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Negative emissions—Part 1: Research landscape and synthesis

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Supplementary material for this article is available online

Abstract

With the Paris Agreement's ambition of limiting climate change to well below 2 °C, negative emission technologies (NETs) have moved into the limelight of discussions in climate science and policy. Despite several assessments, the current knowledge on NETs is still diffuse and incomplete, but also growing fast. Here, we synthesize a comprehensive body of NETs literature, using scientometric tools and performing an in-depth assessment of the quantitative and qualitative evidence therein. We clarify the role of NETs in climate change mitigation scenarios, their ethical implications, as well as the challenges involved in bringing the various NETs to the market and scaling them up in time. There are six major findings arising from our assessment: first, keeping warming below 1.5 °C requires the large-scale deployment of NETs, but this dependency can still be kept to a minimum for the 2 °C warming limit. Second, accounting for economic and biophysical limits, we identify relevant potentials for all NETs except ocean fertilization. Third, any single NET is unlikely to sustainably achieve the large NETs deployment observed in many 1.5 °C and 2 °C mitigation scenarios. Yet, portfolios of multiple NETs, each deployed at modest scales, could be invaluable for reaching the climate goals. Fourth, a substantial gap exists between the upscaling and rapid diffusion of NETs implied in scenarios and progress in actual innovation and deployment. If NETs are required at the scales currently discussed, the resulting urgency of implementation is currently neither reflected in science nor policy. Fifth, NETs face severe barriers to implementation and are only weakly incentivized so far. Finally, we identify distinct ethical discourses relevant for NETs, but highlight the need to root them firmly in the available evidence in order to render such discussions relevant in practice.

Introduction

Due to the limited remaining global carbon budget and heightened ambitions for stabilizing global temperatures, negative emissions technologies (NETs) that remove carbon dioxide from the atmosphere have become an almost indispensable component of strategies to meet the international climate goals established by the Paris Agreement—particularly the 1.5 °C goal (Peters 2016, Rogelj *et al* 2018, 2015, Luderer *et al* 2013, 2016, Minx *et al* 2017b). Despite recent dispute over the exact size of the carbon budget (Millar *et al* 2017), the available scenario evidence so far suggests a remaining carbon budget between 0–200 Gt CO_2 for the 1.5 °C target, i.e. there may be only five years' worth of CO_2 emissions left at current rates before every additional tonne of CO_2 would need to be compensated for again by means of negative emissions (Minx *et al* 2017b). Across the 21st century, this amounts to a total of between 400 and 1000 Gt of CO_2 emissions in most scenarios that are removed and safely stored away (Rogelj *et al* 2018, 2015)—about 10 to 25 years' worth of today's global emissions. In the absence of substantial and sustained reductions of global GHG emissions (Le Quere *et al* 2016), the dependence on negative emissions for reaching the climate goals continues to grow (Minx *et al* 2017b).

Despite various assessments of NETs and more emphasis on NETs in the most recent report of the Intergovernmental Panel on Climate Change (IPCC) (Ciais *et al* 2013, Clarke *et al* 2014, Shindell *et al* 2013), the current knowledge on NETs is still diffuse and incomplete (Fuss *et al* 2016, Smith *et al* 2016), but also fast growing (Minx *et al* 2017c). For the United Nations Framework Convention on Climate Change (UNFCCC) facilitative dialogue in 2018 and upcoming climate change assessments such as the IPCC special report on 1.5 °C of global warming or the Sixth Assessment Report (AR6), a more systematic assessment of what we do and do not know about NETs is urgently required.

This is the first of three reviews—the other two are Fuss *et al* (2018) and Nemet *et al* (2018)—that jointly aim to provide a comprehensive and systematic assessment of the academic literature on NETs. Our emphasis is on determining the potential role of NETs for reaching the international climate goals, with a focus on co-benefits and risks, technology costs, required innovation and diffusion dynamics as well as opportunities and barriers of NET deployment at the required scales. Our systematic review also covers evidence from the social sciences and ethics that have not—thus far—been widely recognized in available NETs assessments.

We begin this review with a definition of terms. We then outline the methodology used to analyze the landscape of NETs literature and subsequently present the results. The next sections of the paper are devoted to taking stock and synthesizing the outcomes of Fuss *et al* (2018) and Nemet *et al* (2018), thus providing a synthetic assessment of the role of negative emissions in climate change mitigation. We then review the ethical discourses on NETs and end by discussing urgent research gaps.

