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TOPICAL REVIEW

Negative emissions—Part 3: Innovation and upscaling

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Abstract

We assess the literature on innovation and upscaling for negative emissions technologies (NETs) using a systematic and reproducible literature coding procedure. To structure our review, we employ the framework of sequential stages in the innovation process, with which we code each NETs article in innovation space. We find that while there is a growing body of innovation literature on NETs, 59% of the articles are focused on the earliest stages of the innovation process, 'research and development' (R&D). The subsequent stages of innovation are also represented in the literature, but at much lower levels of activity than R&D. Distinguishing between innovation stages that are related to the supply of the technology (R&D, demonstrations, scale up) and demand for the technology (demand pull, niche markets, public acceptance), we find an overwhelming emphasis (83%) on the supply side. BECCS articles have an above average share of demand-side articles while direct air carbon capture and storage has a very low share. Innovation in NETs has much to learn from successfully diffused technologies; appealing to heterogeneous users, managing policy risk, as well as understanding and addressing public concerns are all crucial yet not well represented in the extant literature. Results from integrated assessment models show that while NETs play a key role in the second half of the 21st century for 1.5 °C and 2 °C scenarios, the major period of new NETs deployment is between 2030 and 2050. Given that the broader innovation literature consistently finds long time periods involved in scaling up and deploying novel technologies, there is an urgency to developing NETs that is largely unappreciated. This challenge is exacerbated by the thousands to millions of actors that potentially need to adopt these technologies for them to achieve planetary scale. This urgency is reflected neither in the Paris Agreement nor in most of the literature we review here. If NETs are to be deployed at the levels required to meet 1.5 °C and 2 °C targets, then important post-R&D issues will need to be addressed in the literature, including incentives for early deployment, niche markets, scale-up, demand, and—particularly if deployment is to be hastened—public acceptance.

1. Introduction

Meeting even moderately ambitious goals to address climate change could require removing substantial amounts of greenhouse gases from the atmosphere at a rate much faster than existing natural removal processes (Sanderson *et al* 2016). Several methods of anthropogenic removal have been proposed, which fall under the rubric of negative emissions technologies (NETs). The notion of 'technology' here is broad, a means to an end (Arthur 2007), encompassing not only devices or hardware but also soft innovations, such as management practices and behavior. NETs thus include industrial processes, such as bioenergy with carbon capture and sequestration (BECCS), and direct air carbon capture and storage (DACCS), which is sometimes referred to simply as 'direct air capture.' NETs also include ecosystem management approaches (Field and Mach 2017, Griscom 2017) such as: soil carbon sequestration (SCS), biochar, afforestation and reforestation (AR), blue carbon (BC), enhanced weathering (EW), and ocean fertilization (OF). Methods to remove greenhouse gases other than CO_2 include chemical decomposition of methane and laser removal of CFCs; they are typically known as greenhouse gas removal technologies (GGRs) and are not covered in this review, but are reviewed elsewhere (Boucher and Folberth 2010, Stolaroff *et al* 2012, Ming *et al* 2017). We provide a taxonomy for the NETs approaches reviewed here in Minx *et al* (2018).

This review is part of a series of three reviews papers on NETs. The first presents scientometric trends and provides an overall summary (Minx *et al* 2018). The second includes an assessment of costs and potentials of NETs, as well as a summary of the level of NETs included in climate stabilization scenarios such as 1.5 °C and 2 °C (Fuss *et al* 2018). In this paper, we review the extent to which the NETs literature includes topics related to innovation and upscaling.

1.1. Demand, supply, and costs of NETs

An up-to-date assessment of the potential rate (in $Gt\,CO_2\,yr^{-1}$) at which NETs could remove CO_2 from the atmosphere shows that all of these methods—with the exception of soils— have a high-end potential to remove multiple, and in cases tens of, $Gt\,CO_2\,yr^{-1}$, while soils could remove on the order of single-digit $Gt\,CO_2\,yr^{-1}$, albeit all with wide ranges of uncertainty (Fuss *et al* 2018). The heterogeneity of NETs, especially with respect to their limitations, geographical accessibility, and side effects, strongly imply the need to think in terms of portfolios of NETs to manage risk and maximize removal efficacy. The main insight from the small set of studies that do consider more than one NET (Chen and Tavoni 2013, Florian *et al* 2014, Marcucci *et al* 2017), is that when deployed jointly, the total negative emission potential from NETs is increased while the individual deployment of NETs is reduced, suggesting that portfolios provide an avenue to mitigate adverse impacts. An important insight is that even though integrated assessment model (IAM) results typically have a large role for NETs to play in the second half of the 21st-century for meeting the climate goals of the Paris Agreement, there is still urgency in developing NETs now due to the expected lengthy time periods required to deploy them at the scale of gigatonnes-per-year of removal.

Fuss *et al* (2018) also reviews recent cost estimates of various NETs. These estimates vary considerably both within and among NETs technology categories. For example, we see ranges at the low end of single digit dollars per ton of removal (e.g. AR and OF) with high end estimates in the several 100s of dollars per ton (BECCS, DACCS, and EW). Like mitigation technologies, only considerable effort will render NETs technically as well as economically feasible. Importantly, the costs of NETs vary not only quantitatively but also qualitatively; whereas the costs of DACCS include capital equipment purchases and energy input costs, the costs of SCS relate to the permanence of the carbon in soil, the effects on agricultural yields, and the adoption behavior of farmers. Deploying NETs at a meaningful scale will require them to be affordable, including all costs, and socially acceptable, in a broad sense.

1.2. Innovation in NETs

The speed at which NETs can be scaled up so that they are commercially available at affordable costs, deliver climate benefits and non-climate co-benefits, with reasonably tolerable adverse impacts, will determine their utility for addressing climate change. Innovation in NETs and in supporting environments will be central to this scale up process, and thus crucial to their outcomes on the climate and on society. We employ a broad definition of 'innovation' in this review spanning the full range of the process, from scientific discovery to issues associated with widespread adoption. We separate the innovation process into categories that correspond to a succession of stages. Using a dichotomy prevalent in the innovation literature (Nemet 2009, Di Stefano *et al* 2012), we find it useful to group these stages into two categories: (1) those related to the supply of innovation in a technology, e.g. including scientific research, and (2) those related to the demand for innovation in that technology, e.g. public acceptance. Supply side activities involving improving the costs and performance of technology while demand side activities involve the markets in which NETs compete, who wants them, how they use them, and the extent to which the broader public accepts them.

The past two decades have seen a steady increase in publications on NETs. While this body of work represents a small portion of the broader climate literature, it is growing faster–particularly more recently (Minx *et al* 2017b). In a companion piece to this review, Minx *et al* (2018) conduct a scientometric assessment of the extant literature on NETs and find (i) steady growth in the literature across different technologies with notable exceptions of ocean acidification and enhanced weathering; (ii) a development of distinct scientific discourses for all major technologies that in turn broadly cluster into land-based and ocean-based approaches as well as those involving geological storage; and (iii) the lack of a distinct cluster with studies of NETs portfolios.

1.3. This review: literature on innovation and scale up in NETs

As rapid and sustained emissions reductions continue to be forestalled, societies face an increasing dependence on NETs to achieve ambitious climate goals. The study highlights that while a risk management perspective requires limiting the growing importance of NETs in climate policy by ratcheting up short-term ambitions, these efforts will need to be accompanied by a focus on innovation and scale-up in order to realize required levels of carbon removal in the 21st century for meeting the international climate goals. This motivates our review and frames the following research question: *what does the literature on NETs say about innovation and how to achieve up-scaling*?

This review starts with the body of literature identified via the scientometric analysis conducted in (Minx *et al* 2018). We identified 2134 articles that fit a definition of NETs, were published in the peer-reviewed literature, and are cataloged by the Web of Science and Scopus between 1970 and mid-2017. We assess how many of these articles address the process of innovation, the stages associated with: creating new technical knowledge, transforming that knowledge into commercial products, diffusing them widely in society, and dealing with societal issues resulting from their use. We refer to this set of innovation processes as 'innovation and upscaling.' We choose the focus on increasing scale because of the inherently large scale at which NETs need to be deployed in order to have a material impact on the Earth's climate. Even in portfolio approaches, in which multiple NETs are deployed, several gigatonnes of removal for each individual technology are required. We thus categorize each article as covering topics that relate to one or more categories of the innovation process. We provide a descriptive analysis of the trends in publications across both NETs technology categories and innovation stages. We use the articles we identified to summarize some of the key insights that have emerged so far on innovation in NETs. An overview of the entire search selection procedure is provided in Minx *et al* (2018).

We first look (section 2) at general insights from the innovation literature and the framework it provides for evaluating NETs. In section 3, we develop scientometric estimates of the trends and foci of activity in academic publishing on NETs. In section 4, we substantively review the key articles from the literature on innovation in NETs. We provide summary insights and conclusions from this review in section 5.

2. Insights from the innovation literature

2.1. Definitions of innovation

Innovation is central to many aspects of addressing climate change. Innovation includes performance improvements in mitigation technologies, such as in the efficiency of end use devices like electric motors; it also encompasses efforts at adaptation, such as drought resistant crops; and it can also involve new business models, such as providing access to capital for low-carbon technologies in credit-constrained economies. The promise of innovation is that it can make efforts to address climate change more effective and more affordable (Popp 2010).

Depending on the disciplinary venue, innovation is defined in different ways: the general notion of innovation is sometimes referred to as 'technological change,' originally defined as 'new combinations of productive means' (Schumpeter 1934). More specifically in the context of climate change, a useful definition of technological change is: 'a process typically involving stages of invention, innovation, and diffusion, whereby users can produce more or better outputs from the same amount of input.' (Nemet 2013). While this definition carries with it the framework specific to the discipline of Economics from which it originates, it remains apropos for NETs. One can think of innovation in NETs as generating better outputs, such as more carbon removed, fewer adverse side effects, and more societal acceptance. Similarly, one can think of innovation as reducing the amount of capital, labor, land, water, or energy required as inputs. More succinctly, innovation can be reduced to performance improvements and cost reductions (Funk 2015), where performance can encompass a broad set of characteristics, not limited to efficiency, but extending to aspects such as public acceptance (Fri and Savitz 2014).

2.2. Upscaling

An important consideration in all of these definitions of innovation is the speed at which innovation occurs. For climate change and NETs in particular, the rate of innovation is essential (Bromley 2016). Because we are ultimately concerned with NETs removing gigatonnes of CO_2 per year, the notion of 'up-scaling' provides a useful focus within the innovation process. For example, the most recent review of CO_2 removal in 1.5 °C IAM scenarios found a median rate of 15 Gt CO_2 yr^{-1} by 2100, with a range of 3–29 (Rogelj *et al* 2018). The most specific meaning of upscaling is the increase in unit size (e.g. a power plant) to take advantage of scale economies, i.e. that costs rise at less than the rise in output (Wilson 2012). The term is also used in a more general sense when discussing planetary interventions in the climate system. In that case, the focus is not on scaling up a unit, but on scaling up a technological system.

In the case of NETs, this process might involve up-scaling to thousands of CCS plants (Herzog 2011, Nemet *et al* 2015, Peters *et al* 2017), millions of farms (Lal 2004, Woolf *et al* 2017), or teragrams of iron added to the ocean (Boyd and Bressac 2016, Hauck *et al* 2016). One way to consider the magnitudes of scale up required for NETs is to look at the deployments estimated in IAMs under various temperature targets. In figure 1 we display estimates of

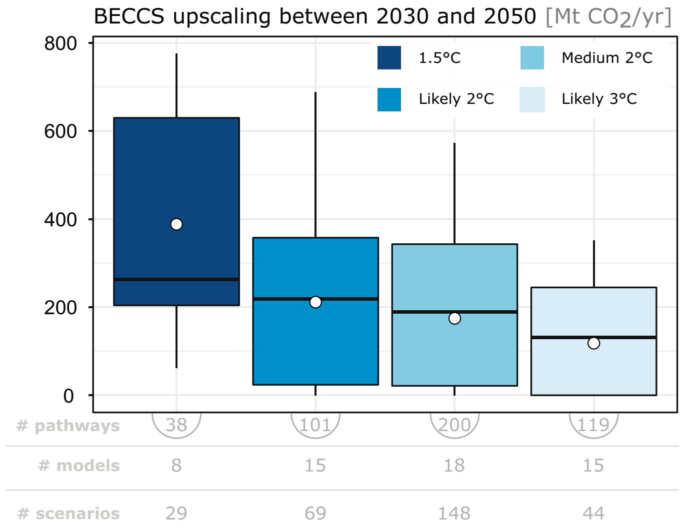

Figure 1. Annual deployment of additional BECCS removal capacity 2030–2050 under various temperature targets, scenarios, and IAMs. The upscaling metric is computed by taking the difference of gross negative emissions in 2050 and 2030 and dividing it by 20 years. Boxplots provide information about the range between the minimum and maximum values (vertical black solid line), the range between the 15*th* and 85*th* percentiles (blue-shaded rectangle), the median (horizontal black thick line) and the mean (white point). Basic descriptive statistics are provided below the plot for each climate target: the number of model runs (observations), the number of model versions and the number of scenarios.

the new BECCS[9] required annually on average between 2030 and 2050 under various scenarios and IAMs that are consistent with three temperature targets (1.5 °C, 2 °C, 3 °C), and the likelihoods of meeting them. Note that 'likely' is a 66% chance of avoiding temperature overshoot over the 21st century and 'medium' is a 50% chance. The 1.5 scenarios feature a different likelihood which corresponds to a 50% chance of keeping warming below 1.5 °C in 2100 (see Box in Fuss *et al* (2018) for more explanation). Additional information on the costs of BECCS, its geographical distribution and its role in the mitigation portfolio is available in the supporting information (SI) (section A.4).

