is vast, I want to do two things here: (1) point out some factors identified in this first-generation literature that have not been mentioned with regards to NETs, but may be quite relevant, and then (2) mention a few studies that are specifically interesting in terms of their focus on second-generation biofuels.

Empirical research on the first-generation biofuel boom reveals three related concerns: (1) the inflexibility of new relations of production, (2) speculative activity and "phantom crops", and (3) the actual status of "marginal" land. Biofuels for domestic use or export can represented employment opportunities, but income effects for growers depend on the model of feedstock cultivation: typical modes include plantations, contract farming or outgrower schemes, independent smallholder farming, and subsistence farming (Creutzig et al. 2013). The switch to cash crops and paid jobs may not be a net gain for rural peoples, since cash crops bring new vulnerabilities like dependency on world markets. For example, Van der Horst and Vermeylen cite the plight of Kenyan commercial rose farmers during the Icelandic ash cloud of 2010, who were stuck with a product that had no local demand (Van der Horst and Vermeylen 2011). They argue that "simplistic proxies" like the number of jobs or the average pay per worker cannot adequately measure the involvement of rural communities in producing liquid biofuels (ibid). In a six-country study of biofuel projects, German et al. report that most of the production models, "whether industrial-scale plantations or outgrower schemes, lock land and labor into relatively inflexible arrangements that hinder the potential to adapt to changing socioeconomic and market conditions" (German et al. 2011). In one example, a jatropha outgrower scheme in Zambia, focus groups and household surveys revealed one-sided contractual obligations that were signed by farmers but not the company, as well as provisions requiring farmers to keep land under jatropha for 30 years and sell only to the company— the risks were borne by the smallholders who could least afford them, instead of the behind-the-scenes investors promoting the scheme (German et al. 2011). Numerous examples of changing relations of production point to concerns not just about income and flexibility, but about repercussions on food security, gender equity, health, etc. To be clear, effects of new relations are not always negative: for example, Riera and Swinnen studied a case of castor biofuel contract farming in Ethiopia where positive spillover effects on food production occurred, perhaps due to better fertilizer access, improved soil quality from the castor, or technical assistance from extension agents (Riera and Swinnen 2016).

A second concern involves what Niemark et al. have dubbed the “phantom commodity”, or a commodity existing in a “parallel economy of expectations and appearances”, which is “used in company rhetoric and policy and development discourse, but does not materialize into any real market exchange or deliver on promised environmental and social benefits” (Niemark et al. 2016). Their case involves jatropha in Madagascar, where in 2011, the total amount of land intended for biofuels was roughly 800,000 to 1 million ha— but only about 60,000 ha were “reportedly” producing biofuels, and much land was classified in either preparation or temporary suspension phases of production (Niemark et al. 2016). A similar situation developed in Ethiopia, where government ministries offered investment licenses to 83 parties to produce biodiesel feedstock, but 3–5 years later, only 7.2 % had started production, and that on a limited scale; notably, state enterprises are producing much more (Shete and Rutten 2014). The concern is that speculative investments in “phantom production” is driving land prices upwards (Niemark et al. 2016). While modelers calculated impressive production potentials, some companies were merely interested in financial, speculative profits rather than the complicated work of producing new feedstocks in areas without advanced processing infrastructure and proximity to markets. Expectations and hype giving way to phantom commodities is a cautionary tale for development of NETs.

Without “ground-truthing” these investments and projects, it would be difficult to know about changing relations of production, livelihood impacts, or the phenomenon of phantom production. Similarly, it would be hard to assess the true uses of “marginal land”, which is often categorized using remote sensing methods. Fieldwork has shown that (1) much land classed as marginal is actually used in various ways (Nalepa and Bauer 2012), (2) the designation of “marginal” or “degraded” often is done for political reasons (Lyons and Westoby 2014), and (3) though biofuel crops can theoretically be grown in marginal land, or using rain-fed irrigation, growers may decide to use non-marginal land if crops do better there and profits will be higher. This is all highly relevant for second-generation biomass production, as it is projected to use marginal land. Notably, BECCS is imagined to use significant amounts of crop and forest residues, in which case the first-generation biofuel analogy would be less applicable.