Assessing negative emissions

A short history of negative emissions[14]

Human interventions into the Earth's climate, including the direct removal of CO_2 from the atmosphere, have been a subject of research for more than a century. In fact, the link between atmospheric CO_2 reductions and global temperature change is as old as the discussion around climate change itself (Arrhenius 1896). Initial discussions concerned the benefits of human-induced warming on agricultural productivity and forestalling a future ice age by adding CO_2 to the atmosphere (Ekholm 1901, Fleming 2000, Keith 2000, National Research Council 2015, Arrhenius 1896). The idea that humans could remove CO_2 from the atmosphere at large-scale to counter global warming was part of early suggestions on how to solve the problem of climate change (Callendar 1938, National Research Council 2015). During the second half of the 20th century more concrete proposals were made on how to remove CO_2 from the atmosphere by planting trees among others (Baes *et al* 1980, 1977, Dyson 1977, Marchetti 1977, 1979).

With the start of international climate diplomacy in the late 1980s and the establishment of the UNFCCC and the IPCC, interest in human response strategies started growing. Yet NETs as such only received attention peripherally in the early assessments (Keith 2000). The mainstreaming of the discussion on NETs has occurred recently and is closely related to the emergence of a new suite of climate change mitigation scenarios from integrated assessment models (IAMs) that feature BECCS (Bioenergy with Carbon Capture and Storage) as an explicit carbon dioxide removal option in the technology portfolio. Scenarios with (large) NETs deployments and net negative emissions during the second half of the century were first summarized in the IPCC's Fourth Assessment Report (AR4) (IPCC 2007b). This assessment was based on a small set of publications covering a limited number of models that appeared just before AR4's finalization (Azar *et al* 2006, Rao and Riahi 2006, Riahi *et al* 2007, van Vuuren *et al* 2007). The report concluded from the analysis of these initial scenarios that negative emissions might be essential for achieving stringent climate targets—particularly those

[14] This section heavily draws on the National Research Council (2015). For more details, readers are referred to this study and its underlying sources.

achieving climate stabilization at atmospheric concentrations below 490 ppm CO_2eq[15].

In the aftermath of AR4 there was growing interest in the international climate policy debate to explore mitigation pathways that keep warming below 2 °C. Thus, the BECCS option was added to all major IAMs (Blanford *et al* 2014) and negative emissions became a feature of most IAM scenarios subsequently collected for the IPCC's Fifth Assessment Report (AR5) (Fuss *et al* 2014). In the AR5 period, the major modelling inter-comparison exercises focused on understanding the technological and economic requirements of meeting stringent long-term climate goals (Kriegler *et al* 2014, 2013b, 2015, Riahi *et al* 2015, Clarke *et al* 2009). Two major innovations contributed to a broader understanding of alternative long-term mitigation pathways: (1) the exploration of the impact of excluding individual technologies or technology clusters (Krey *et al* 2014, Kriegler *et al* 2016, Rose *et al* 2014, Kriegler *et al* 2014), and (2) the exploration of the impact of less optimal policy trajectories (delayed action; fragmented action) for meeting a particular climate goal (Eom *et al* 2015, Schaeffer *et al* 2015, Blanford *et al* 2014). In both cases, the availability of NETs played an important role in keeping stringent climate goals within reach (Luderer *et al* 2013, Riahi *et al* 2015). AR5 therefore highlighted the importance of NETs in 2 °C and other stringent mitigation scenarios, but pointed to the uncertainties about the availability, scale and side-effects of BECCS and other NETs (Clarke *et al* 2014).