Annual deployment of BECCS increases with more ambitious temperature targets but spans a considerable range within each target, more than an order of magnitude. It is striking that for even the least stringent targets (likely 3 °C), the median deployment rate involves adding 150 Mt CO_2 yr^{-1} of new removal capacity each year between 2030 and 2050. This is, because NETs are deployed both because they are biophysically required and because they are economically attractive once carbon prices are sufficiently high (Minx *et al* 2017b, Fuss *et al* 2018). To put these numbers in perspective, the first large scale BECCS project, in Decatur, IL USA, will remove about 1 Mt CO_2 yr^{-1} once in full operation. Worldwide, no other operational projects exceed 0.3 Mt CO_2 yr^{-1}. Only one project in planning exceeds 1 Mt CO_2 yr^{-1}. So, these scenarios involve bringing online hundreds of new plants of Decatur-scale each year between 2030 and 2050. To further put these results in context, scaling up 1Mt of a specific NET in 2020 to 1Gt in 2050, average deployment growth rates of 26% must be sustained for 30 years. Such a scale of growth had been observed for other technologies before, in particular solar PV (Creutzig *et al* 2017), but is nonetheless extremely challenging.

To see what factors deployment rates are sensitive to, besides target stringency, figure 2 shows deployment rates across four different assumptions. The lowest deployment, and lowest uncertainty, occurs under the assumption that bioenergy is constrained ('limited bioenergy') or unavailable ('no CCS/BECCS'), e.g. due to high social opposition to land use impact such as food prices. We note that the NET being modeled here is BECCS so it is among the most sensitive to land use constraints. At about the same central tendency, but with much lower confidence, the 'low energy intensity' scenario includes some very low BECCS deployment outcomes, as well as some moderate ones. The two highest scenarios are 'full portfolio' and a scenario in which global mitigation is delayed until 2030. The latter involves some very high deployment possibilities for BECCS and none below 150 Mt CO_2 yr^{-1} of new capacity annually.

The historical evidence consistently finds that innovations can take decades to be scaled up (Wilson 2012) and widely adopted (Grubler *et al* 2016), even if examples of rapid transitions exist (Sovacool 2016). Given the severe constraints imposed by the global carbon budget (Rogelj *et al* 2016, van Soest *et al* 2017), the speed at which NETs can be scaled up to make a favorable planetary scale impact is a paramount issue (Fuss *et al* 2016). But the innovation literature makes clear that there are risks involved even if this

[9] BECCS is the only technology for which gross negative emission data are available (for afforestation, only net land-use emission changes are reported).

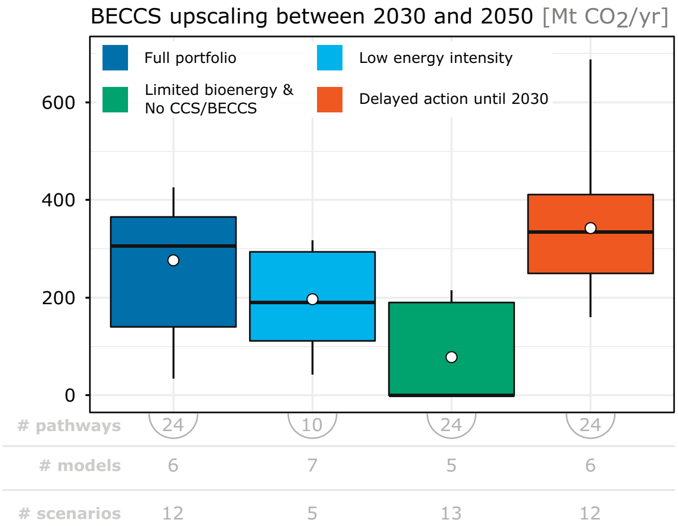

Figure 2. Annual deployment of additional BECCS removal capacity 2030–2050 under various assumptions, scenarios, and IAMs. The upscaling metric is computed by taking the difference of gross negative emissions in 2050 and 2030 and dividing it by 20 years. Boxplots provide information about the range between the minimum and maximum values (vertical black solid line), the range between the 15*th* and 85*th* percentiles (blue-shaded rectangle), the median (horizontal black thick line) and the mean (white point). Basic descriptive statistics are provided below the plot for each climate target: the number of model runs (observations), the number of model versions and the number of scenarios.

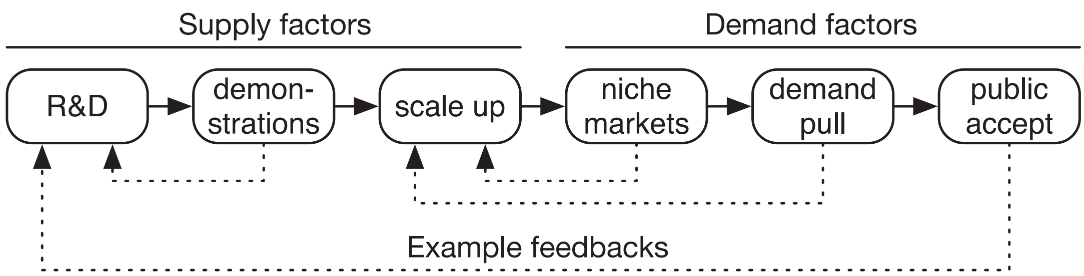

Figure 3. Stages of innovation. Arrows indicate flows of knowledge.

scale up successfully achieves its required rate (Buck 2016). Sustained demand for the technology's benefits as well as public acceptance of its risks and side effects will also condition its overall effectiveness.

2.3. Stages of innovation

A basic framework we take from the literature on innovation is that it can be described as occurring in a progression of stages (figure 3). Sources useful for describing and delineating these stages include: Grubler (1998), Weyant (2011), Gallagher *et al* (2012), Nemet (2013), Fri and Savitz (2014), Grubler and Wilson (2014) and more recently Anadon *et al* (2016). The stages used in these articles use varied terminology and levels of specificity. The use of successive stages is often critiqued as a simplistic or linear model (Godin 2005) that abstracts from important features, such as networks of actors or innovation systems (Geels 2004, Hekkert *et al* 2007). Some of these critiques address a strawman version; for example, a consistent insight from work using the notion of stages is that knowledge flowing between stages does not always flow in one direction, rather feedbacks from later stages to earlier ones are important; see dashed arrows in figure 3 for examples. Still, the notion that innovation includes a progression from early stages to later ones, that there is an essential sequence to them, remains relevant and useful (Balconi *et al* 2010). The literature is also consistent in describing that the mechanisms at work, capital required, level of risk, and actors involved are distinct across stages. With this review's goal of assessing the innovation-related literature, we adopt innovation stages as a framework for assessing the locus of publication output in NETs.

Work from the innovations literature makes the case that this innovation lifecycle sits in a context. Networks of actors influence the process (Hekkert *et al* 2007, Bergek *et al* 2008). The emergence of a new technology to replace others, a technological transition, involves institutions, financing mechanisms and niche formation (Rotmans *et al* 2001, Geels 2002, Jacobsson and Jacobsson 2014). This perspective is particularly important for NETs in that, for example, land-based NETs have the largest potential in the institutionally weakest regions of the world (Fuss *et al* 2018). While we acknowledge the importance of these contextual factors in accurately describing the innovation process, for the purposes of this review we adopt a stylized version of this context by focusing on the distinction between supply and demand drivers affecting the direction and speed of the process. 'Technology-push' drivers reduce the costs of innovation, e.g. through education and research. 'Demand-pull' drivers increase the pay-offs to innovation, e.g. by increasing the demand for new technologies in the market place (Nemet 2009). In figure 3 we simply refer to supply and demand side factors. We also focus on knowledge (represented by arrows), the most fundamental part of the innovation process (Lundvall 1998).

For NETs, as with any technology, the ultimate measure of success for a particular technology is adoption. Adoption of a technology is a function of its relative advantage—in terms of cost, efficiency, quality, environmental impact, etc.—and its alignment with consumer preferences (Rogers 2003, Fouquet 2010). Adoption is far from certain. Many, if not most innovations, make it through only a few stages before being abandoned (Scherer *et al* 2000, Thomke 2003). An inherent aspect of the process is the lack of ex ante knowledge about which innovations are likely to be successful (Fleming 2001). The stakes of this uncertainty are heightened by the robust research finding of highly skewed payoffs to innovations, implying that there will be many losers, only a few winners, and large returns for the latter (Scherer and Harhoff 2000).

We thus employ the stylized framework of the innovation process depicted in figure 3 to provide a taxonomy of six stages to characterize the literature on NETs.

2.3.1. Research and development

R&D involves the discovery and assimilation of new scientific and technical knowledge (Holdren and Baldwin 2001). The research part of R&D includes studies of thermodynamics and computer modeling of NETs systems. The development part of R&D involves experiments and prototypes to improve the technology. It can also involve studies of the future impacts of a technology at scale. In our study, all of the papers we have collected from the Web of Science could be considered R&D under this definition. To enhance clarity, we classify papers with a narrower definition; papers are classified as R&D if they do not get classified in one of the other innovation categories.

Major efforts to increase energy R&D were agreed upon during COP21 (Mission Innovation 2015). Yet, the NETs technologies differ in their technological maturity and the extent to which R&D funding is the most critical factor in enhancing knowledge about them. Public R&D is particularly important as there are many open questions, needs for improvement in knowledge, for which firms may not have sufficient incentives (Jones and Williams 1998, Cohen *et al* 2002). But it is also limited in that there is only so much that can be accomplished without market feedback. One important insight is that R&D is effective when it is maintained even as technologies progress closer to commercial use, e.g. because new problems develop in later stages that require new knowledge (Hendry and Harborne 2011). The notion of 'formative phases,' (Wilson 2012, Bento and Wilson 2016), in which the optimal designs and configurations undergo experimentation, are particularly important and several NETs appear to be at this stage at present.

2.3.2. Demonstrations

As they emerge from R&D, technologies need to prove that their performance is adequate and that they can function reliably in non-laboratory environments. Even early adopters will be skeptical of technologies at this stage. Firms need to reduce the risk of technologies at this stage by building one or more examples. One problem that emerges, known as knowledge spillovers, is that competitor firms, or countries, can observe these demonstrations and learn from them without having to make the required investments themselves (Teece 1986). This free-rider problem creates weak incentive for companies to fund demonstrations (Hartley and Medlock 2017). Furthermore, even though incentives for private investment are weak, governments are often hesitant to fund these investments (Weyant 2011, Zhou *et al* 2015), in part due to the scales of the investment required (Lupion and Herzog 2013), a mixed track record of success (Anadon and Nemet 2014), and to some extent due to perceptions that they will be 'picking winners' (Cohen and Noll 1991). This problem, known as the technology 'valley of death' results in an abundance of promising technologies that never become tested in commercial markets because they fail to attract sufficient investment to prove their reliability.

Work assessing the 'valley of death' problem for analogous technologies provide several insights applicable to at least some of the NETs. One is that demonstration programs should be designed as a portfolio of projects so that the program is robust to failure in a single project (Hart 2017). However the scale of the investments required can require some prioritization (Watson 2008). A fundamental goal of demonstrations is to generate knowledge, i.e. to learn (Reiner 2015); that is a higher priority than production, such as how much CO_2 is removed. Excess focus on production in past demonstrations has reduced much of their social value (Anadon and Nemet 2014). Similarly, it is possible to learn from technical failures (Leoncini 2016). A key to learning is making sure that knowledge generated is codified, maintained, and disseminated (Grubler and Nemet 2014), which is often not the case.

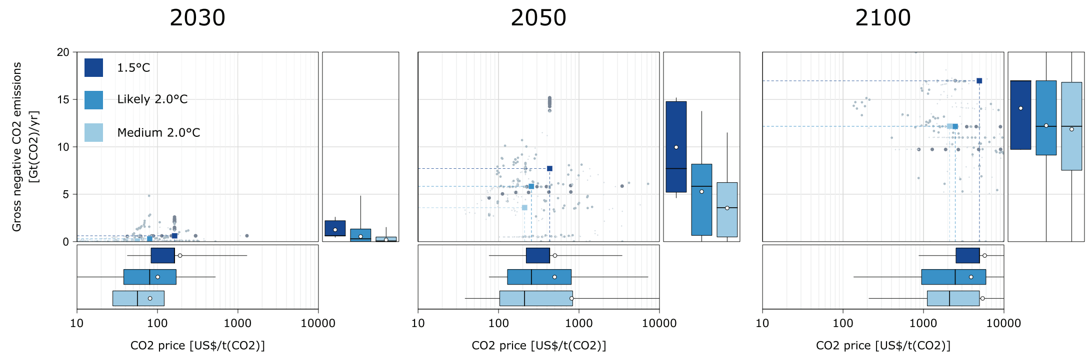

Figure 4. Effect of carbon pricing on demand for NETs (i.e. BECCS) at three time periods in integrated assessment models.

2.3.3. Scale-up

The process of increasing the unit size of technologies to commercially-viable scales is non-trivial and can take considerable time (Wilson 2012). This, associated with increasing scale, is a repeated theme in the literature. It is clear that just because we know we eventually need large scale it does not imply we are ready to do so today. See for example the megawatt scale German and US wind turbines in the 1970s that proved to be dead ends (Gipe 1995). Furthermore, the extent of the need to integrate NETs into existing infrastructures affects deployment speed and similarly varies across NETs categories (Geels 2002). For example, some NETs will involve access to CO_2 pipeline systems (BECCS, DACCS), others will require extensive mining and transportation infrastructures (EW, OF, BECCS).