The literature on second-generation biofuels is much smaller and more recent. It focuses less on impacts, and more on anticipatory issues of social acceptance and interest. Creutzig et al. suggest that for rural livelihoods, second-generation plantations would provide higher income and land rent compared to first-generation biofuels, but would again marginalize local people with informal land tenure, though they note that residues are promising for energy and livelihood improvement (Creutzig et al. 2013). However, very little research has been done on advanced biofuels and rural livelihoods in the developing world. Most research has focused on high-income countries and involves gathering social data from various groups: the public, experts, and producers. For example, Longstaff et al. (2015) reported on a deliberative democracy event about advanced biofuels in Canada, which discussed biotechnology and citizen participation in government policy. Also in Canada, Rollins et al. (2015) used a choice experiment to examine public opinion on planting genetically improved poplars on public lands, with the majority allowing it if the fiber is used for biofuels. Raman et al. (2015) employed stakeholder and expert interviews to assess the assumptions, values, and future visions around lignocellulosic biofuels in the UK, while Ribiero and Quintanilla used the

Delphi method to survey experts from several countries on the potential social impacts of cellulosic ethanol (Ribiero and Quintanilla 2015). Producer decision-making is also considered: Brunner et al. (2015) found that among 505 forest decision-makers surveyed in northern Michigan, 47 % would be willing to harvest trees for cellulosic ethanol feedstock, with most having non-market factors such as recreation, conservation, and “other worthwhile goals” part of their decision-making. Caldas et al. surveyed 1984 Kansas famers about their willingness to grow cellulosic biomass, and found differences between Eastern and Western Kansas, with farmers’ perceptions about risk and profits as a key factor in decision-making, compared to biophysical factors (Caldas et al. 2014). These studies— all from high-income nations— indicate that social factors play a large role in both public and producer decision-making. These results warrant more attention when thinking about a scale-up of terrestrial CDR, particularly when considering genetically modified feedstocks.

These three aspects of the first-generation scale-up — new relations of production, phantom commodities, and alternative uses of marginal land — were examined here because they are aspects not easily teased out from modeling studies. There are certainly other social implications of scaling up advanced biofuels, and perhaps more relevant ones. But these three offer an example of why the literature on first-generation biofuels is useful to bring in: it illustrates the gap between the promise of the technology and the reality on the ground when it is deployed, as well as what can happen on local scales. These results may darken the promise of projections regarding BECCS. Yet ideally, the three observations point to how policymakers could be smarter in designing incentives or devoting R&D funding for this new generation of biofuels, when the imperative is not just greener fuel but greenhouse gas removal.

3.2 Forest carbon projects

Afforestation is a way of enhancing the carbon sink, and there is a robust literature about how existing programs and projects attempt this. For example, Thomson Reuters Web of Science article citations in the Social Science database for “REDD” number 325; there are 114 articles for “forest carbon” + “social”. Many if not most of these are field-base case studies; some aggregate monitoring and evaluation information about REDD+ program effectiveness (e.g. Caplow et al. 2011). Impacts data is of varying quality, with indicators like employment more common than health or literacy (Caplow et al. 2011). Fieldwork can illustrate several social implications of afforestation. Here, two will be explored: changes in forest ownership and forest access, and concerns about who benefits from afforestation projects.

Crucially, people who currently use forests (for food, fuel, grazing, etc.) may not be the ones making the decision to afforest for carbon projects. They may not even be the owners, since nation-states own much forestland. In 36 of the world’s most forested countries, representing 85 % of the world’s forest estate, national governments have statutory ownership of 60 % of lands— a legacy of state appropriation in many countries (Sunderlin et al. 2013). State ownership varies regionally: governments have official control of about a third of Latin American forests, about two-thirds in Asia, and virtually the entire area in Africa (ibid.). This matters because people with communal or unclear land tenure may be displaced if governments launch forest carbon sequestration efforts. Some studies report limitations to access, which takes various forms. For example, Lyons and Westoby studied the largest plantation forestry operator in Africa, in Uganda, and describe restrictions on crop cultivation, grazing, bee keeping, and collection of firewood; the confiscation of animals that strayed into the plantation area, with expensive payments required to collect them; fines and jail time for "trespassing"; and destruction of burial sites (Lyons and Westoby 2014). Another broad governance problem with scaling up terrestrial carbon sequestration is that nation-states are not equally strong, cohesive, or efficacious. Recommendations in carbon-woody biomass literature may work using assumptions that a developing country government actually controls all the lands within its borders, while in reality its influence might meet resistance rather than compliance (Unruh 2011). Unruh's blunt assessment: "In reality the derivation and implementation of improved policies, laws, and 'will' in the developing world, particularly over large multicountry areas needed for carbon storage to be a mitigation option, are unrealistic within the needed time frame" (Unruh 2011). These disjoints between imagined forest projects where nation-states guarantee smooth operations and conditions on the ground can lead to both conflict in particular places and disappointment for remote policymakers.