The prevalence of large-scale NETs deployment in many 2 °C scenarios was controversially received after AR5 (Anderson 2015, Anderson and Peters 2016, Williamson 2016, Geden 2015, Fuss *et al* 2014). Yet, as the ambition to pursue further efforts to limit further warming to below 1.5 °C was added to the Paris Agreement (UNFCCC 2015), NETs have secured a place directly in the spotlight of many climate change mitigation discussions ever since (Hallegatte *et al* 2016, Hulme 2016, Schleussner *et al* 2016, Luderer *et al* 2013, Peters 2016, Rogelj *et al* 2015, 2018). A series of high level commentaries picked up on the issue (Field and Mach 2017, Gasser *et al* 2015, Lomax *et al* 2015a, Parson 2017, Peters and Geden 2017, Obersteiner *et al* 2018, Vuuren *et al* 2017, Anderson 2015, Anderson and Peters 2016, Geden 2015, Williamson 2016, Fuss *et al* 2014). Scenario evidence has been center-stage to this discussion. Authors have highlighted the importance of NETs for achieving the climate targets (Gasser *et al* 2015, Fuss *et al* 2014), stressed the limits to global carbon sequestration potentials (Smith *et al* 2016, Field and Mach 2017), questioned the feasibility of NETs in climate change mitigation (Anderson 2015, Geden 2015), and pointed out the bias in the exploration of alternative NETs futures (Obersteiner *et al* 2018). At the same time, modelling teams have started with the implementation of larger portfolios of NET options beyond BECCS (e.g. Chen and Tavoni 2013, Marcucci *et al* 2017, Streffler *et al* 2018). This could lead to even larger cumulative carbon dioxide removal in upcoming mitigation scenarios, as suggested by these initial studies. Hence, the discussion on NETs is set to continue. Doing so based on a comprehensive and sound understanding of the scientific literature is a pre-condition for accelerated learning.

Defining negative emissions

CO_2 emissions from human activities currently exceed 40 $GtCO_2 yr^{-1}$, but less than half of these emissions are currently accumulating in the atmosphere—i.e. adding to the growth in atmospheric CO_2 concentrations (Le Quéré *et al* 2016). The remainder are being absorbed by 'natural' carbon removal processes that counteract the human perturbation of the carbon cycle, i.e. emissions are taken-up by the terrestrial and ocean sinks (National Research Council 2015). It is important to note that discussions of negative emissions are not about natural processes of carbon dioxide removal. We define negative emissions as *intentional human efforts to remove CO_2 emissions from the atmosphere*. We apply this simple definition throughout our entire review (Fuss *et al* 2018, Nemet *et al* 2018).

Despite this simplicity, there has been considerable discussion and confusion around definitions of negative emissions and how they relate to other key concepts of climate policy (table 1)—most importantly mitigation, adaptation and geoengineering (Boucher *et al* 2014, Shepherd 2012, Shepherd *et al* 2009, Vaughan and Lenton 2011, IPCC 2014b, Keith 2000). Mitigation has been traditionally defined within the IPCC as 'a human intervention to reduce the sources or enhance the sinks of greenhouse gas emissions' (IPCC 2014c, 2013, 2014a, 2014b). This definition subsumes all those NETs that focus on natural sink enhancement such as afforestation and reforestation (AR), soil carbon sequestration (SCS), ocean fertilization (OF), biochar (BC) or enhanced weathering (EW) as an integral part of mitigation, while other NETs that geologically store the sequestered CO_2 such as BECCS or direct air capture with carbon capture and storage (DACCS) do not qualify. All NETs are further, in principle, covered by the definition of carbon dioxide removal technologies as one distinct technology cluster under geoengineering or climate engineering (subject to the interpretation of scale in that definition), resulting in blurry boundaries among key concepts in climate policy (IPCC 2013, 2014b, 2014c, 2014a).

To establish clear boundaries between the major human response options, it is instructive to consider the causal chain underlying the climate problem as shown in figure 1. In contrast to the current IPCC definition (see table 1), we limit mitigation to all measures that target CO_2 emissions prior to their release

[15] These scenarios have a greater than 50% probability to keep mean temperature rise below 2 °C throughout the 21st century.

Table 1. Key concepts around human response options to climate change and their definition in IPCC assessments.