NETs technologies span a wide range of sizes and thus each will involve quite different scale-up processes. In some cases, such as BECCS, the scale up process involves major increases in unit scale (Nykvist 2013). In other cases, e.g. in DACCS, there may also be unit scale increases, but the main scale-up challenge could be in mass manufacturing DACCS units (Lackner *et al* 2012). A strategy of iterative upscaling (Nemet *et al* 2016)—a series of demonstrations in which later projects learn from earlier ones and adjust their designs at larger scales—has proven successful, e.g. with Danish wind turbines (Garud and Karnoe 2003) as well as with PV manufacturing (Powell *et al* 2015). NETs could benefit from a similar orientation to scale-up involving a process of starting deployment early, gradually increasing unit and manufacturing size, and iteratively improving in the migration to larger scales.

2.3.4. Demand pull

Innovation is affected not only by technology push (e.g. R&D) but also by the markets in which it competes: demand pull (Nemet 2009). Learning by doing in the course of meeting demand can improve the cost and performance of technologies (Lohwasser and Madlener 2013). Because the climatic benefits of NETs are public goods, these markets will be highly affected by policy, which are often uncertain (Brunner *et al* 2012). As a result, demand for NETs will be heavily conditioned by policies, including carbon pricing. Indeed, in IAMs, carbon pricing is the mechanism that triggers BECCS deployment, with the scale (or demand pull) determined by the price levels required to achieve a given temperature goal (Fuss *et al* 2018). Other analyses have shown required investment in BECCS capacity on the scale of hundreds of billions of dollars annually (McCollum *et al* 2013). In figure 4, using IAM results from 207 scenarios in 12 models[10], we show the effect that demand for NETs—in the form of a carbon pricing associated with various temperature targets—has on deployment of BECCS in 2030, 2050, and 2100. On the horizontal axis (log scale) one can see the distribution of carbon prices associated with each stabilization target. Carbon prices are decreasing in the stringency of the temperature target (including the likelihood of achieving it), but with large overlapping ranges. Deployment of BECCS is shown on the vertical axis (linear scale). Deployment is also decreasing in the target stringency but increasing in the year. We note a substantial amount of scatter in the data, due to among other items, assumptions about mitigation technologies, climate sensitivity, and heterogeneity in model structure. One insight from this analysis is that the effect of demand for NETs, in the form of a temperature target, affects the urgency of NETs deployment rather than its end-of-century level. Deployment of BECCS is quite similar across targets in 2030 and in 2100; it diverges most in 2050—noting again the different biophysical and economic rationales NETs use can have (Fuss *et al* 2018). We note that the NET modeled in this case is mostly BECCS, which in some models includes exogenous constraints on upper bounds of deployment in 2100 and thus may contribute to the similarity of deployment levels therein.

More generally, other policy mechanisms such as subsidies for deployment, technology mandates, and even intellectual property regimes can affect demand

[10] Model versions are counted as individual models (i.e. GCAM 3.0, GCAM 3.1, IMACLIM 1.1, IMAGE 2.4, MERGE (EMF27), MESSAGE (v4), POLES (AMPERE), REMIND (1.4), REMIND (1.5), TIAM-ECN, WITCH (AMPERE), WITCH (LIMITS)).

for NETs. There may also be co-benefits that NETs provide that are independent of the value to society of carbon removal (Hong-Mei *et al* 2017). For example, some ecosystem-oriented NETs provide ecosystem services such as flood control that create value and thus additional demand for NETs; AR can provide co-benefits with respect to local livelihoods and biodiversity.

Other insights from the innovation literature include the importance of expectations (Alkemade and Suurs 2012). Expected future demand is often more important than the level of existing demand for investment. Adoption settings are crucial, for example appetite for risk in agricultural settings affects demand for new technology (Chatrchyan *et al* 2017). Learning by doing can occur during the adoption process; improvement continues after the R&D stage (Arrow 1962, Thompson 2012). Moreover, learning by doing often is distinct and complementary to R&D, not a substitute for it (Newell 2010, Corradini *et al* 2014). This implies that early deployment of NETs may need to be subsidized, e.g. as an infant industry, in order to achieve scale, improve carbon removal performance, and reduce costs over time. Finally, if demand depends on policies this adds additional risk to adopters in that the policies can change and thus payoffs can change as well. Policy credibility is an important issue in climate policy in general (Nemet *et al* 2017), and will likely become even more central to the success of NETs.

2.3.5. Niche markets

Niche markets exist when early adopters have a higher than average willingness to pay for a technology. An example would be carbon capture utilization and storage (CCUS), where oil field operators might value CO_2 above the existing carbon price and thus pay for CO_2 for enhanced oil recovery. Even if the climatic benefits of CCUS, or just CCU, are unclear at best (von der Assen *et al* 2013), it can enable subsequent scale up to more definitively beneficial removal at much larger levels. Niche markets can be important to launching risky new technologies (Kivimaa and Kern 2015), especially those whose initial costs are high but may fall subsequently through learning by doing. They may provide some temporary insulation from competition, e.g. when the scales of existing competitors might make them uncompetitive (Kemp *et al* 1998) (Raven *et al* 2016).

Given the issues of policy credibility described above, niche markets can provide hedges against uncertain policy. For example, the existence of carbon utilization markets can render investments in NETs technologies profitable even if future carbon prices falls to (or remains at) zero (MacDowell *et al* 2017). These benefits seem especially important for NETs whose value ultimately is determined by governments finding ways to price the value of the removal of CO_2. An important caveat about niche markets is that they are generally very small compared to scales relevant for climate stabilization, in which gigatonnes are what matter. Niche markets are useful as a way to get started and possibly hedge in the near term. The urgency of addressing atmospheric carbon means that some niches, such as using CO_2 to produce fuels, are only viable for a limited period. There is also a risk that serving niches diverts innovation toward characteristics that may not be useful for bulk carbon removal. However, having an early market with high willingness to pay and low competition has been essential for other technologies, and given the uncertain policy environment, is likely to be essential for NETs as well.

2.3.6. Public acceptance

While often treated as a separate issue, public acceptance of new technologies is crucial to their widespread adoption. In one sense, acceptance matters in terms of technology adoption and depends on whether adopters see value in the new technology, how much risk they are willing to accept in adopting it, and whether any adverse side-effects are worthwhile in comparison to the benefits. Potential adopters have heterogeneous preferences about these and other aspects. For example, early adopters of photovoltaics demonstrated high willingness to pay for the green or low-carbon status of the technology (Sundt and Rehdanz 2015). Adopters also have varying degrees of agency in determining whether they will adopt the technology or not. In the case of NETs, many of the ecosystem management technologies, such as soils, biochar, and forestry, involve aspects of this form of acceptance (Zinda *et al* 2017).

A broader form of public acceptance has to do with individuals and communities who do not make the adoption decision directly (Krause *et al* 2014, Bidwell 2016). They may influence the decision via democratic processes, public protests, or other politically-oriented means. But they do not have direct agency, in deciding whether or not to adopt. Thus, this broader notion of public acceptance includes social, cultural, and political concepts, including power. Issues with public acceptance can also emerge before widespread deployment, e.g. in anticipation. For example, consider CCS demonstrations in Germany (Braun 2017). The need to deploy NETs at the gigatonne scale heightens the likelihood that public acceptance issues will emerge and need to be addressed. Deploying any tech at scale large enough to meaningfully benefit the climate implies likely side-effects (Grubler 1998), which may not be positive. These can lead to public acceptance issues (Batel *et al* 2013). Some NETs, such as soil carbon sequestration, seem more challenged by the first set of public acceptance issues, while others, such as BECCS and DACCS seem more likely to encounter the second type.

A third and more abstract issue is whether NETs ought to be pursued as a mitigation strategy in the first place. Ethical reasoning suggests that the availability of NETs presupposes deep, immediate, and costly emissions reductions, pushing this task to later generations (thus raising moral hazard), and that they raise considerable procedural and distributive justice concerns (Anderson and Peters 2016, Shue 2017). These issues may significantly influence the public acceptability of individual NETs, as well as a NETs strategy in general, although they are rarely discussed in a public context (Campbell-Arvai *et al* (2017) is an exception), nor even in the climate policy realm (Peters and Geden 2017). The ethics of NETs are not discussed in this article, but are reviewed in Minx *et al* (2018).

3. Scientometrics on innovation in NETs

Our data for the scientometrics part of this review are the set of 2134 articles identified in Minx *et al* (2018). Whereas Minx *et al* (2018) coded papers by NETs technology, here we code each of these articles by stages of the innovation process. As with the technology categories, each article could also be coded into multiple innovation categories. Ultimately, we coded each NETs article as belonging to one or more of the six categories described above: (1) research and development, (2) demonstrations, (3) scale-up, (4) demand pull, (5) niche markets, and (6) public acceptance.

3.1. Methodology

We began with a set of six innovation stages used in the literature as described in section 2. We then established a set of keywords describing each stage as follows. First, we selected key words and phrases from the brief description of innovation stages in section 2.1. To find synonyms and related words, we submitted this set of words and phrases to Google Scholar and collected relevant words and phrases from the results.

Second, we selected key words and phrases from four comprehensive review articles on climate change-related innovation (Weyant 2011, Anadon 2012, Gallagher *et al* 2012, Fri and Savitz 2014). We entered the text of each article into the free phrase and word counters provided by writewords.org.uk. The tools return a frequency count for each word and phrase. The list includes non-substantive words such as '*the*' as well as many substantive words such as '*innovation*.' For example, it is clear from this search method that words beginning with the stem '*invest*' are important because '*investments*' appears in the (Gallagher *et al* 2012) article 91 times, '*investment*' appears 30 times, '*investors*' appears five times, and '*investing*' and '*invested*' each appear twice.

Third, we assigned these words and phrases to the six innovation stage queries and began sampling to establish shares of articles that are relevant to our intended innovation stage categories. Because we manually read every abstract we designed our searches to err on the side of including irrelevant articles to ensure that we do not exclude relevant ones. However, after sampling, our query for stage '6. Public Acceptance' returned very few relevant articles. We thus expanded the search by adding frequently used words from two more public acceptance articles (Krause *et al* 2014, Bidwell 2016). The supporting information (SI) provides the actual Boolean strings used in our searches. We applied this search string to abstracts and titles of the articles identified in Minx *et al* (2018).

Finally, we manually read the title and abstract of each article and coded it as relevant or not for each innovation stage in which it was identified using the Boolean string above. Two researchers read each article. We coded an article as relevant to that innovation stage if either researcher coded it as relevant (81% were coded the same by each researcher). We performed the manual coding using a coding rubric that reflects the characterization of each innovation stage in section 2.1. We include details on the manual coding rubric in the SI.

3.2. Results on locus of research emphasis

Our main result from this analysis is that the literature on NETs is best described as still 'scientific,' which in our framework we categorize as 'research and development.' The subsequent stages of the innovation process are represented in this literature, but at much lower levels of activity. One implication of this main result is that if NETs are to be deployed at the levels needed to meet 1.5 °C and 2 °C targets, then important post-R&D issues will need to be addressed—for example including early deployment, niche markets, scale-up, demand, and public acceptance. For the NETs literature to contribute to this process, it will need to vastly increase its insights on post-R&D topics.

In table 1 we show the counts of NETs articles by technology category and innovation stage. In addition to the NETs technology categories we include one for 'synonyms', which includes cross-cutting mentions of NETs, geo-engineering, carbon removal etc (note that we do not include solar radiation management in this review). These counts are made after all cleaning and removal of irrelevant articles. The R&D category is distinct in that the search string captures a large set of articles, over half of all NETs articles. Articles can be counted in multiple technology categories as well as in multiple innovation stages. The totals for rows and columns ('total positive codes') sum to amounts higher than the total number of articles ('total distinct articles'). As in paper 1, we see that, by far, the largest articles counts are for the ecosystem management technologies: SCS and AR. A second tier includes DACCS, OF, and BECCS. Biochar and EW are much smaller.

Pooling across NETs technologies, R&D dominates all innovation categories. The next largest counts are in scale up, demand pull, and public acceptance. But even these most well-represented innovation stages include only a minority of the articles. Table 2 shows that 21% of the articles cover scale-up, 9% demand pull, and 7% public acceptance. Demonstrations

Table 1. Counts of NETs articles by technology (rows) and innovation stage (columns).

Technology	Supply-side categories			Demand-side categories				
	RD	Demos	Scaleup	Demand pull	Niche markets	Public accept	Total positive codes	Total distinct articles
Afforestation/reforestation	149	9	62	24	1	7	252	197
BECCS	61	7	37	31	5	10	151	106
Biochar	48	1	15	4	1	5	74	58
Direct air capture	92	7	30	8	2	5	144	108
Enhanced weathering	13	1	7	1	–	5	27	19
Ocean alkalinisation	5	–	6	2	–	2	15	10
Ocean fertilisation	94	4	21	5	–	15	139	103
Soil carbon sequestration	183	4	37	11	–	22	257	209
NETs - General	52	6	30	20	5	9	122	75
Total positive codes	697	39	245	106	14	80	1181	885
Total distinct articles	679	29	208	99	10	79		

Table 2. Share of NETs articles in each stage (%), as a proportion of all articles (R&D).