Who benefits from existing forest carbon projects? In the Ugandan case study, foreign investors were the primary beneficiaries, as well as domestic power elites, company staff, and "local elites with 'special' access rights to graze animals and grow food crops within the license areas" (Lyons and Westoby 2014). Cases like this can be found elsewhere. For example, Niemark et al. studied a REDD readiness site in Laos, where higher status families were able to organize themselves and capture initial benefits, and chiefs and their families became local knowledge brokers on REDD+ and carbon trading (Niemark et al. 2016). Unruh identifies two complications regarding benefits: first, the benefits earned from forest carbon projects have to be compared with the counterfactual; second, people often interact with forest resources for immediate needs, while carbon storage is theoretically long-term, so there is a temporal mismatch (Unruh 2011).

What of social safeguards? Protections for forest people designed to deal with the above issues may have limited efficacy. Within the REDD+ framework, social safeguards for REDD-readiness mandate tenure clarification. The Climate, Community, and Biodiversity Alliance has established certification schemes to ensure biodiversity and community livelihood goals are met through REDD+ projects (e.g. standards) to ensure that biodiversity and community livelihood goals are met through just means while also reaching carbon mitigation goals; however, these standards are not always met (Suiseeya and Caplow 2013). As in the biofuel example, the disjunct between idealized reality and actual reality was recognized, experts attempted to intervene (in the biofuel case, by developing sustainable biofuel standards); then a literature evaluating the effectiveness of that intervention emerged. This literature offers a wealth of information for thinking about how the scale-up of carbon dioxide removal would deal with the issues of natural resource ownership and access and distribution of benefits.

The above examples draw largely from the developing world, but there are also helpful studies addressing forest carbon in countries where land ownership is clear. For example, in a survey of Australian landholders, relevant factors in their willingness to adopt afforestation for carbon sequestration included the design and social acceptability of afforestation, as well as the socio-demographic attributes, knowledge, skills, and experience of landholders (Schirmer and Bull 2014). Empirical research can suggest not just barriers to scaling-up carbon dioxide removal activities, but information to help target new projects.

4 Thinking beyond negative emission technologies towards carbon practices

With a carbon budget as tight as 590–1240 $GtCO_2$ from 2015 onward to have a likely chance of keeping global mean temperature below 2 °C relative to pre-industrial levels

(Rogelj et al. 2016), the stakes for understanding how society can scale-up carbon dioxide removal are quite high. The previous section identified several social aspects that would need to be confronted for a successful scale-up: (1) new arrangements of production of advanced biofuels or carbon commodities for biological sequestration; (2) the phenomena of speculation and phantom commodities as investment is scaled up, including the role of science and policy in creating or curbing speculative investment; (3) issues of informal land tenure and “marginal” land; and (4) the question of who accesses the benefits of new technologies. The existing empirical work on these factors in previous biofuel and carbon policy suggests a few recommendations for scientists, entrepreneurs, and policymakers hoping to scale up NETs.