Subject	Definition	Reference
Carbon sink	Any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere.	IPCC, AR3; WG1, WG2, WG3; AR4: WG1, WG2, WG3; AR5: WG1, WG2, WG3
Mitigation	A human intervention to reduce the sources or enhance the sinks of greenhouse gases.[…]	IPCC, AR3: WG1, WG2, WG3; AR4: WG1; AR5: WG1, WG2, WG3
Adaptation	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.	AR3: WG3; AR4: WG2; AR5: WG2, WG3
Geoengineering	(Technological) Efforts to stabilize the climate system by directly managing the energy balance of the earth, thereby overcoming the enhanced greenhouse effect.	AR4: WG3
	Geoengineering refers to a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change. Most, but not all, methods seek to either (1) reduce the amount of absorbed solar energy in the climate system (solar radiation management) or (2) increase net carbon sinks from the atmosphere at a scale sufficiently large to alter climate (carbon dioxide removal). Scale and intent are of central importance.	AR5: WG1,3
Carbon dioxide removal	Carbon dioxide removal methods refer to a set of techniques that aim to remove CO_2 directly from the atmosphere by either (1) increasing natural sinks for carbon or (2) using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration. CDR methods involve the ocean, land and technical systems, including such methods as iron fertilization, large-scale afforestation and direct capture of CO_2 from the atmosphere using engineered chemical means. Some CDR methods fall under the category of geoengineering, though this may not be the case for others, with the distinction being based on the magnitude, scale, and impact of the particular CDR activities. The boundary between CDR and mitigation is not clear and here could be some overlap between the two given current definitions.	AR5: WG1,3

References: AR3- WG1 (IPCC 2001c); WG2 (IPCC 2001a); WG3 (IPCC 2001b); AR4- WG1(IPCC 2007c);WG2 (IPCC 2007a); WG3 (IPCC 2007b); AR5- WG1 (IPCC 2013); WG2 (IPCC 2014a); WG3 (IPCC 2014b)

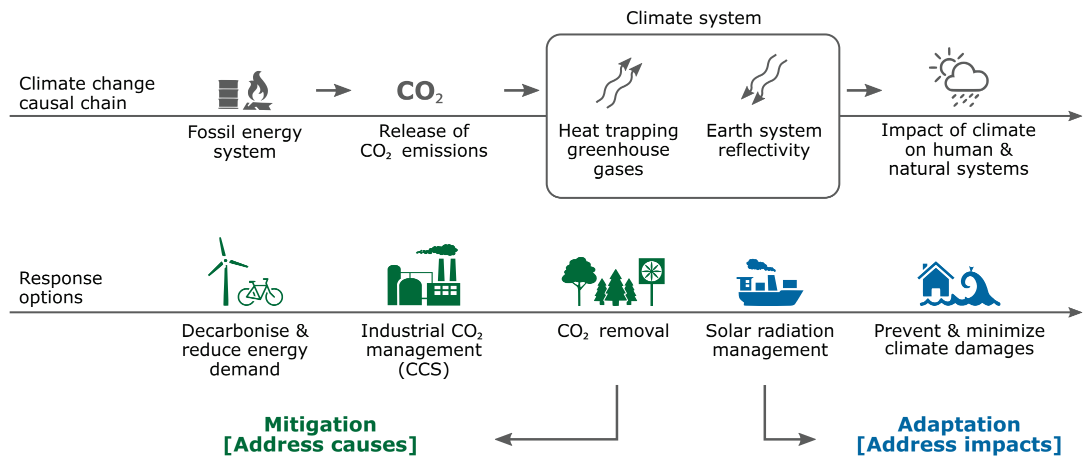

Figure 1. Human response options to the climate problem. Horizontal arrows in the top row show the causal chain of the climate change problem. Vertical arrows and bottom row define locus and modes of intervention for climate policy. Graph further developed from Keith (2000).

to the active biosphere. These include (a) all efforts to avoid and reduce CO_2 emissions through energy demand reductions, switching to low or no carbon fuels or lifestyle changes; and, (b) industrial carbon management that captures and stores CO_2 emissions from fossil fuel power plants. NETs only remove CO_2 again after release to the atmosphere. By doing so, they still directly address the causes of global warming: the heat-trapping effect on out-going long-waved radiation. In this sense, NETs are still conceptually very similar to mitigation measures. In contrast, solar radiation management (SRM) approaches - the other technology cluster covered by the geoengineering concept - attempt to modify and enhance the reflectivity of the Earth system (albedo), thereby reducing incoming short-wavelength solar radiation. Hence, SRM methods temporarily compensate positive forcing from CO_2 with negative forcing from other agents. They focus purely on the management of climate impacts and are therefore conceptually much closer to adaptation measures, which attempt to deal with the impacts of (unavoidable) climate change on human and natural systems.