Technology	Supply-side categories			Demand-side categories			Toal
	RD	Demos	Scaleup	Demand pull	Niche markets	Public accept	Demand side
Afforestation/reforestation	59	4	25	10	0	3	13
BECCS	40	5	25	21	3	7	30
Biochar	65	1	20	5	1	7	14
Direct air capture	64	5	21	6	1	3	10
Enhanced weathering	48	4	26	4	–	19	22
Ocean alkalinisation	33	–	40	13	–	13	27
Ocean fertilisation	68	3	15	4	–	11	14
Soil carbon sequestration	71	2	14	4	–	9	13
NETs - General	43	5	25	16	4	7	28
Total positive codes	59	3	21	9	1	7	17

and niche markets, which the innovation literature describes as crucial, are addressed in only a small number of articles across all NETs; only 1% of the articles refer to niche markets and 3% refer to demonstration programs.

Table 2 also reveals the disparity between publications involving the supply side of NETs and those involving the demand side. The overwhelming share of work has been on the supply side. When we pool article counts across the demand side categories and divide by the total number of innovation codes assigned, we get an estimate of this supply side focus. For all NETs, 17% of the codes are on the demand side, 83% involved supply side. Technologies with an above-average demand side activity are: BECCS (30%) and enhanced weathering (22%). There are low counts of demand side discussions for ocean fertilization (14%), biochar (14%), soils (13%), and direct air capture (10%). Correspondingly, a typical way in which these technologies are discussed is that they are 'deployed' rather than 'adopted.'

Looking at the innovation categories by technology, beginning with the supply side: table 2 shows very low shares of articles on demonstrations. The only technologies with more than 4% on demonstrations are BECCS and DACCS. We note that these are two technologies that are most tightly connected to industrial processes, so the notion of needing to demonstrate the technology before widely using it is most well accepted there. Still, these are very low values considering that the most immediate next step toward planetary-scale deployment for all of these technologies is demonstrating reliability, efficacy, affordability, and safety. We see much higher counts for scale-up, especially for ocean alkalinisation (40%), BECCS (25%), EW (26%), and DACCS (21%). We note however that many of the mentions of scale-up did not typically discuss a pathway or sequence of steps to scale up the technology. Rather, they indicated that scale up was necessary and often left it at that, at least in the abstracts, which are what we read for coding.

On the demand side, we see only BECCS with well above average mentions of mechanisms that would create incentives to adopt ('demand pull'). Typically, this involved modeling studies in which these technologies became widely deployed once a carbon price was applied. Another frequent demand-pull mechanism was the REDD(+) program relevant to AR. Very few articles discussed niche markets. BECCS perhaps is the notable exception in which a few articles discussed carbon utilization, e.g. for food or enhanced oil recovery. Public acceptance was much more represented than niche markets. BECCS, and enhanced weathering have above average mentions of public acceptance. Technologies notable for very low counts of public acceptance articles include DACCS (3%), AR (3%), and BECCS (7%). We do not have a way to tell whether these technologies have inherently fewer public concerns or whether these concerns are simply being

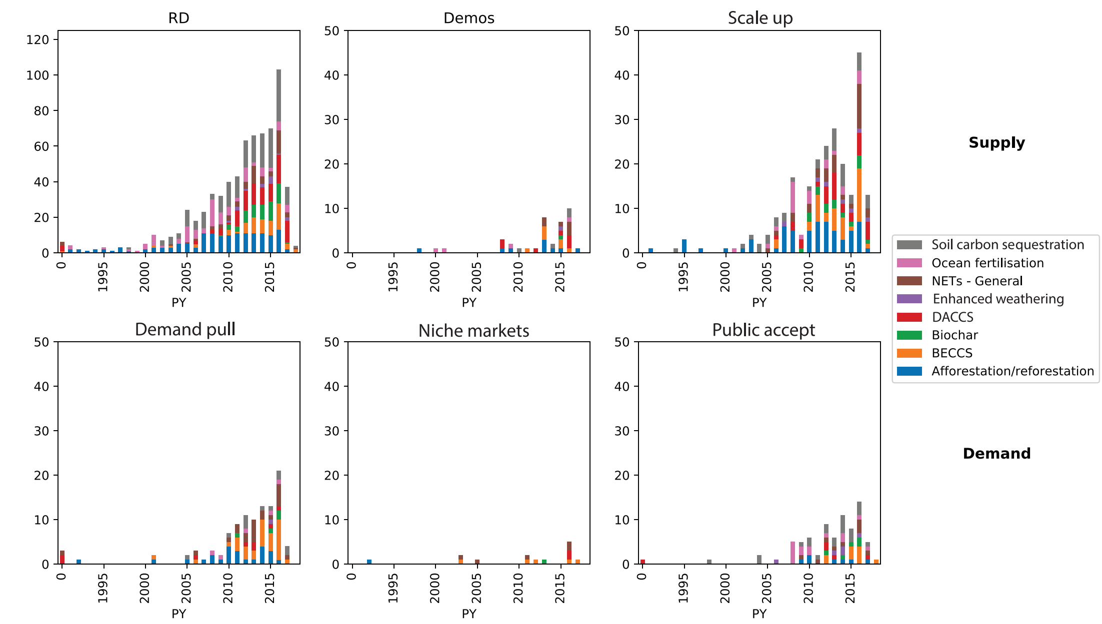

Figure 5. Trend in NETs publications by innovation stage and by technology. Each panel includes one innovation stage.

overlooked, perhaps because the technologies are at an early stage.

3.3. Trends in research emphasis

In figure 5 we show the trend in NETs publications by innovation stage. As in the table above, we see the general emphasis on R&D publications and much smaller counts for the other stages. Note that R&D has a larger y-axis range than the others. In figure 5 we add information on the technology categories as stacked colors for each bar. In figure 8, we show the trend in publications within each NETs category. Each color in each stacked bar is an innovation stage.

4. Review of innovation topics in the NETs literature

Going beyond the scientometrics, we review the main claims about innovation made in the articles. We include some discussions of innovation stages that were not positively coded as described in section 3, which only reflect coding of titles and abstracts rather than the full content of the article which this section includes.

4.1. Bioenergy carbon capture and storage (BECCS)

We found 106 articles focusing on innovation in BECCS, which put it in the middle of the range of technologies we assessed. These articles covered a richer set of innovation stages than did the other technologies. BECCS was more balanced between supply and demand side topics than were the other technologies; it had the highest portion of counts on the demand side. One possibility is that this is due to their use in IAMs, which connect demand, in the form of carbon prices, with deployment of BECCS. Compared to other technologies, it also had a higher share of articles that covered innovation stages other than R&D. It had a higher share of articles on demonstration than any other technology. It also had the highest on scale up, demand pull, niche markets, and public acceptance.

Although BECCS included a smaller share of pure-R&D articles, it still included many articles covering the science on, for example, designing optimal feedstocks, increasing yields, capture efficiency, and how to allow for multi-functional land use. Representative examples include testing a gasification technology at the sub-MW scale (van der Meijden *et al* 2010) and comparing costs of various proposed plant configurations (Schmidt *et al* 2010). However, since so few plants and infrastructure have actually been built, projections rely on models (Azar *et al* 2013, Kriegler *et al* 2013, van Vuuren *et al* 2013, Klein *et al* 2014, Rose *et al* 2014) and in exceptional cases on expert elicitations (Vaughan and Gough 2016). Along with AR, BECCS is one of only two NETs to be regularly and specifically represented in IAMs, other than some individual extensions (Popp *et al* 2011, Riahi *et al* 2015).

4.1.1. *Demonstrations and scale up*

Proving that BECCS plants are reliable and trusted is a key open issue and an obstacle to widespread adoption (van Alphen *et al* 2009). While only seven articles discuss BECCS demonstration projects, this is still relatively high compared to other technologies and considering the very limited BECCS deployment to date. Globally, less than a dozen small demonstrations have been built (Kemper 2015) with more ambitious projects having recently come online. One important development is a full scale (1 Mt CO_2 yr^{-1})

BECCS demonstration plant online at Decatur, IL USA (McCulloch 2016). More effort has involved small pilot scale plants, at scales of hundreds of kWs e.g. as described in Diego and Alonso (2016). A larger example is a study in Inner Mongolia of a 24 MW BECCS plant using desert shrubs and storing the CO_2 in algae (Pang *et al* 2017). A helpful preliminary assessment of these plants shows that their performance is quite similar considering their diversity (Bhave *et al* 2017). Kemper (2015) points out that lack of demonstration creates significant uncertainties about feasibility of large scale deployment. Gough and Upham (2011) point to feedstock availability, system integration, and CO_2 transportation infrastructure as critical components of the scale-up challenge for NETs.

4.1.2. *Niche markets and demand*

Turning to the demand side for BECCS, Bhave *et al* (2017) make the point that early demonstration plants struggle with weak or practically non-existent incentives to generate negative emissions. Where CO_2 emissions are priced, these markets are volatile and uncertain (Iyer *et al* 2015), while incentives for CO_2 capture are even more so. BECCS is unique among NETs in that it produces energy thus also exposing them to the vagaries of energy prices (MacDowell and Fajardy 2017).

Early niche markets are identified as sugar and paper processing facilities (Mollersten *et al* 2003) as well as industrial and municipal waste (Sanna *et al* 2012). One of the more circumspect studies on the important role of niche markets raises the issue of whether fossil fuel niches, such as EOR, could lock in fossil fuels rather than phase them out (Vergragt *et al* 2011).

For adoption in the longer term, Muratori *et al* (2016) use an IAM to assess very widespread deployment of BECCS and point to their impact on food prices, although they also indicate that such massive diffusion assumes many barriers are overcome. Others point to N_2O emissions due to associated intensification of agriculture (Popp *et al* 2011). Fridahl (2017) uses a survey to show that while IAMs depend heavily on BECCS for long-term decarbonization, BECCS have featured very rarely in policy debates, raising serious questions about the near-term incentives for adoption. BECCS is unique among NETs in that it produces useful energy in the form of electricity. However, some studies question whether the price of this electricity can compete with renewables in a mostly decarbonized system (MacDowell and Fajardy 2017). And in IAMs BECCS are adopted due to rising carbon prices not due to the value their electricity provides. The ability of BECCS to alter their use of inputs and capture rates provides a way to make them competitive in changing markets for both carbon and power (Sanchez and Kammen 2016). Modeling studies also make the point that scaling up to meaningful levels could take 'decades' (Azar *et al* 2013) or even 'half a century' (Azar *et al* 2010). Beyond IAM studies, a comprehensive review of impacts of BECCS on sustainable development finds positive economic effects but negative social and environmental impacts (Robledo-Abad *et al* 2017).

4.1.3. *Public acceptance*

BECCS' share of its articles on public acceptance was close to the NETs average. It is striking how many of the articles we reviewed claim to take a comprehensive approach to BECCS but neglect to mention public acceptance issues, a sentiment shared in the literature (Dowd *et al* 2015). Fridahl (2017) makes the point that people are still very unfamiliar with BECCS but that public acceptance of the technology will be crucial. They claim it does have more likelihood of acceptance than fossil CCS. Some argue that the agricultural links in BECCS will make it more publicly acceptable than CCS from fossil fuels (Wallquist *et al* 2012). Still, land use concerns (Searchinger *et al* 2008, Wise *et al* 2009, Plevin *et al* 2010, Popp *et al* 2011) and the essential tradeoff with food production, even with large uncertainties about the precise impacts (Smith *et al* 2013, Stevanovič *et al* 2016, Boysen *et al* 2017) could be difficult to overcome (Robledo-Abad *et al* 2017). However, the transportation of massive quantities of biomass may make it less acceptable than CCS. Open issues in accounting of land-use change emissions render the climate benefits of bioenergy and BECCS highly uncertain (Creutzig *et al* 2012, Plevin *et al* 2014); this uncertainty in climate benefits translates directly into investment uncertainty into BECCS as a NET. Regulation of stored CO_2 and its leakage is another key public acceptance issue (Boot-Handford *et al* 2014). Gough *et al* (2014) find that CO_2 pipelines are perceived more favorably than gas pipelines, although safety and risk concerns remain paramount. Given these concerns, Rodriguez *et al* (2017) discuss ways in which mitigation could be enhanced to reduce the need for BECCS or alternatively to use non-food feedstocks, such as algae (Sharp *et al* 2017). Similarly, Boysen *et al* (2017) argue that scale-up will be bounded, due to socially unacceptable levels of deforestation and food availability, so that BECCS potential is limited to a role supporting other mitigation options. Gough and Upham (2011) suggest smaller scale BECCS will be more acceptable. In an intriguing analysis using analogous technologies Buck (2016) describes some of the challenges to scale up (such as volatile markets) as well as concerns that could emerge with BECCS (such as unequal distribution of benefits) due not just to the extent of deployment but also from its speed. Indeed many of the concerns for CCS apply to BECCS (Wallquist *et al* 2012), as do those for generic bioenergy development, including public perceptions of facility siting, local air pollution, and feedstock transportation and handling (Thornley *et al* 2009).

4.2. Direct air carbon capture and sequestration (DACCS)

More than any other NET, direct air capture articles primarily focus on the technology and supply-side innovation topics. It has an above average share of articles on both demonstrations and scale up. It has the lowest share of articles on demand side topics of any NET. Indeed, in the companion paper that systematically reviewed costs and potentials, very little was found on the removal potential of DACCS (Fuss *et al* 2018). Plausibly this reflects the current understanding that economic costs rather than biophysical boundaries or concerns will determine future success of DACCS (Smith *et al* 2016).

R&D is currently the focus of innovation effort. This emphasis aligns with a recent National Academies report that recommended DACCS R&D 'to minimize energy and materials consumption, identify and quantify risks, lower costs, and develop reliable sequestration and monitoring.' At the center of research activity, various chemicals for absorbing and adsorbing CO_2 are investigated (Choi *et al* 2011, Goeppert *et al* 2011, Kong *et al* 2016). One area of R&D involves comparing the technical characteristics of various methods with which to capture CO_2 from ambient air, and the associated mechanisms to maintain this process, e.g. the energy used for pumping and compressing (Lackner 2013), as well as chemical processes for regenerating solvents (Goeppert *et al* 2012, NRC 2015, Sanz-Pérez *et al* 2016). Humidity is a concern for DACCS technologies, and R&D involves addressing humidity issues in ambient air (Darunte *et al* 2016).