Firstly, researchers and policymakers should examine intermediate scales. While modeling can illustrate global processes, strategies for scaling up CDR are going to be extremely context-specific, with local challenges. The regional level is a promising place to start bridging these scales. Few regional or national models have looked at NETs, with Sanchez et al.’s (2015) study of BECCS for power generation on the west coast of the US being an exception, and a blueprint for other studies (Bauer 2015). Another useful scale is the landscape level, as it can spur holistic thinking about ecological and social feedbacks (see Hunsberger et al. 2015). Regional and landscape-level expertise from environmental sociologists, anthropologists, and human geographers can illuminate challenges particular to local cultural dynamics. In regards to bioenergy, Creutzig et al. (2013) called for a comprehensive assessment by human geographers and agricultural economists to think about distributional livelihood effects and the particulars of biofuel deployment schemes, from crops to institutional arrangements and tenure schemes; they noted an “ample opportunity to soft-couple integrated assessment models with local livelihood analyses and CGE and partial equilibrium sector models”. This kind of work will be essential in transcending scalar disconnects between coarse models and local impacts for CDR.

Secondly, previous research on analogous and related technologies and projects suggests governments worldwide will need to employ a stronger hand in many aspects of the process of scaling up NETs — the market is not going to deliver outcomes that are good for broad swathes of societies without copious support and guidance. The research on the existing “social safeguards” for REDD+ and safeguards for allocating land to large-scale biofuel feedstock should be extended, as the current body of work suggests that voluntary guidelines are not to curb adverse effects of new land uses. Governments will need to provide clearer definitions of “marginal land” and revisit productive use requirements (Cotula et al. 2008)—both in terms of tenure security and avoiding phantom commodities. This stronger role of government involves, obviously, setting up a carbon price and revisiting energy subsidies. It also involves support for technologies to cross the valley of death from pilot-stage to implementation, training the workforce for new opportunities, as well as agricultural extension support and incentives for new land use practices. Moreover, this greater state involvement goes beyond what may immediately seem to be related to negative emissions technologies. Proceeding towards a greater economic valuation of carbon will not work without institutions that support livelihoods, good governance, and land tenure security in developing countries; current efforts from rich countries to provide aid to these goals must be expanded. In short, actually scaling up NETs will require policies that are out of line with hands-off, market-led approaches to environmental management and technology development. It is better to reckon with this now, rather than separating the technology out from the social changes necessary to scale it up, and imagining that it can develop on its own.

Finally, all of this suggests that “technologies” being “deployed” is not the most helpful way to think about these practices. In regards to “negative emissions technologies”, the focus on “technologies” is misplaced to the degree that it treats technologies as objects or artifacts — what Corry has called the “contraption fallacy” (Corry 2014). Rather, it matters how the forest or crop is grown, how the infrastructure is built, who is changing their soil management practices to sequester carbon: where the profits go, the commodity chains, the social groups that experience differential opportunities or constraints, etc. An alternative framing might be useful in emphasizing these features, such as a holistic discipline of “carbon management”, though “management” implies a precision and control that is lacking at present. Within agriculture, “carbon farming” is a useful approach to emphasize the activity of farming. Perhaps “carbon production” will become a concept, in terms of storing carbon in long-lasting wood products or plastics. In any case, a focus on the activities (negative emissions practices, emphasizing the verb and action, rather than the noun or technological object) keeps the social dimensions of people and place in the picture. Empirical social science can work towards understanding the contexts, changing social relations, and barriers to these activities on the ground in ways that are crucial to bringing carbon dioxide removal from pilot-scale theory to scaled-up practice.

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References

Anderson K (2015) Duality in climate science. Nat Geosci 8:898–900

Bäckstrand K et al. (2011) The politics and policy of carbon capture and storage: Framing an emergent technology. *Glob Environ Chang*. doi:10.1016/j.gloenvcha.2011.03.008

Bauer N (2015) Power systems: carbon negative at the regional level. Nat Clim Chang 5(3):196–197

Brunner A, Currie WS, Miller S (2015) Cellulosic ethanol production: landscape scale net carbon strongly affected by forest decision making. Biomass Bioenergy 83:32–41

Caldas M et al. (2014) Factors affecting farmers' willingness to grow alternative biofuel feedstocks across Kansas. Biomass Bioenergy 66:223–231

Caplow S et al. (2011) Evaluating land use and livelihood impacts of early forest carbon projects: Lessons for learning about REDD+. *Environ Sci Pol* 14:152–167. doi:10.1016/j.envsci.2010.10.003

Corry O (2014) Climate engineering and the contraption fallacy. Forum for Climate Engineering Assessment, http://dcgeoconsortium.org/2014/05/06/guest-post-olaf-corry-open-university-climate-engineering-and-the-contraption-fallacy/, accessed 3 May 2016.

