Environmental Research Letters

EDITORIAL • OPEN ACCESS

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To cite this article: R B Jackson *et al* 2017 *Environ. Res. Lett.* **12** 110201

Environmental Research Letters

OPEN ACCESS

RECEIVED
22 September 2017

REVISED
19 October 2017

ACCEPTED FOR PUBLICATION
20 October 2017

PUBLISHED
13 November 2017

EDITORIAL

Focus on negative emissions

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Stabilizing climate at temperatures below 2 °C will require rapid and sustained emission reductions and near-zero or negative emissions before the end of the century (e.g. Clarke *et al* 2014, UNFCCC 2015). During the past decade, however, emissions from fossil fuel use and cement production have remained high. Emissions in recent years have been fairly stable at ~10 Pg C yr^{-1} but are still 60% greater than in 1990 (Le Quéré *et al* 2016, Jackson *et al* 2016).

Climate stabilization temperature depends on the cumulative emissions since the beginning of the fossil era some two centuries ago. As a way to reconcile current emission trends with the small carbon budgets compatible with 1.5 °C and 2 °C average increases in global temperature, one option invoked in integrated assessment models (IAMs) and, increasingly, in policy circles is negative emissions (NEs) (e.g. Royal Society 2009, Tavoni and Socolow 2013, McLaren 2013, NRC 2015, Smith *et al* 2016). A NE technology results in the net removal of CO_2 from the atmosphere (also sometimes referred to as carbon dioxide removal, CDR). Examples of the most commonly proposed negative emission technologies (NETs) include biomass energy with carbon capture and sequestration (BECCS), afforestation, and industrial direct air capture (DAC).

Current 1.5 °C scenarios all feature rapid deployment of NETs, and most scenarios limiting global warming to 2 °C rely on NETs, as well (Rogelj *et al* 2015). Relatively little is known, however, about the global potential of emerging and future NETs, the sustainability and cost of large-scale deployment needed to meet 'safe' climate stabilization targets, carbon-climate feedbacks of entering a new carbon-negative world, and socio-institutional barriers to the deployment of NETs, including governance and public acceptance of new technologies. These and other knowledge-gaps are the focus of this focus issue in *Environmental Research Letters.*

The focus issue begins with an overview of research needs by Fuss *et al* (2016). Their analysis builds upon an earlier paper (Fuss *et al* 2014) to identify critical research gaps for NETs and their potential role in reaching climate targets. Whereas the first paper highlighted BECCS deployment and impediments to it, the newer paper examines NETs more broadly, emphasizing additional NETs and governance and policy needs in particular. Fuss *et al* (2016) identify five research priorities:

1. Competing land requirements for food, fuel, and other uses should be quantified for BECCS and afforestation in more detail and in spatially explicit ways.
2. Sustainability impacts are critical, maximizing co-benefits in CO_2 capture and energy use and minimizing tradeoffs in water, species conservation, and other aspects central to UN Sustainable Development Goals.
3. Carbon-cycle responses to negative emissions are important because the same processes slowing the growth rate of CO_2 today will respond in reverse to negative emissions, requiring relatively greater deployment per unit CO_2 reduction (see Jones *et al* 2016 above).
4. Governance will strongly influence demand for NETs through consensus, or its lack, and far less research has been undertaken on social issues compared to physical and economic ones.
5. Cross-cutting research opportunities include developing new metrics and examining issues of public acceptance and siting.

Using this set of five research priorities from Fuss et al (2016) to organize our discussion of the other articles in the feature, Boysen et al (2016) and Kreidenweis et al (2016) examine land requirements and different sustainability aspects of biomass supply from plantations and afforestation. Boysen et al (2016) use a spatially explicit biosphere model to estimate the potential—and potential trade-offs—for giga-hectare planting of biomass plantations. In the most extreme biomass scenario, they estimate this deployment could remove as much as 649 Pg C cumulatively from the atmosphere by year 2100, delaying by 73 years the carbon budget otherwise reached that year under RCP4.5. Not surprisingly, their most aggressive scenarios result in stronger trade-offs with food production and biodiversity as well as additional impacts on forest extent, biogeochemical cycles, and biophysical properties (e.g. Smith and Torn 2013, Jackson et al 2005). As one example, Boysen et al (2016) identify temperate and tropical forests in Asia as some of the most suitable land for carbon-removal technologies, but native forests would face 'massive replacements'. Their intermediate scenarios have large, but less extreme, ecological and social effects.

Kreidenweis et al (2016) also suggest that afforestation could provide extensive carbon potential, in their estimate covering 2580 Mha globally and sequestering 235 Gt C by the end of the 21st century. Using a partial equilibrium land-use model and assuming a global incentive for carbon sequestration, they also estimate that food prices could increase ~80% by 2050 and >300% by 2100 through competition for land and other factors. They suggest that focusing on tropical regions for afforestation provides the greatest potential benefit with the smallest relative impact to food prices and albedo, another factor they examined. They conclude that policies and economic incentives should be crafted to assure the stability of the plantations, to increase crop yields per hectare, and to redistribute funds to the people and segments of society most vulnerable to increased food prices.