4.2.1. Demonstrations and scale up

One reason for the focus on pure R&D is that the technology is arguably at a nascent stage. For example, Boot-Handford *et al* (2014) put DACCS in the context of power plant CCS and mainly dismiss the technology as 'in its infancy' and far more expensive that other mitigation options. Going beyond R&D, they compare their results to a conventional alternative—using power plant flue gas—and model the result at full commercial scale, 1200 MW. However, we do see some examples of demonstrations. Agee and Orton (2016) discuss a laboratory-scale air capture method, which achieves deposition of atmospheric CO_2 via refrigeration; they extend by discussing the advantages (avoiding refrigeration needs) and challenges (metal fatigue) of deploying this scheme in Antarctica. Holmes *et al* (2013) present a prototype of a cooling tower design, where air flows orthogonal to a downward flowing hydroxide solution; they demonstrate more than 1000 hours of operation, validating the cross-flow contactor design. Rau *et al* (2013) describe experiments with absorption of CO_2 via electrolyzed solution but use most of the article to discuss the energy requirements and costs at scale.

DACCS has an above average a share of articles on scale-up. The possibilities for mass production of air capture devices are a very attractive characteristic (Lackner *et al* 2012). The costs of DACCS appear to be a much more prominent topic than in other NETs. For example, a subset of the comparisons mentioned above involve cost estimates and financial comparisons (Socolow *et al* 2011, Sinha *et al* 2017). Other work more explicitly focuses on scaling up DACCS and includes estimates of cost reductions associated with >10Gt of CO_2 removal per year using component cost estimates (Lackner 2009) as well as bottom-up learning by doing and scale effects (Nemet and Brandt 2012). Comparisons of other estimates to mitigation costs also shows the feasibility of DACCS at very large deployment (Pielke 2009). Stolaroff *et al* (2008) provide an especially detailed bottom-up cost model of a sodium hydroxide spray capture system deployed at scale. Li *et al* (2015) consider integrating DACCS with wind power. Comprehensive information on costs and potentials can be found in (Fuss *et al* 2018).

4.2.2. Niche markets

Unlike other NETs, DACCS has received significant attention from entrepreneurial firms. This activity may be in part due to its main barrier being direct costs, rather than side effects nor social concerns. Direct implementation costs could be significantly reduced with successful innovation. In addition, there is additional investment safety in that CO_2 sequestered from ambient air can be accurately and precisely accounted for, in contrast to, for example, BECCS. Another driver of entrepreneurial activity is the existence of robust niche markets.

DACCS has been utilized routinely in spacecraft and submarines to reduce the CO_2 levels of ambient air in closed systems. High indoor concentrations of CO_2, as prevalent in bed rooms, and classrooms, have negative effects on performance, health, and human health (Kotol *et al* 2014). DACCS applications focusing on indoor air have the advantage of tangible benefits for occupants, and can work at higher efficiency due to up to 10 fold higher concentration compared to ambient open air (Lee *et al* 2015), and thus could hold promise as niche market.

Other startups can develop in niche markets that are focused on utilizing CO_2 for applications, such as greenhouse fertilization, industrial use, or enhanced oil recovery (Lackner *et al* 2012, Hou *et al* 2017, Ishimoto *et al* 2017). Enhanced oil recovery and microalgae cultivation are judged the most suitable niche markets where also dilute CO_2 is an adequate feedstock, thus requiring less energy for separation (Wilcox *et al* 2017). For example, a business case for power-to-liquid synfuels has been proposed that would make use of combined hybrid wind/PV, electrolysis, and hydrogen-to-liquid, involving also scrubbing CO_2 from ambient air powered by excess heat from electrolysis (Fasihi *et al* 2016). Carbon Engineering is a company that has published substantial data on important aspects of its technology (Holmes *et al* 2013, Holmes and Corless 2014). In addition, Climeworks had as its original aim the production of synfuels, relying on direct air capture. Yet, now, Climeworks is running the first commercial DACCS plant using the CO_2 to fertilize plants in a greenhouse. Climeworks also opened a DACCS facility in cooperation with Reykjavik Energy in Iceland, making use of waste heat from a neighboring thermal power plant to adsorb CO_2 from the filter, and injecting CO_2 underground as carbonated water, which then mineralizes in basaltic bedrock. Its technology is based on amine-based nanocellulose materials, but specifics have not been disclosed. These startups can develop in niche markets that are focused on utilizing CO_2 for applications, such as greenhouse fertilization, industrial use, or enhanced oil recovery (Ishimoto *et al* 2017).

4.2.3. Demand and public acceptance

Although niche markets exist, our coding found that DACCS has the lowest share of demand side articles among the NETs. Those that do consider demand for DACCS, primarily focus on carbon prices that would be required to justify the costs of DACCS (Pielke 2009). An integrated assessment modeling study found a primary impact of DACCS is that it extends the use of oil under climate policy (Chen and Tavoni 2013). Another IAM study found that the availability of DACCS can substitute for BECCS to achieve 1.5 °C targets (Marcucci *et al* 2017). Another source of demand, potentially, comes from oil producers concerned about the value of their reserves under climate policy (Nemet and Brandt 2012).

Only a few articles grapple with public acceptance. Lackner and Brennan (2009) lay out a broad set of possible public concerns and provide some initial assessments of their risks to the public. Leakage of stored CO_2 is one prominent concern, relevant to other NETs as well (Vilarrasa and Carrera 2015, van der Zwaan and Gerlagh 2016). DACCS is general seen as more benign than CCS, as fossil fuels are not involved. Cheng *et al* (2013) even develop a vision of an acceptable use of DACCS within a 'green town' to subsequently also improve public acceptance of CCS.

4.3. Biochar and soil carbon sequestration (SCS)

Soils on their own have the most articles of any NETs, followed by AR. The count of biochar articles is below the median. This literature on soils and biochar as NETs is large and mature, with several articles from the 1990s, though biochar is a more recent topic than soil carbon sequestration, which has been an active field for research for decades. Soils articles were quite representative of NETs in their distribution across innovation stages. Soils were relatively low on scale up and slightly lower than the average on demand pull, but generally were close to the averages in other innovation categories. Biochar was low on demonstrations and scale up compared to the average NETs. It was also low on all demand side categories. Due to biochar becoming an active topic of research more recently, biochar articles were the least likely to cover non-R&D stages of any technology; most work on biochar is still scientific.

Recurring R&D topics in prominent articles include: the amount of soil carbon retained by agricultural practices (Piccoli *et al* 2016), the corresponding amount lost (Sanderman *et al* 2017), and the impacts of tillage (Sohi *et al* 2010). Effects on carbon content and the overall health of soil from application of biochar is a large focus area (Fang *et al* 2016, Novak *et al* 2016, Pandian *et al* 2016), including for example N content (Prommer *et al* 2014). Temperature for pyrolysis is an important topic among biochar articles (Sohi *et al* 2010). Assessing the multiple benefits of biochar productions and use, e.g. via sugar cane is another research direction (Quirk *et al* 2012).

For R&D, two helpful reviews (Olson 2013, Olson *et al* 2014) establish research design choices that would make these experiments most useful for the next stage of demonstration. There are developing estimates of global resource potentials for soil carbon storage (Mishra *et al* 2012, Paustian *et al* 2016, Smith 2016) (Mishra *et al* 2012) as well as life cycle analysis of greenhouse gas impacts from various cropping systems (Cooper *et al* 2011).

The maturity of work on biochar and soils has led to a set of strong comprehensive review articles, including Lal (2005), Lal *et al* (2007), Woolf *et al* (2010), Paustian *et al* (2016), and more recently Woolf *et al* (2017).

4.3.1. Demonstrations and scale up

A recurring assertion in the soils literature is the need for large and long term demonstrations (Ringius 2002). Only one such study exists, which the authors claim is unique (Vochozka *et al* 2016). Other experiments have been relatively large (Piccoli *et al* 2016) and long term (Gutzloe *et al* 2014, Triberti *et al* 2016) and therefore approach a scale sufficient for demonstrations to generate new knowledge. Some use large scale assessments over long periods to quantify potentials (Liu *et al* 2014). Large and long term demonstrations seem most convincing as models for later adoption (Six *et al* 2004, Diacono and Montemurro 2010). Promisingly, unlike other NETs very long term (i.e. several decades) field experiments are common for soil carbon management (Hofmockel *et al* 2007, Smith *et al* 2012).

For scale up, some studies use field experiments to model large scale applications of techniques such as conservation tillage (Jiang *et al* 2014, Novak *et al* 2016). Global potentials have been estimated (Paustian *et al* 2016, Smith 2016). One focus has been the challenge of moving from dispersed land use decisions to managed and coordinated ones to enable scale up (Valujeva *et al* 2016). For biochar, financing mechanisms are also covered as a means to support scale up (Whitman and Lehmann 2009).

4.3.2. Demand and public acceptance

Even though the overall share of studies on demand is quite low for soils and especially biochar, several articles make the point that creating incentives for farmers to adopt is central to policy design (Dilling and Failey 2013, Stavi and Lal 2013). Estimating and reducing the costs of biochar are put forth as a key way to spur demand for it (Spokas *et al* 2012, Dickinson *et al* 2015), in particular, the costs of pyrolysis (Meyer *et al* 2011).

A key practical issue is how the accounting would work (Sanderman and Baldock 2010, Downie *et al* 2014). One model is a carbon credit scheme in Montana (Watts *et al* 2011). A small number of articles focus on the policy aspects that would affect demand (Smith *et al* 2007). Less directly, we often see that demand is implied in the context of discussions of land and soil management (Valujeva *et al* 2016).

Given their centrality as adopters, articles discussing public acceptance generally focus on farmers rather than the more general population (Olsson and Jerneck 2010, Jørgensen and Termansen 2016). Beyond farmers, a focus is on stakeholders and especially how the world poor stand to benefit (Stringer *et al* 2012). One notable study actually surveyed people on their perceptions of its risks and benefits (Glenk and Colombo 2011). Quite a few studies make the point that interdisciplinary research from many disciplines including social sciences is needed, even if such work isn't conducted by themselves (Lal 2008). One way the considerable transactions costs might be overcome is through international coordination. For example, the 4p1000 Initiative (www.4p1000.org) creates incentives for farmers to increase C to improve their soil quality (with C removal as a co-benefit) with a goal of increasing soil carbon content by 0.4% per year.

4.4. Ocean fertilization (OF)

The share of ocean fertilization articles on demonstrations and scale up was close to the NETs average. There were considerably fewer articles on the demand side, including none on niche markets. Scale up was the most prominent non-pure R&D topic. One observation is that the early papers (early 2000s) seem much more focused on scale up (both optimistically and skeptically) than later ones, which tend to be more focused on R&D.

4.4.1. Demonstrations and scale up

A number of experiments have taken place, some of which are substantially large enough to be considered demonstrations. For example, Boyd and Bressac (2016) describes 12 'mesoscale' iron fertilizations conducted in the GEOTRACES global survey. Others include an early small experiment, almost a demonstration (Bakker *et al* 2001) and an early mesoscale experiment (Boyd *et al* 2000). These 'experiments' in the Southern Ocean are also close to demonstrations (Smetacek and Naqvi 2008). Two articles take a distinctly innovation-oriented perspective, one stressing that we need to learn about it to scale up (Lampitt *et al* 2008) and another describing research design for a set of demonstration projects of increasing scale (Watson *et al* 2008).

Even though 15% of the articles discuss scale up, few explicitly address the process of getting from small experiments and demonstrations to large scale deployment. Exceptions include an early article including some discussion of the progression (Benemann 1992), as well as upscaling from experiments to global scale (Aumont and Bopp 2006). Another focuses on side effects but in doing so simulates growth of of over time (Oschlies *et al* 2010). We also see articles on the costs of scale up (Jones 2014) and also a focus on governance associated with scale up (Rabitz 2016). A more typical topic is to report what the impacts of very large deployment would be (Cao and Caldeira 2010, Keller *et al* 2014, Williamson *et al* 2012) and including for example, a model that considers teragrams of iron additions (Hauck *et al* 2016). A cluster of articles from a decade ago considered implementation issues, such as the legal framework necessary for scale up (Freestone and Rayfuse 2008), modeling large scale deployment (Zeebe and Archer 2005), and the need to involve businesses, not just scientists (Leinen 2008). It is interesting that these quite practically oriented articles are a decade or more old.

4.4.2. Demand and public acceptance

Discussion of the demand for ocean fertilization is notably lacking. We do see articles on how carbon markets could lead to demand for OF (Rickels *et al* 2012), accounting and incentives (Rickels *et al* 2010) and consideration of CDM applied to OF (Bertram 2010). We found no articles that we would classify as discussing niche markets for ocean fertilization.

The share of public acceptance articles is above the NETs average. Some work is not explicit about public acceptance, but does try to anticipate issues, for example recommending waiting until we figure out downstream effects of OF and unintended consequences (Cullen and Boyd 2008). Some cover governance issues (Williamson *et al* 2012), legal status (Bertram 2010), and the Law of the Sea (Freestone and Rayfuse 2008). Others discuss the social implications for people making a living from coastal areas (Mayo-Ramsay 2010). Work acknowledges that the public debate is intensifying—we don't know enough to drop it now (Strong *et al* 2009). One quite risk averse perspective claims that uncertainty about future state after deploying OF makes it unacceptable (Hale and Dilling 2011). Others also cover the public acceptance of experiments (Strong *et al* 2009) and why these tend to be unpopular (Smetacek and Naqvi 2008).