Cotula L, Dyer N, Vermeulen S (2008) Fuelling exclusion? The biofuels boom and poor people's access to land. IIED, London

Creutzig F et al. (2013) Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment. Environ Res Lett. doi:10.1088/1748–9326/8/3/035047

Creutzig F et al. (2015) Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*. doi:10.1111/gcbb.12205

De Coninck H, Benson S (2014) Carbon dioxide capture and storage: issues and prospects. Annu Rev Environ Resour 39:243–270. doi:10.1146/annurev-environ-032112-095222

Dowd A, Rodriguez M, Jeanneret T (2015) Social science insights for the bioCCS industry. Energy 8:4024–4042. doi:10.3390/en8054024

Fuss S et al. (2014) Betting on negative emissions . *Nature*. Clim Chang 4:850–853

Gallagher E (2008) The Gallagher review of the indirect effects of biofuels production. Renewable Fuels Agency, July 2008, http://www.renewablefuelsagency.org/reportsandpublications/reviewoftheindirecteffectsofbiofuels.cfm.

Gasser T et al. (2015) Negative emissions physically needed to keep global warming below 2 °C. *Nat Commun*. doi:10.1038/ncomms8958

Geden O (2015) Climate advisers must maintain integrity. Nature 521:27–28

German L, Schoneveld GC, Pacheco P (2011) Local social and environmental impacts of biofuels: global comparative assessment and implications for governance. Ecol Soc 16(4): 29.

Hartmann J et al. (2013) Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Rev.* Geophysics 51:113–149

Hulme M (2016) 1.5 °C and climate research after the Paris agreement. *Nature*. Clim Chang 6:222–224

Hunsberger C, et al (2015). *Land-based climate change mitigation, land grabbing and conflict: understanding intersections and linkages, exploring actions for change*. MOSAIC Working Paper Series No. 1.

IPCC (2014) : Summary for Policymakers. In: Edenhofer O et al. (eds) In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press,, Cambridge, United Kingdom

Iyer G et al. (2015) Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technolo Forecast Sol Chang*. doi:10.1016/j.techfore.2013.08.025

Kuchler M (2014) Sweet dreams (are made of cellulose): sociotechnical imaginaries of second-generation bioenergy in the global debate. Ecol Econ 107:431–437

Leach M, Fairhead J, Fraser J (2012) Green grabs and biochar: revaluing African soils and farming in the new carbon economy, J Peasant Stud, 39, (2):285–307

Lomax G et al. (2015a) Investing in negative emissions. Nat Clim Chang 5:498–500

Lomax G et al. (2015b) Reframing the policy approach to greenhouse gas removal technologies. Energ Policy 78:125–136

Longstaff H et al. (2015) Fostering citizen deliberations on the social acceptability of renewable fuels policy: the case of advanced lignocellulosic biofuels in Canada. Biomass Bioenergy 74:103–112

Lyons K, Westoby P (2014) Carbon colonialism and the new land grab: plantation forestry in Uganda and its livelihood impacts. J Rural Stud 36:13–21

Markusson N, Shackley S, Evar B (2012a) The social dynamics of carbon capture and storage: understanding CCS representations, governance, and innovation. Routledge, New York

Markusson N et al. (2012b) A socio-technical framework for assessing the viability of carbon capture and storage technology. *Technol Forecast Soc Chang* 79:903–918

McLaren D (2014) Capturing the Imagination: Prospects for Direct Air Capture as a Climate Measure. Forthcoming in Geoengineering our Climate: Ethics, Policy, and Governance

Meadowcroft J (2013) Exploring negative territory Carbon dioxide removal and climate policy initiatives. *Clim Chang*. doi:10.1007/s10584–012–0684-1

Moosdorf N, Renforth P, Hartmann J (2014) Carbon dioxide efficiency of terrestrial enhanced weathering. Environ Sci Technol 48:4809–4816