Cost effectiveness also features strongly in the papers by Muratori et al (2016) and Frank et al (2017). Muratori et al (2016) examine the consequences of BECCS as a potential source of NEs using the Global Change Assessment Model. In scenarios with CCS available, mitigation costs drop by half and the price of carbon declines substantially in a 2 °C scenario compared to scenarios without CCS (see also Kriegler et al 2014). In addition to changing the flow of carbon tax revenue in an economy, CCS affects net energy trade, tempering the decline in fossil fuel use. Although a carbon price puts upward pressure on prices of food and other agricultural commodities, implementating BECCS lowers carbon prices in climate-change mitigation scenarios. Some critical assumptions in the authors' scenarios include a globally homogeneous carbon price by 2020, global availability of advanced low-carbon technologies, and the large-scale availability of biomass. Muratori et al (2016) acknowledge that technological and institutional challenges related to large-scale bioenergy and CCS deployment need to be addressed before scenarios such as the ones presented in their paper could be realized.

Frank et al (2017) use a partial equilibrium modeling framework to explore ways to minimize competition between agricultural carbon mitigation and food production. Scenarios that limit global temperature increases to 1.5 °C using only the land sector for mitigation and carbon removal suggest that global food caloric intake could decline by 100–300 kcal per person daily in 2050; this extreme case could result in undernourishment of 80–300 million people. Less ambitious scenarios reduce these effects, of course, as does carbon removal from other sectors of the global economy. Frank et al also find that relatively land-rich countries, such as Brazil, could reduce emissions with minor effects on food availability; higher-population-density countries such as India and China are unlikely to do so.

Two studies in the focus issue examine the mechanics and feasibility of upstream capture technologies, with an eye to improving efficiencies. Boot-Handford et al (2016) study a BECCS-based system using chemical-looping combustion, a process that uses a solid sorbent to transfer oxygen from the combustion air to the fuel, thus avoiding direct contact between fuel and air. Using a 6 kWe reactor they designed and built, they show that sorbents reduce the amount of biomass tars exiting the reactor by up to 71 mass% compared to experiments in which the biomass tar compounds were exposed to an inert bed of sand. Their study illuminates a critical step in the use of biomass for BECCS.

Wilcox et al (2017) examine the conditions in which CO_2 capture may be energetically feasible for applications not requiring high-purity CO_2. Examples include enhanced oil recovery (an active market today) and microalgae cultivation, where higher CO_2 concentrations can increase photosynthesis and biological growth. They analyze the amount of work needed to obtain CO_2 for different end purities and % captures. Economically viable cases emerge where the separation of CO_2 from air to low and moderate purities is energetically equivalent to the work required for flue-gas CO_2 separation. They conclude that dilute CO_2 may be an adequate feedstock in such applications and that future studies should investigate the energy and cost pathways of mineral carbonation and fuel synthesis.

Jones et al (2016) examine multi-century responses to the deployment of NETs in the global carbon cycle, the third priority outlined by Fuss et al (2016). Currently, only 44% of CO_2 emitted by human activities remains in the atmosphere, a metric known as the 'airborne fraction.' The remaining 56% of CO_2 is absorbed by the oceans and by land plants through photosynthesis; the respective ocean and land sinks today are large: ~2.6 and 3.2 Gt C yr^{-1}, respectively. Jones et al (2016) suggest sinks will weaken—even reverse—under future low-emission scenarios, as already incorporated in some IAMs (e.g. (Chen and Tavoni 2013). CO_2 dissolving into the ocean today as concentrations in air rise will eventually be released when concentrations fall and the oceans and land equilibrate with the atmosphere over centuries. A weakening of the natural land and ocean sinks will reduce the net effectiveness of NETs and increase the deployment needed to achieve a climate stabilization target. The authors also introduce a new metric, the perturbation airborne fraction (PAF), defined as the fraction of the CO_2 removed from the atmosphere by a given negative emission technology that stays out of the atmosphere. The PAF is important for scientific understanding and for policy makers, who need to know how much negative emissions are needed to reduce atmospheric CO_2. If the PAF is ~0.6, then 1.67 units of CO_2 must be removed to maintain a permanent 1 unit drop in the air.