4.5. Afforestation and reforestation (AR)

Forests were second only to soils in the counts of articles. AR is a mature 'technology' (using our broad definition), it already exists at scale, and the potential for storing gigatonnes of carbon has been recognized for decades (Canadell and Raupach 2008, Jurgensen *et al* 2014). The share of AR articles is close to the average in all innovation categories. It is slightly higher in scale up and demand pull, and quite a bit lower in public acceptance. R&D articles include many reporting experiments on the sequestration potential of forests, at various spatial scales and time periods. In our initial filtering of articles, we discovered hundreds of AR studies that focus on site or species-specific carbon sequestration rates. These studies are not considered or reviewed here as their specificity does not allow for a straightforward assessment of NET potential or scale up possibilities. Nonetheless, the AR option should be considered against a backdrop of substantial empirical research into the basic characteristics and growth patterns of forests globally.

4.5.1. *Demonstrations and scale up*

We identified 62 AR articles that address scale up, however with widely differing interpretations of the ultimate scale needed. Articles we coded as demonstrations include: Returning Farmland to Forest Program in China (Zinda *et al* 2017), Forest Restoration Experimental Project (Gong *et al* 2013), and a project in Guangdong, China (Zhou *et al* 2008). A different type of demonstration included looking at the financial outcome of a CDM project after 6 years (Katircioglu *et al* 2016).

In contrast to other NETs, in many articles there is an implicit premise that scale could be achieved if societies wanted to and thus the research frontier is about side effects and potential size. For example, some articles discuss implications of scale up but not with a focus on how to accomplish this, even from quite a while ago (Alpert *et al* 1992, Shvidenko *et al* 1997). Others consider the scale-up process itself more analytically (Zhang *et al* 2015) (Caughlin *et al* 2016), even from earlier (Canadell and Raupach 2008) and even very early on in the AR literature (Myers and Goreau 1991). Some of these articles include experiments that explicitly try to assess the potential for scale up; a small portion of these are demonstrations. Several projects are already quite large, including government-led efforts at reforestation, typically for purposes other than carbon storage, and projects assessing AR outcomes at the scale of watersheds (Cunningham *et al* 2015).

A recurring theme is the identification of barriers to scale up, and overcoming them (Vadas *et al* 2007), often under the rubric of implementation issues (Polglase *et al* 2013). For example we see a focus on measuring monitoring and contracting (van Kooten and Johnston 2016). There is an ongoing stream of research into the costs of AR, either in terms of direct establishment costs (Summers *et al* 2015), opportunity costs (Nijnik *et al* 2013), or land-use switching under certain carbon price assumptions (Monge *et al* 2016). Already a decade ago a review study compiled the preceding 12 years of cost studies (Richards and Stokes 2004).

4.5.2. *Demand and public acceptance*

Discussions of the demand for AR typically focus on carbon markets (Adams and Turner 2012, Carwardine *et al* 2015, Liu and Wang 2016). Demand for ecosystem services can also lead to AR (Meyfroidt and Lambin 2011), especially with supportive policies (Liu *et al* 2008). For example reduced salinity is one benefit (Harper *et al* 2012). A consequence of these multiple sources of demand is how to optimize across these, especially when AR and soils are considered jointly (Valujeva *et al* 2016). A more precise conception of demand arises in more spatially explicit estimates of willingness to pay for AR (Sagebiel *et al* 2017).

An important agent in AR studies are farmers. For example one can see small scale family forests as a niche (Charnley *et al* 2010). Looking into farmers' preferences seems crucial to adoption, yet unusual in the literature, with exceptions (Lienhoop and Brouwer 2015). We see some emphasis on the role of farmers' negotiating power in these markets. A big barriers is transactions costs of lots of small scale transactions (van Kooten *et al* 2002).

The share of articles on public acceptance was low compared to other NETs. As with soil carbon sequestration and biochar, discussion is typically focused on private landholders (Schirmer and Bull 2014, Trevisan *et al* 2016), rarely going into realm of the public and their attitudes, beyond occasional economic incentives. AR directly impacts on the visual features of a landscape, so it is surprising to see such a lack of engagement between sequestration studies and the rich literature on landscape aesthetics and social/cultural expectations of 'nature' (Hunziker 1995, Daniel 2001). We do see some critical discussions of the impacts of 'carbon farming' (Funk *et al* 2014), water use (Jackson *et al* 2005), nutrient cycling (Smith and Torn 2013), and the need for stakeholder engagement (Atela *et al* 2016). A survey on attitudes toward AR was a notable exception to the dearth in this area (Nijnik and Halder 2013), including also a survey by Schirmer and Bull (2014).

4.6. Enhanced weathering (EW)

After ocean alkalination, EW was the NET with the lowest number of articles. Within EW, shares were relatively close to NETs averages; above average share of articles were on scale up and public acceptance.

4.6.1. *Demonstrations and scale up*

In response to the minimal body of work, Hartmann *et al* (2013) argue that there is a 'need for specific experiments'. They propose a cascade of experiments bridging the scales from millimeters to meters to 100s of meters as a means to scale up. Chemical engineering studies are particularly well positioned to consider the issues and opportunities of scale up

(Morales-Florez *et al* 2011, Hall *et al* 2014). Computer models are used to estimate potentials (Taylor *et al* 2016) which in a very general way simulates scale up, even if admittedly 'idealized' and missing important processes like the biological pump. Studies also draw on data sets of surface rock types to assess carbon removal potentials if kinetics are understood (Moosdorf *et al* 2014, Strefler *et al* 2018). The speed of weathering is a critical issue for scale up. It has been studied using empirical data on natural systems (Li *et al* 2008, Power *et al* 2009, Ollivier *et al* 2010), in particular the effect of temperature (Li *et al* 2016), as well as using laboratory-scale experiments (Renforth and Manning 2011). In addition, the applied rock material has fresh surfaces and fines from the production process, which will lead to enhanced kinetics, but is still not reliably quantifiable for upscaling. This can be seen in field studies if comparing kinetics of pyroclastics, remains from volcanism with fine grains, with other rocks (Hartmann 2009).

Interactions of minerals with soils and the biology is a key research area and important to scale up (Hartmann *et al* 2013, Manning and Renforth 2013, Taylor *et al* 2017, Beerling *et al* 2018). An early paper included a lab scale experiment showing that waste concrete and algae could be used to fix CO_2 as calcium carbonate (Takano and Matsunaga 1995). Use of waste materials as a source of minerals is included in more recent work as well (Sanna *et al* 2012).

As EW also releases geogenic nutrients it will affect biomass production, and can in addition to inorganic CO_2 sequestration be used to enhance biomass production (Hartmann *et al* 2013). However, this part has not been studied for upscaling so far and would be important to consider in the simultaneous use of AR and EW or BECCS and EW over large areas, specifically in areas with low geogenic nutrient contents in soils and bedrock.

4.6.2. *Demand and public acceptance*

We found only a small number of articles that discussed the demand side of EW; one on demand pull and five on public acceptance. As with other NETs, much of demand will come from carbon pricing; since EW costs are anticipated to be large they will require a substantial carbon price (Hartmann and Kempe 2008, Taylor *et al* 2016). A separate source of demand is the application of EW to increase agricultural yields, specifically in areas with depleted soils (van Straaten 2002, Hartmann *et al* 2013)—however, this is not currently a widespread practice.

A survey of public perceptions of geo-engineering technologies found that EW scored in the mid-range in terms of acceptability; in part because it is considered 'indistinct' relative to other GE technologies, public response was expected to be muted (Wright *et al* 2014). Specific public concerns mentioned are health effects of atmospheric suspension of pulverized rock (Taylor *et al* 2016) although there is little analysis to date of the risks of each, which depend also on the chosen application procedures. An important advantage of EW in the public domain is that rather than imposing competition for land it could enhance productivity (Strefler *et al* 2018), a major issue for public acceptance of BECCS and AR.

4.7. Papers that consider innovation topics across multiple NETs

One way NETs are combined is through comparisons of their deployment potentials to their risks. For example, Field and Mach (2017) argue that the risks are high even if potentials are large, thus advocating a focus on research, limited expectations, and a renewed emphasis on mitigation. Another group compares costs and potentials (Johnson *et al* 2017), as well as storage capacity (Scott *et al* 2015). Some policy related topics also involve multiple NETs. For example, Coffman and Lockley (2017) consider, but ultimately reject as infeasible, a carbon removal futures market to account for the delay in deployment. And in terms of actual policy, the £8.6 m UK Greenhouse Gas Removal Research Programme aims to test several approaches, although at that scale these would be at best pilot and prototype experiments rather than demonstrations in the sense we use it here. Ying and Yuan (2017) provide a Chinese perspective on designing policy for NETs. Other papers are less specific on the removal technique used but raise upscaling issues, such as game theoretic incentives (Sandler 2017). In the US, the National Academies is working on a scale up oriented report on NETs (National Academies 2017).

5. Conclusions

Our assessment of the extant literature on innovation and scale up in NETs shows a growing literature across all NETs technologies. The literature on emerging mitigation technologies emphasizes diversification to manage risk (Anadon *et al* 2017); that many NETs are at early stages in their development makes such an approach even more appropriate. The heterogeneity of these technologies, especially in their limitations and adverse side effects, strongly suggests a portfolio-based risk management approach to scaling up NETs, rather than a singular focus.

An important insight from the reviews in (Minx *et al* 2018) and (Fuss *et al* 2018), as well as in the IAM results included in this paper, is that even though IAM model results typically have a large role for NETs to play in the second half of the 21st-century, there is still urgency in developing them. This urgency derives in part from the generally long time periods required for the diffusion of technologies to attain widespread adoption, as described in section 2 of this review. That these technologies need to be removing CO_2 at the rate of gigatonnes-per-year (Fuss *et al* 2018) implies truly massive deployment, and consequently long

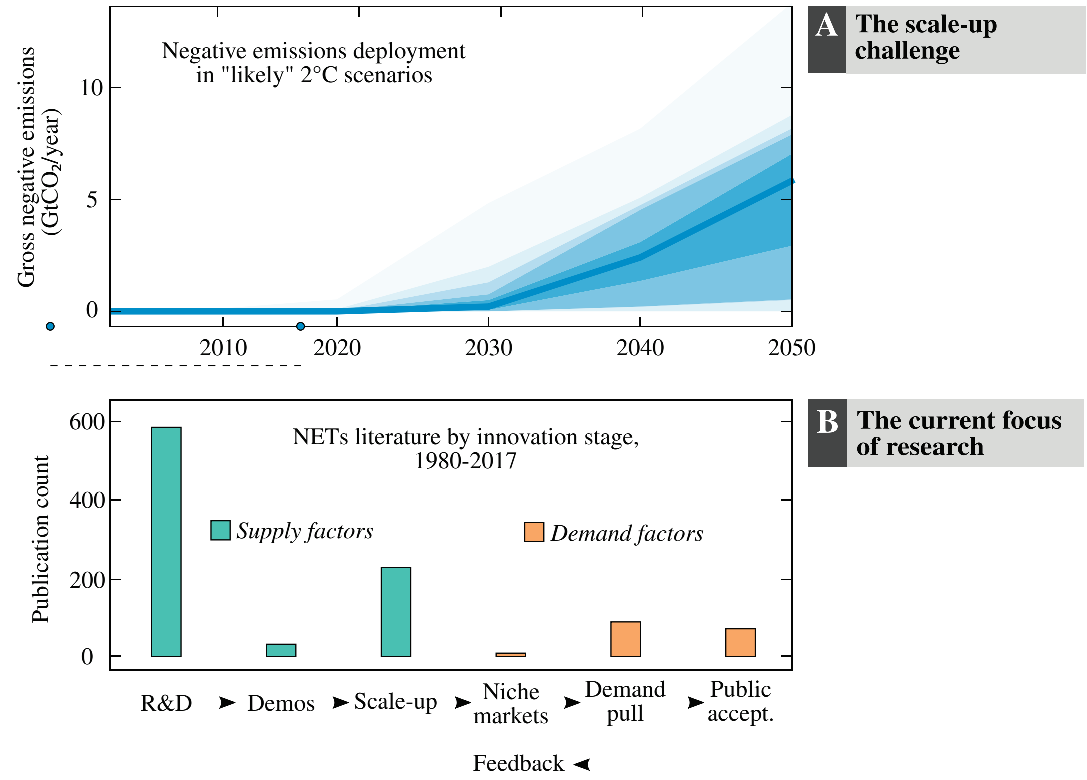

Figure 6. The growing need to scale up NETs from IAM results (A. upper) and the R&D-focused literature on NETs (B.lower). We see a dearth of work on the areas that will be crucial to the widespread deployment of NETs, notably in demonstration projects, niche markets, demand pull mechanisms, and public acceptance.

diffusion times. Thus, the extent of long term deployment depends to a great extent on a variety of decisions in the coming 10–20 years, not just in the second half of the 21st century (figure 6(*a*)). The IAM results also show that delays in mitigation are increasingly locking us into NETs dependent pathways for achieving the climate goals. In fact, if current NDCs are good indications of 2030 emission levels, targeting 2 °C from 2030 would require a similar net emissions pathway to targeting 1.5 °C today; that is, a NETs-intensive pathway. Yet, none of the NDCs contains plans to develop negative emissions.