It is because intervention points of both SRM and NETs are *after* CO_2 emissions are released to the active biosphere that many scholars and assessments have discussed both jointly under the notion of geoengineering (Bellamy *et al* 2012, IPCC 2011, Johannessen and Macdonald 2016, Maas *et al* 2012, Williamson *et al* nd, IPCC 2014b, Vaughan and Lenton 2011, Marchetti 1977, Shepherd 2012, Shepherd *et al* 2009). It is therefore reasonable to summarize NETs and SRM as geo-engineering options, because they intervene into the climate system directly (Keith 2000). Moreover, authors argue that SRM and NETs are both subject to potentially severe moral hazard (Preston 2013). More recently, there has been growing skepticism with such an approach due to the danger of subsuming two very different technology clusters under one heading (Lomax *et al* 2015b, Boucher *et al* 2014, IPCC 2011, National Research Council 2015). Above all, while NETs address the high atmospheric carbon concentrations that cause the climate problem, SRM schemes do not. But there are many other important differences such as the novel global risks introduced by SRM schemes, the fundamentally different time scales at which SRM and NETs work or the very different governance challenges (National Research Council 2015). Acknowledging the presence of other positions in this debate, we argue that geoengineering is not a useful term for informing discussions on human responses (as well as their trade-offs and side-effects) to climate change. Therefore, we treat SRM and NETs in addition to mitigation and adaptation as distinct human response options rather than categorizing them together under geoengineering.

A taxonomy for negative emissions technologies

A variety of NETs that remove carbon dioxide from the atmosphere have been proposed. We define 'technology' in broad terms as a means to an end. This includes both devices or hardware but also practices and behavior (Arthur 2007, Nemet *et al* 2018). Some technologies—afforestation and reforestation, or soil carbon sequestration—are very well-known and have been researched with other mitigation technologies from very early on in the debate (Kupfer and Karimanzira 1991, Jepma *et al* 1995, Hourcade *et al* 1996, Kauppi *et al* 2001, Nabuurs *et al* 2007, Smith *et al* 2007). Others, like DACCS and BECCS, have been subject to a structured scientific discourse only rather recently. Our focus is on CO_2 removal only, but we note the existence of technologies that remove other non-CO_2 greenhouse gases from the atmosphere (de Richter *et al* 2016, Ming *et al* 2016, Stolaroff *et al* 2012, Lomax *et al* 2015b, Boucher *et al* 2014).

Figure 2 provides a taxonomy for NETs. We distinguish NETs across a variety of dimensions: (1) capture process; (2) technology clusters and their various implementation options; (3) earth system; as well as, (4) storage medium. Five out of the seven technology clusters considered (AR, SCS, BECCS, OF, BC) use photosynthesis for capturing the CO_2. Only EW (incl. ocean alkalinization) and DACCS bind the CO_2 through chemical processes. For almost all technologies there are distinct implementation schemes available that can differ in their effectiveness of sequestering and storing the CO_2 away (Fuss *et al* 2018). Note that agro-forestry is an implementation option that cuts across the AR and SCS cluster. Further, we understand biochar conceptually as an implementation option of SCS, but will later treat it individually as it has attracted a large amount of attention—particularly during the last 15 years (Minx *et al* 2017c).

A central distinction is whether the technology is land or ocean-based, as the latter can involve trans-boundary pollution issues and will require higher levels of international coordination—particularly if larger scale applications are intended. In fact, Boucher *et al* (2014) usefully divide NETs up into domestic and trans-boundary removal methods—a distinction that runs along this dimension. In this sense, OF and at least some forms of blue carbon (Johannessen and Macdonald 2016) and EW (land- and ocean-based approaches) are potentially constrained by this. Finally, the storage medium is of great interest as there can be a significant variation in the reliability, permanence and overall quantity of available CO_2 storage. In principle, the literature highlights that land management approaches such as AR and SCS provide more vulnerable (and less verifiable) storage options, where stored CO_2 can be released again within short time frames. Geological reservoirs, on the other end of the spectrum, for CO_2 from BECCS and DACCS are thought to provide a larger and less vulnerable storage option.