Also examining carbon cycling and sustainability, Harrison (2017) analyzes a different NET, ocean macronutrient fertilization (OMF), combining global oceanographic measurements and outputs from a high-resolution global circulation model to provide 'the first comprehensive assessment of the global potential for carbon sequestration from ocean macronutrient fertilization.' Ocean fertilization is a NET that has received relatively little attention over the past decade, as the uncertainties around carbon storage, fertilization costs, and social acceptance were higher than expected. Previous studies primarily examined the potential of iron fertilization to stimulate carbon uptake and transport to the deep ocean (e.g. Buesseler *et al* 2004). Examining fertilization with N and P, Harrison (2017) estimates a technical potential of $\sim 1.5\,\mathrm{Pg\,C\,yr^{-1}}$ that could be sequestered through both N-only fertilization and N + P fertilization. However, a doubling of global phosphate production would be needed to achieve this macro-fertilization goal. He also notes that environmental risks and societal concerns could limit the implementation of OMF regardless of technical feasibility.

Vaughan and Gough (2016) use expert elicitation to examine the assumptions and feasibility of BECCS as represented in IAM scenarios, including issues of and governance and social acceptability (the fourth and fifth priorities highlighted by Fuss *et al* 2016). Eighteen experts were split into three groups based on expertise and evaluated nine factors, including available land area, future yields, storage capacity and capture rates for CCS, and cross-cutting issues including policy frameworks and social acceptability. In general, the experts were reasonably confident that the technical aspects of CCS were modelled realistically in IAMs. However, they were more negative about a number of other underlying assumptions. In particular, the experts believed IAMs used unrealistic assumptions both for the scale of bioenergy deployment (i.e. overly optimistic assumptions about land availability and global yields) and for the development of policy frameworks and societal acceptability needed to enable large-scale NETs. Given this relatively negative assessment, Vaughan and Gough (2016) issue a strong call for additional research to understand the conditions for and consequences of pursuing NETs.

Good governance and financial institutions will be important for all aspects of NETs deployment, including carbon-trading systems. As outlined in Coffman and Lockley (2017), a person or entity selling goods and services with a carbon impact could mitigate future CO_2 pollution with NE credits. The credits need not be purchased for immediate delivery. A financial sector would typically construct a futures market for trading credits bought at time of manufacture or sale. Coffman and Lockley conclude that strongly regulated markets would be more likely to result in reliable contracts, minimizing the moral hazard of carbon offsets purchased but never delivered. Overall, however, they conclude that only governments can provide assurance that offsets would be delivered; they therefore recommend the use of state-backed futures for assuring delivery.

Several papers examine crosscutting research priorities. Mac Dowell and Fajardy (2017) contribute an economic analysis of BECCS with an eye to CO_2 removal and electricity supply. BECCS facilities are flexible in providing both electricity to the grid and CO_2 removal from the atmosphere, in combinations that depend on market conditions. Mac Dowell and Fajardy examine three scenarios: (1) a BECCS plant operating on a load-following basis, ramping electricity production up and down with demand, (2) a BECCS plant operating instead in baseload mode, constantly removing CO_2 from the air and supplying electricity in response to demand, but with no payment received for the electricity generated but not supplied to the grid, and (3) the same as scenario 2 except the excess bioelectricity is used for the production of electrolytic hydrogen which can, in turn, displace natural gas from the heating system. This carbon-negative heating service is compensated on the basis of the value of displaced fossil energy. The authors conclude that the most profitable arrangement may be operating the BECCS facility in baseload fashion (scenarios 2 and 3), constantly removing CO_2 from the atmosphere and dispatching electricity on an as-needed basis. A primary caveat for their conclusions is whether CO_2 emissions accompanying the biomass supply chain are large enough to reduce the amount of net CO_2 removal and change the economics.

Finally, Minx *et al* (2017) analyze the rapidly growing literature on NETs using scientometric methods and topic modelling to address cross-cutting issues. They examine the contents of ~2900 published papers, ~500 in 2016 alone. Much more research has been done on energy systems and specific technologies (e.g. BECCS, direct-air capture, biochar) than on integrated analysis of NET portfolios. Such integrated analysis is important for understanding the extent to which NETs are feasible, and at what costs and risks. Minx *et al* (2017) argue against singular adoption of one technology; if NETs are to be deployed, they recommend a diverse portfolio that spreads risk across technologies. Finally, they recommend answering three questions for each technology: (1) How much is desirable and feasible? (2) What are the economic, social, and environmental costs and benefits? (3) What are the risks associated with each technology?

This focus issue highlights opportunities and some limitations and unexplored risks of a large reliance on NETs. Such reliance is implicitly assumed in the Paris Agreement and in almost all scenarios that keep global average temperature increases below 2 °C. Future research on NETs will require progress in the fields of Earth system science, technology transfer, economics, governance, and many other fields, all needed to examine critically the large-scale deployment of NETs.

Acknowledgments

This paper and the organization of the focus issue in *Environmental Research Letters* is a contribution of the Global Carbon Project (globalcarbonproject.org) and its MaGNET initiative (www.cger.nies.go.jp/gcp/magnet.html).

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