The primary insight from the scientometric analysis is the relative preponderance of articles on the supply of NETs and the dearth of articles on demand for NETs (figure 6(*b*)). The literature on NETs is best described as still in the R&D phase. The subsequent stages of the innovation process are represented in this literature but are much less prevalent. Only one out of six NETs articles focused on topics related to the 'demand' for that technology. BECCS and ocean alkalization had the highest ratio on the demand side, about 1/3. Air capture had strikingly low counts of articles addressing demand for it. The language used reflects this supply-side focus: NETs are typically discussed as being 'deployed' rather than 'adopted.' Yet the reality is that for many NETs the array of stakeholders involved in adoption are manifold. Meeting median removal potentials for BECCS would involve bringing on-line hundreds of Decatur-scale CCS facilities each year; DACCS and others would involve transporting CO_2 to thousands of storage locations; soils and biochar would involve the activities of millions of farmers. A focus on 'deploying' NETs ignores the preferences and attidudes of these actors as well as the communities, in which they operate. NETs thus have much to learn from successfully diffused technologies, for which appealing to heterogeneous users, managing policy risk, as well as understanding and addressing public concerns are all crucial elements of the technology adoption process. Who wants them, for what reason; who will adopt them; and how will various publics respond to them are crucial questions, but ones which the literature has only marginally addressed. It needs to catch up for it to be relevant.

Taking the IAM results and the innovation scientometrics together in figure 6, we see an urgency to develop NETs and yet the research directions as evidenced in our scientometrics do not seem to anticipate the urgency of the challenge and the need to provide insights on the upscaling challenges to come. If NETs are to be deployed at the levels needed to meet 1.5° C and 2 °C targets, then important post-R&D issues will need to be addressed, for example including early deployment, niche markets, scale-up, demand, and public acceptance. For the NETs literature to be relevant and contribute to the opportunities provided by NETs, it will need to grow its efforts in post-R&D topics.

A. Supporting information

This section provides additional detail on the methods used to assign NETs articles to innovation categories, as well as additional descriptions of the results.

A1. Search string applied to web of science

We developed the innovation search queries as described in the main text. We applied the resulting Boolean search strings to the Web of Science. We applied one string for each innovation stage.

1. Research and development query:
   TS = (research or develop∗ OR 'R&D' OR lab∗ OR 'technology push' OR experiment∗)
2. Demonstrations query:
   TS = ((demonstrat∗ NOT ('we demonstrate∗' OR 'study demonstrate∗' OR 'result∗ demonstrate∗') OR pilot∗ OR 'non-laboratory' OR 'Valley of Death' OR 'field trial∗' OR prototype∗))
3. Scale-up query:
   TS = (scal∗ OR upscal∗ OR 'unit size' OR commercial∗ OR deploy∗ OR gigaton∗ OR Gt)
4. Demand pull query:
   TS = ((demand NOT ('N demand' OR 'demand for N')) OR consumer∗ OR learning OR experience OR diffuse∗ OR deploy∗ OR REDD OR 'carbon pric' OR 'carbon tax' OR 'climate policy' OR 'climate change policy' OR (climate NEAR regulation) OR (('1.5 °C' OR '1.5 degrees C') NEAR/3 (warming OR temperature)))
5. Niche markets query:
   TS = (niche OR 'willingness to pay' OR (utilize∗ NOT ('we utilize' OR 'study utilize∗' OR 'project utilize∗' OR 'was utilized' or 'were utilized' OR 'is utilized' OR 'are utilized')) OR (utiliz∗ AND (early NEAR/3 market OR early NEAR/3 application or early NEAR/3 use)))
6. Public acceptance query:
   TS = (accept∗ OR opinion∗ OR attitude∗ OR 'public support" OR oppos∗ OR perceive∗ OR perception OR adopt OR demand OR voice OR consensus OR educat∗ OR communicat∗ OR people OR residents OR individuals OR members OR customer∗ OR public OR popular OR soc∗ OR backyard OR (communit∗ NOT 'bacterial communit∗" NOT 'microbial communit∗" NOT phytoplankton communit∗) OR home OR population OR officials OR advoca∗ OR ethic∗ OR moral∗ OR legitima∗ OR safe∗ OR justif∗ OR democra∗ OR (survey AND (respondent∗ OR participat∗ OR express OR ∗agree)) OR food)
7. Innovation general query:
   This 'catch-all' search query is intended to include relevant articles not otherwise identified by our stage-specific queries.
   TS = ((innovat∗ OR 'technological change' OR 'technical change' OR learn∗ OR invent∗ OR knowledge OR appropr∗ OR understand∗ OR creat∗ OR experience∗ OR process∗ OR information OR differen∗) OR (invest∗ OR fund∗ OR finance∗ OR cost∗ OR spend∗ OR venture OR expenditure∗ OR econ∗ OR produc∗ OR price OR cost OR supply OR efficien∗ OR demand OR appl∗ OR design) OR (global OR diffuse∗ OR large OR scale OR many OR quantit∗) OR (public OR private OR business OR corporate OR institut∗) OR ('technological maturity' OR 'enhance knowledge' OR phase or stage) OR (effort∗ OR future OR role OR level OR basic OR approach OR department or need∗ or industr∗ or structure or resource∗ or activit∗ or trust or firm∗ or change or business or capital or agency or incentive∗ or benefi∗ or spillover∗ or challeng∗ or assess∗ or approach∗ or advanc∗ or early or strategy∗ or project or compet∗ or uncertainty or trade∗ or mechanism or local or value or transition or potential or outcome or hub or good or coordinat∗ or build∗ or tax decision or compan∗ or mission or lab∗ or evidence or commercial or challenge or budget or success∗ or pull or adopt∗ or produce∗ or own∗ or network∗ or manage∗ or implement∗ or goal or effect∗ or stage∗ or portfolio∗ or enterpris∗ or depreciate∗ or capacity or better or best or result∗ or actors or 'private sector' or 'public sector' or phase or concept or 'technology push' or success))

A2. Coding rubric used to manually code abstracts

The search string above provided a set of articles from which we manually coded each article into innovation categories. Two researchers coded each article as relevant to the innovation category for which it had been selected. The researchers used the following coding rubric as further guidance, which is meant to provide more context to the Boolean search strings for each innovation category. In contrast to a Boolean these words are meant to convey meaning so that the researchers would not use these terms strictly, but could for example use synonyms or related ideas. The terms below are to be used in addition to the Boolean terms, not to replace them.

1. R&D: model, laboratory, experiment, investigate, demonstrate, field trial. Articles that are not assigned to categories 2–6 are coded as R&D.
2. Demonstrations: pilots, prototypes, larger scale, long term. Do not include if: laboratory, experiment, or if any of the triggering words in previous list are mentioned in passing or for future research rather than a central part of the study.
3. Scale up: economies of scale, global, gigatonnes, increasing unit size, costs, increasing manufacturing capacity, integrated assessment, expansion. Do not include if any of the triggering words in previous

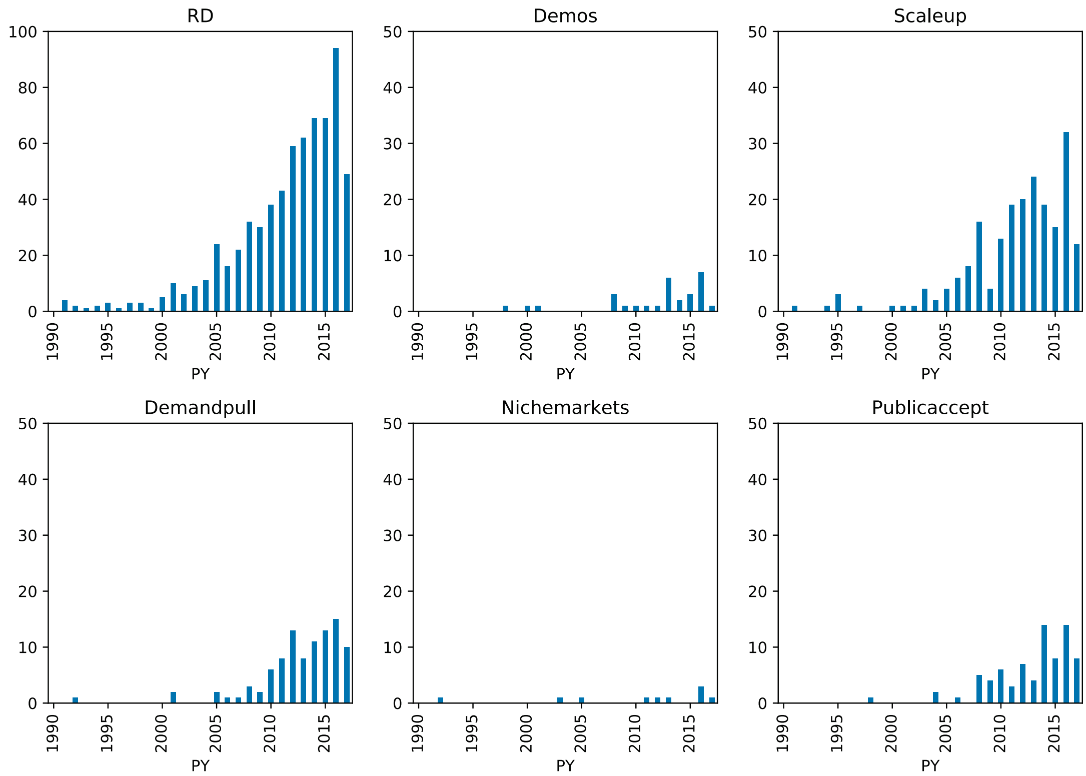

Figure 7. Trend in NETs publications by innovation stage.

Table 3. Share of articles in each technology and innovation stages that manual reading classified as 'relevant' to that technology and innovation stage.

	Supply-side categories			Demand-side categories			Total
Technology	RD	Demos	Scaleup	Demand pull	Niche markets	Public accept	Demand side
Afforestation/reforestation	100	69	78	57	33	8	68
BECCS	100	41	65	55	100	24	63
Biochar	100	11	71	44	100	23	67
Direct air capture	100	29	71	53	67	25	73
Enhanced weathering	100	50	78	100	0	63	82
Ocean alkalinisation	100	60	77	69	100	39	77
Ocean fertilisation	100	0	100	100	0	33	79
Soil carbon sequestration	100	57	62	56	0	58	81
NETs - General	100	31	65	58	0	15	61

list are mentioned in passing or for future research rather than a central part of the study.

4. Demand pull: markets, carbon tax, policy, prices, 1.5 or 2 degrees, adoption. Do not include if only deployment, or if any of the triggering words in previous list are mentioned in passing or for future research rather than a central part of the study.
5. Niche markets: willingness to pay, carbon utilization, enhanced oil recovery, co-benefit, early adopters.
6. Public acceptance: acceptance, public, governance, ecosystems.

A3. Additional analyses

We include descriptive statistic that show the result of our manual coding of the articles identified in each category. For example, in the cell BECCS/Demos, the 41% indicates that of the BECCS articles that our Boolean search identified as 'demonstrations', the researchers coded 41% of them as relevant using the manual coding rubric.

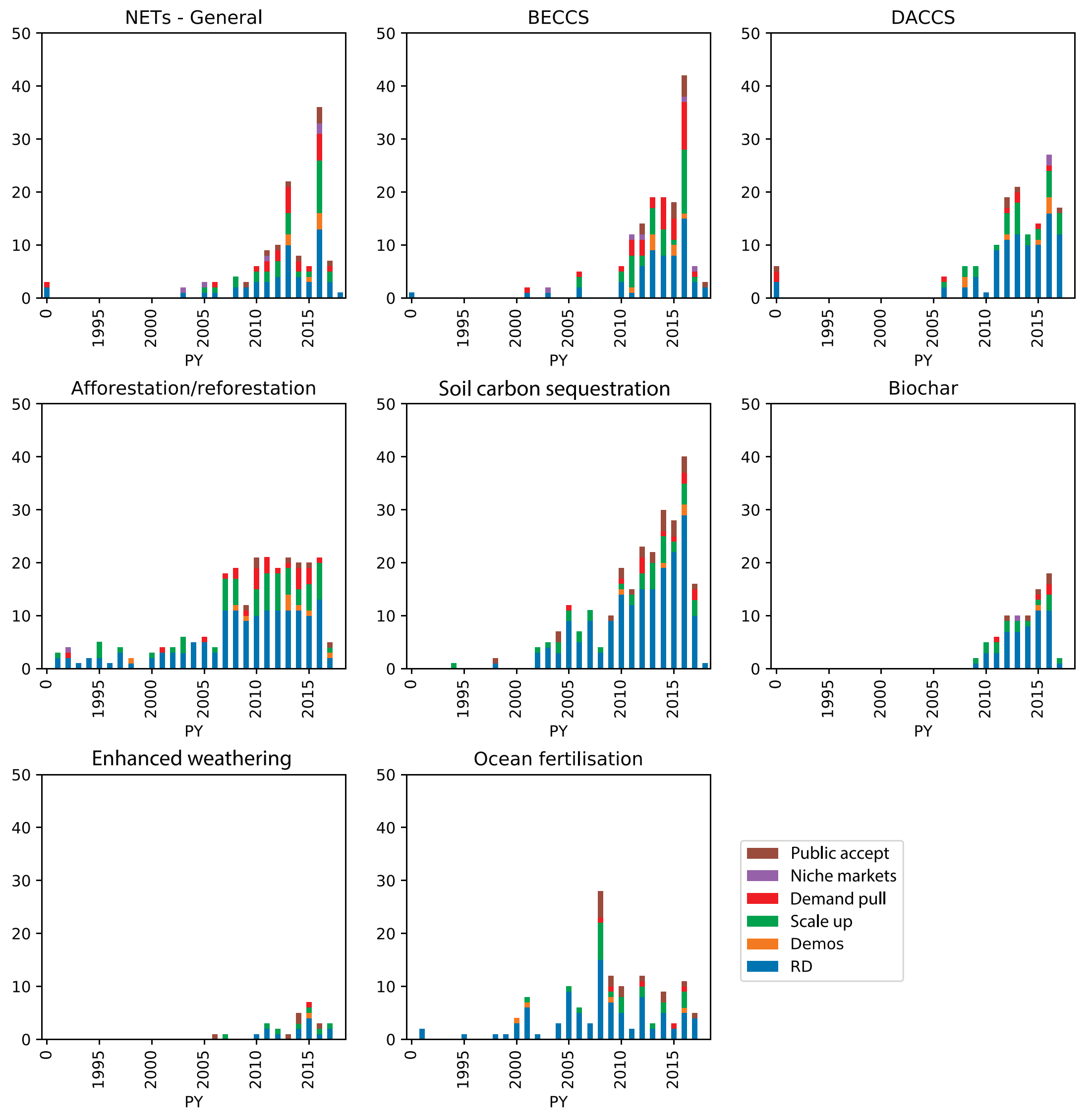

Figure 8. Trend in NETs publications by technology and innovation stage. Each panel includes one technology.