Assessments of negative emissions

Climate change assessments by the IPCC (1996b, 1996c, 1996a, 2014b, 2001c, 2001a, 2001b, 2007c, 2007a) and others (Keith 2000) do not have a tradition of systematically reviewing NETs despite some early exceptions (National Research Council 1983, National Academy of Sciences *et al* 1992). Usually, some NETs options related to sink enhancement were considered to varying degrees, but no comprehensive portfolios of NETs options were considered (Keith 2000). Only the

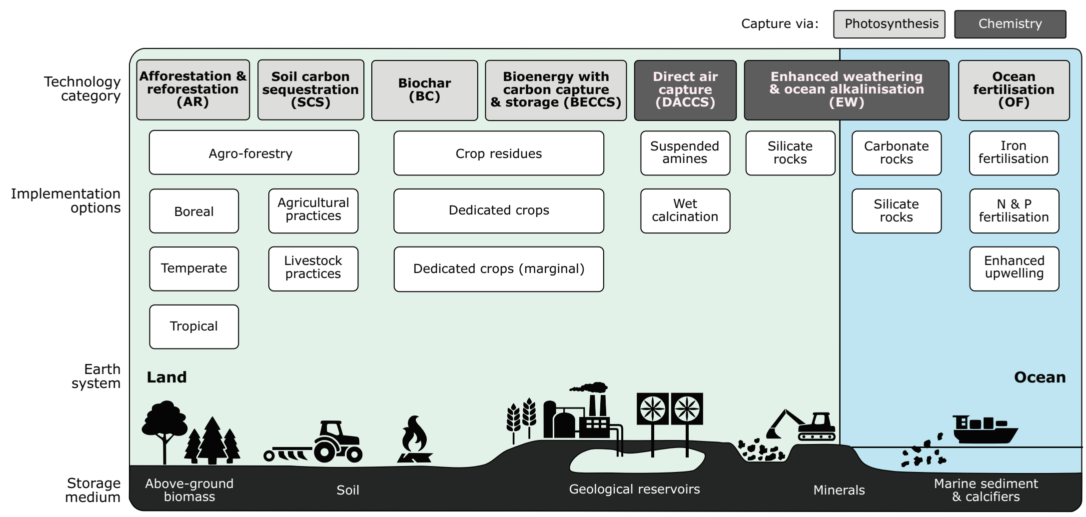

Figure 2. A taxonomy of negative emissions technologies (NETs). NETs are distinguished by approach to carbon capture, earth system and storage medium. Major implementation options are distinguished for each NET.

most recent fifth assessment report provided dedicated sections in the Working Group I (Ciais *et al* 2013) and III (Clarke *et al* 2014) reports, and a box in the synthesis report (IPCC 2014d) as well as dedicated findings in some of the summary documents (Edenhofer *et al* 2014, IPCC 2014d).

The time period after AR4 has seen NETs as a topic mushrooming in climate change assessments. Today, the literature already provides a number of reviews that consider a wide spectrum of options (table 2). Standing out among these reviews are two formal scientific assessments conducted by the National Academy of Sciences and the Royal Society (National Research Council 2015, Shepherd *et al* 2009), but there are other assessments available, both in- and outside the peer-reviewed literature (Friends of the Earth 2011, McLaren 2012, Caldecott *et al* 2015, Vaughan and Lenton 2011, Smith *et al* 2016, Fuss *et al* 2016). This flurry of assessments and increasing engagement among scientific organizations, as well as governmental funding bodies reflects a perceived need for authoritative reviews, both due to the rising prominence of NETs in mitigation scenarios, and the ensuing controversies.

Nonetheless, few of the existing reviews cover both a breadth of technologies and consider their broader ethical, socio-economic, and innovation challenges (table 2). Many reviews focus only on biophysical limits and potentials (Lenton 2010, 2014, Smith *et al* 2016) (IPCC AR5). Where ethical and legal considerations are raised, they predominantly focus on ocean fertilisation (National Research Council 2015), do not distinguish between NETs and SRM methods (Kolstad *et al* 2014, IPCC 2014b, Shepherd *et al* 2009), or focus only on SRM. Innovation, upscaling and socio-political challenges have a similarly superficial treatment in assessments, with a few giving consideration to 'technology readiness', and only the Royal Society report extending a discussion to the socio-political challenges of upscaling (Shepherd *et al* 2009).