Nalepa R, Bauer DM (2012) Marginal lands: the role of remote sensing in constructing landscapes for agrofuel development. J Peasant Stud 39(2):403–422

National Academies of Science (2015) *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. doi:10.17226/18805

Niemark B, Mahanty S, Dressler W (2016) Mapping value in a ‘green’ commodity frontier: revisiting commodity chain analysis. Dev Chang 47(2):240–265. doi:10.1111/dech.12226

Peters G (2016) The ‘best available science’ to inform 1.5 °C policy choices. *Nat Clim Change.*

Rai V, Victor D, Thurber M (2010) Carbon capture and storage at scale: lessons from the growth of analogous energy technologies. Energ Policy 38:4089–4098

Raman S et al. (2015) Integrating social and value dimensions into sustainability assessment of lignocellulosic biofuels. Biomass Bioenergy 82:49–62

Ribiero R, Quintanilla M (2015) Transitions in biofuel technologies: An appraisal of the social impacts of cellulosic ethanol using the Delphi method. *Technoll Forecast Soc Chang* 92(2015):53–68

Riera O, Swinnen J (2016) Household level spillover effects from biofuels: evidence from castor in Ethiopia. Food Policy 59:55–65

Rogelj J et al. (2016) Differences between carbon budget estimates unravelled. Nat Clim Chang. doi:10.1038/NCLIMATE2868

Rollins CL, Boxall PC, Luckert MK (2015) Public preferences for planting genetically improved poplars on public land for biofuel production in western Canada. Can J For Res 45:1785–1794

Sanchez DL et al. (2015) Emissions accounting for biomass energy with CCS . *Nature*. Clim Chang 5:230–234

Schirmer J, Bull L (2014) Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects. *Glob Environ Chang*. doi:10.1016/j.gloenvcha.2013.11.009

Shackley S, Thompson M (2012) Lost in the mix: will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables? Clim Chang 110:101–121

Shete M, Rutten M (2014) Biofuel feedstock production in Ethiopia: Status, challenges and contributions. In: Akinyoade A et al. (eds) In *Digging Deeper: Inside Africa's Agricultural, Food and Nutrition Dynamics*. Leiden, Brill.

Smith LJ, Torn MS (2013) Ecological limits to terrestrial biological carbon dioxide removal. Clim Chang 118(1): 89–103

Smith P et al. (2015) Biophysical and economic limits to negative CO2 emissions. *Nat Clim Chang*. doi:10.1038/nclimate2870

Suiseeya K, Caplow S (2013) pursuit of procedural justice: Lessons from an analysis of 56 forest carbon project designs. *Glob Environ Chang* 23:968–979

Sunderlin W et al. (2013) How are REDD+ proponents addressing tenure problems? Evidence from Brazil, Cameroon, Tanzania, Indonesia, and Vietnam. World Dev 55:37–52

Swallow B, Goddard TW (2013) Value chains for bio-carbon sequestration services: lessons from contrasting cases in Canada, Kenya and Mozambique. Land Use Policy 31:81–89. doi:10.1016/j.landusepol.2012.02.002

Tavoni M, Socolow R (2013) Modeling meets science and technology: an introduction to a special issue on negative emissions. Clim Chang 118:1–14. doi:10.1007/s10584-013-0757-9

Taylor L et al. (2016) Enhanced weathering strategies for stabilizing climate and averting ocean acidification. Nat Clim Chang. doi:10.1038/NCLIMATE2882

Unruh J (2011) Tree-Based Carbon Storage in Developing Countries: Neglect of the Social Sciences. *Soc Nat Res Int J* 24(2):185–192

Van der Horst D, Vermeylen S (2011) Spatial scale and social impacts of biofuel production. Biomass Bioenergy 35:2435e2443

Vaughan N and Gough C (2015) Synthesizing existing knowledge on feasibility of BECCS: Workshop report.

Vergragt P, Markusson N, Karlsson H (2011) Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in. Glob Environ Chang 21:282–292

Williamson P (2016) Scrutinize CO2 removal methods. Nature 530:153–155

Wylie L, Sutton-Grier A, Moore A (2016) Keys to successful blue carbon projects: lessons learned from global case studies. Mar Policy 65:76–84