In figure 7 we show the trend in articles for each innovation stage. In figure 8 we show the trend in articles for each technology.

A4. Additional scenario data

In this section, we include additional scenario information on (i) the costs of and investments in BECCS and other mitigation technologies, (ii) the role of BECCS and other technologies in climate change mitigation and (iii) the geographical distribution of BECCS.

Costs and investments in BECCS and other mitigation technologies

Technology costs are important factors that drive scenario results. In figure 9 we show the total costs of various power plant technologies that are required to be deployed annually between 2020 and 2050 to keep global warming below 2 °C. Nuclear costs dominate other technology costs between 2020 and 2030. However as other mitigation technologies get deployed, this effect diminishes gradually. In 2050, renewables (i.e. solar and wind) constitute the major part of global energy system costs (US$200–1200 per year). In comparison the costs of BECCS are moderate (range: US$0–850 per year, median: US$200 per year). Importantly there is a great variability across results. This can be explained by differences in scenario and model assumptions as well as model structures.

Another important factor to consider is investment in technologies. Investments are a share of the total costs. Likewise we display the investments in various power plant technologies required annually between 2020 and 2050 to keep global warming below 2 °C. Again, most investments go into renewable energy technologies (US$ 250–1500 per year in 2050). Investments in nuclear and BECCS technologies remain moderate (US$ 100–300 per year and US$ 0–400 per year in 2050, respectively).

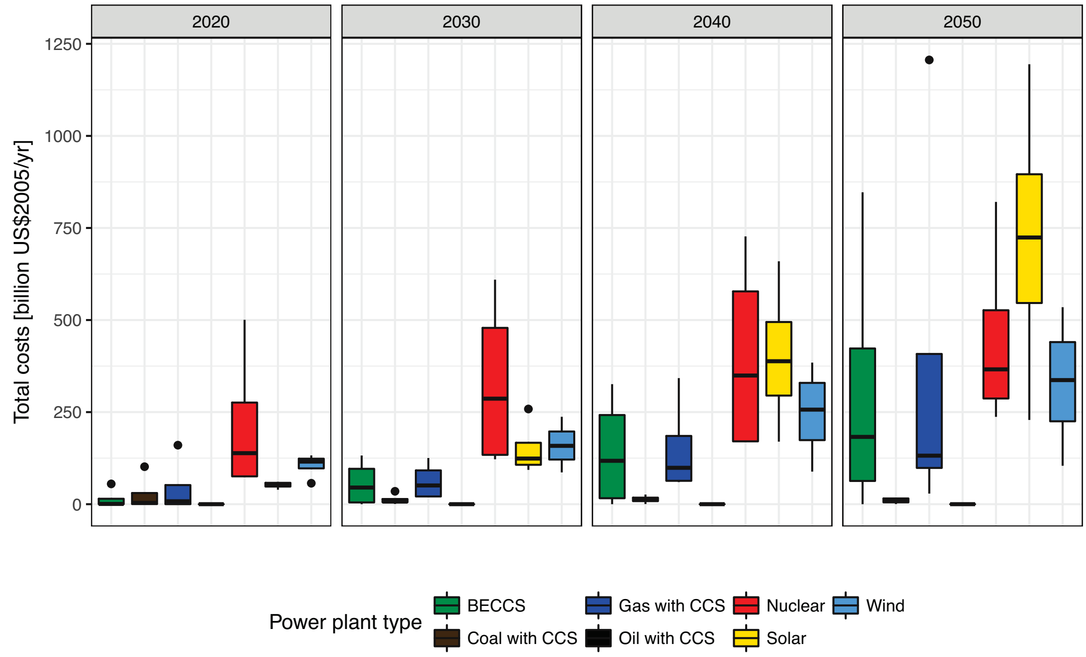

Figure 9. Annual total costs of various power plant technologies in a 2 °C scenario with immediate action. Boxplots show the statisical variability across models in the LIMITS-450 scenario. They are provided for each technology in 2020, 2030, 2040 and 2050. For each boxplot, the middle thick black bar represents the median. The lower and upper bounds of colored rectangles correspond to the first and third quartiles (the 25th and 75th percentiles). The whiskers extend in both directions to the minimum and maximum values, but no more than 1.5 time the inter-quantile range. Data beyond the end of the whiskers are defined as outliers and are shown as black dots. Data sources: LIMITS (Kriegler *et al* 2013).

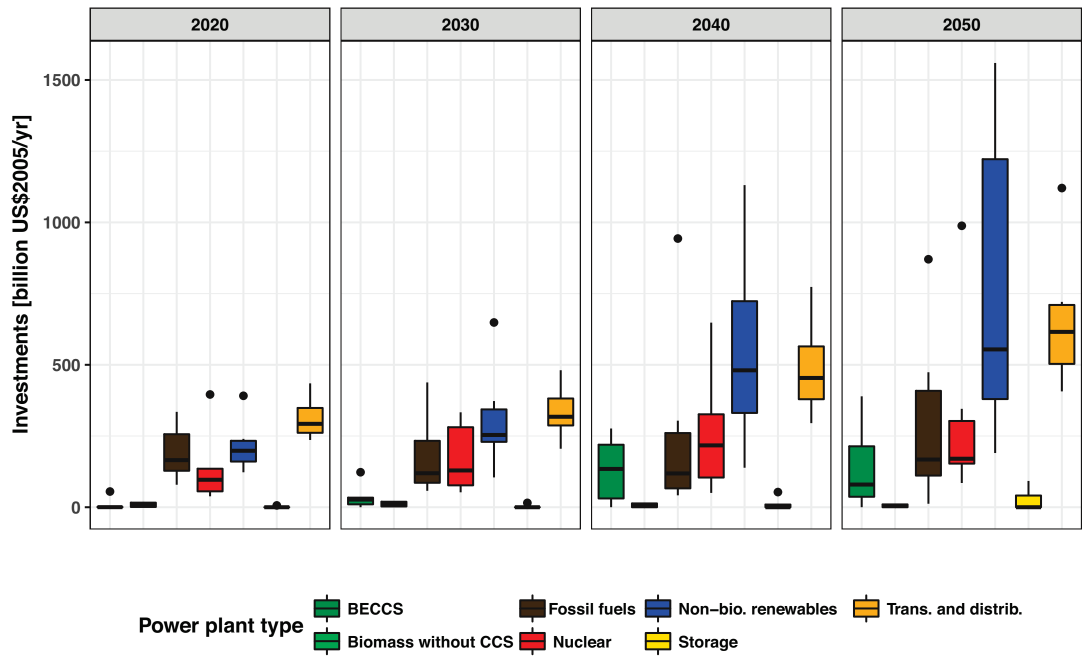

Figure 10. Annual investments in various power plant technologies in *a* 2 °C scenario with immediate action. Boxplots show the statisical variability across models in the LIMITS-450 scenario. They are provided for each technology in 2020, 2030, 2040 and 2050. For each boxplot, the middle thick black bar represents the median. The lower and upper bounds of colored rectangles correspond to the first and third quartiles (the 25th and 75th percentiles). The whiskers extend in both directions to the minimum and maximum values, but no more than 1.5 time the inter-quantile range. Data beyond the end of the whiskers are defined as outliers and are shown as black dots. 'Non-bio. renewables' stand for non-biomass renewables whereas 'Trans. And distrib.' stands for transmission and distribution. Data sources: LIMITS (Kriegler *et al* 2013).

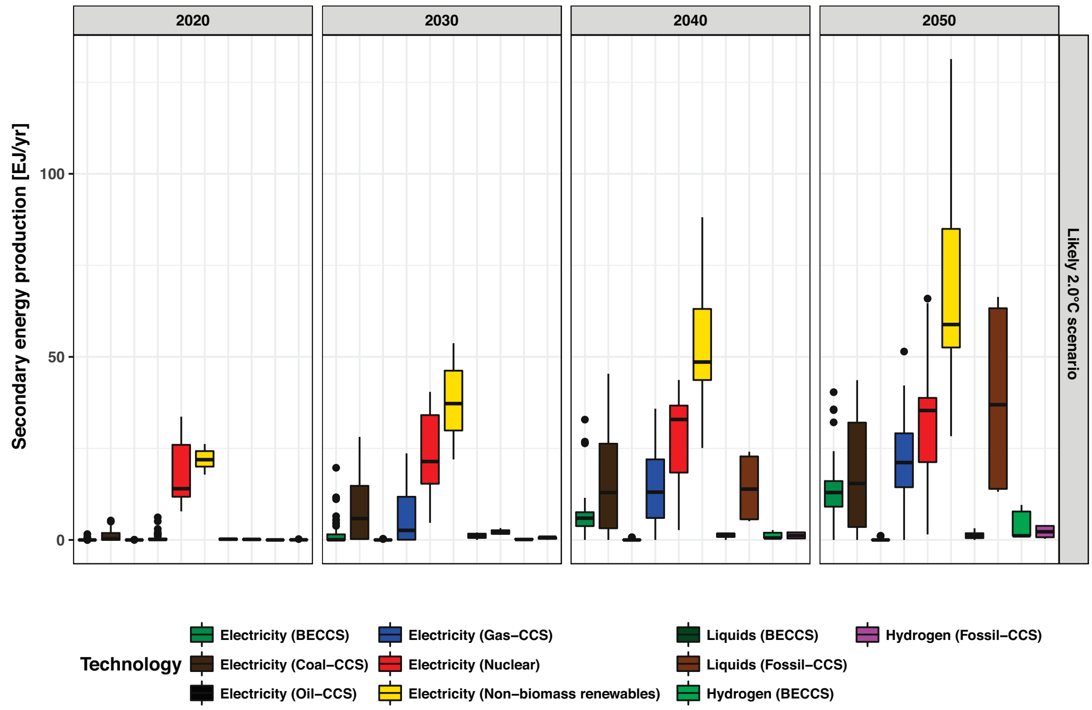

Figure 11. Annual secondary energy production from various technologies in likely 2 °C scenarios with immediate action. Boxplots are provided for each technology in 2020, 2030, 2040 and 2050. For each boxplot, the middle thick black bar represents the median. The lower and upper bounds of colored rectangles correspond to the first and third quartiles (the 25th and 75th percentiles). The whiskers extend in both directions to the minimum and maximum values, but no more than 1.5 time the inter-quantile range. Data beyond the end of the whiskers are defined as outliers and are shown as black dots. Data sources: AMPERE (Kriegler *et al* 2015), LIMITS (Kriegler *et al* 2013), RoSE (Kriegler *et al* 2016) and data from Luderer *et al* (2013) and Rogelj *et al* (2014).

Role of BECCS and other technologies in climate change mitigation

The role of various mitigation technologies can be understood by looking at the energy contribution from individual technologies to the global energy system. In figure 11, we show the global secondary energy production split by technologies that is required annually to keep global warming below 2 °C with a 66% chance. Overall all technologies play a role in mitigating CO_2 emissions. For electricity generation, renewables seem to be the most important technologies (hence the large investments shown in figure 10). Nuclear and gas power plants with CCS also play an important role. Over this time frame, liquids fuels are mostly produced with fossil technologies with CCS. BECCS does not play a large role in energy production. This is because the role of BECCS power plants is mainly to remove CO_2 from the atmosphere and not to generate electricity.

Geographical distribution of BECCS

Cumulative amounts of negative emissions from BECCS in various world regions over the period 2010–2050 are given in table 4 for the 2 °C climate goal (66% chance of keeping the increase in global mean temperature below 2 °C). These data provide insight about the geographical distribution of BECCS. Although results are subject to great variability, they seem to indicate that Latin America and the USA have a great negative CO_2 emission potential. Japan has the lowest potential.

Table 4. Geographical distribution of cumulative sequestered carbon by BECCS over the period 2010–2100 Units are Gt(CO_2). Data sources: AMPERE (Kriegler *et al* 2015), LIMITS (Kriegler *et al* 2013), RoSE (Kriegler *et al* 2016) and data from Luderer *et al* (2013) and Rogelj *et al* (2014).

World region/Country	Minimum	Median	Maximum	Number of scenarios
Africa	0	55	147	49
China	0	66	208	128
Europe	0	44	99	130
Former Soviet Union	0	46	159	130
India	0	38	149	130
Japan	0	6	22	96
Latin America	0	108	191	115
Middle East	0	15	122	49
Pacific OECD	9	18	44	12
Southeast Asia	0	45	63	49
USA	0	70	136	130

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