Considering the costs and potentials reported in these reviews, we observe differing levels of agreement by technology. For example, there is significant disagreement on the cumulative sequestration potentials for biochar (ranging from 143 $GtCO_2$ by 2100 in Caldecott *et al* (2015) to 477 $GtCO_2$ in IPCC (2013)) and BECCS (with estimates below 500 $GtCO_2$ by 2100 in in Caldecott *et al* (2015) and IPCC (2013), but exceeding 1000 $GtCO_2$ in the Royal Society (Shepherd *et al* 2009) and National Academy of Sciences (National Research Council 2015)). There is also a clear need for clarity on the costs of direct air capture and storage, enhanced weathering, and ocean fertilisation, which range across an order of magnitude in each case. The cost and sequestration potentials for afforestation are, however, relatively consistent across reviews, probably because tree planting is a long established practice for which costs are readily available. This divergence is rooted not only in the consideration of different technologies (e.g. BECCS from fuel production or combustion for electricity) and their progress, but also in the application of different feasibility criteria.

Methodology

Literature review methods are rarely discussed in the field of climate change research, despite their central importance to knowledge synthesis and policy-relevant assessments (Minx *et al* 2017a, Ringquist 2013, Petticrew and Roberts 2008, Petticrew and McCartney 2017, Higgins and Green 2008). Typical reviews take on a narrative form and aim to survey the literature around one or more key themes, to the best of the author's knowledge. A systematic review proceeds on a more formal basis, and usually includes the following steps: (1) a research question is defined; (2) the literature is

Table 2. Overview of results from existing assessments of NETs.

Potential (flux)		Potential (cumulative)		Costs	Notes	Source
$GtCO_2$/yr		$GtCO_2$		$/t$CO_2$		
2050	2100	2050	2100			
Afforestation (AR)						
			147–260			IPCC 2013
			80–100	$20–100		Caldecott *et al* 2015
	2–5		100	$1–100		NRC 2015
1.5–3				$20–100		Friends of the Earth 2011, McLaren 2012
	4–12.1			$18–30		Smith *et al* 2016
0.73–5.5	1.1–12.1					Lenton 2010, 2014
	4.03–12.1					Fuss *et al* 2016
		671			Estimate for 2060	Vaughan and Lenton 2011
Biochar (BC)						
			477			IPCC 2013
			78–390		Includes biomass	Royal Society 2009
1				$30–40	Potential and cost estimates for 2030	Friends of the Earth 2011
0.9–3				$8–300		McLaren 2012
	1.47–2.57					Fuss *et al* 2016
			143	$0–135		Caldecott *et al* 2015
2.75–4.95	4.04–4.95					Lenton 2014
0.9–1.3	20–35					Lenton 2010
	20–35		1468		Potential achieved over long term (year 3000)	Vaughan and Lenton 2011
				$135	costs for a 0.1 ppm deployment target	McGlashan *et al* 2012
Bioenergy carbon capture and storage (BECCS)						
			459			IPCC 2013
			390–1170			Royal Society 2009
	15–18		100–1000	~$100		NAS 2015
2.4–10				$70–150		Friends of the Earth 2011
2.4–10				$70–250		McLaren 2012
	12.1					Smith *et al* 2016, Fuss *et al* 2016 l
			178–453	$45–250		Caldecott *et al* 2015
5.5–11	19.81–69.73					Lenton 2014
6.4	11–38.5					Lenton 2010
		1094			Estimate for 2060	Vaughan and Lenton 2011
				$59–111	costs for a 0.1 ppm deployment target	McGlashan *et al* 2012
Direct air capture (DAC)						
			No obvious limit			IPCC 2013
	10		1000	$400–1000	Estimates for the US only	NAS 2015
multiple Gt CO_2				>$250		Friends of the Earth 2011
10				$40–600	Over two technologies (supported amines and wet calcination)	McLaren 2012
	12.1			$436–567	No date for cost	Smith *et al* 2016l
	3.67–12.1					Fuss *et al* 2016l
			108->260	$40–600		Caldecott *et al* 2015
0–11.01	36.7					Lenton 2014
				$95–155		McGlashan *et al* 2012
Enhanced weathering (EW)						
			367			IPCC 2013
	2		~100	$20–1000	Estimates for the US only	NAS 2015
0.01–5				$20–40	Lower bound cost estimates	Friends of the Earth 2011

Table 2. *Continued.*

Potential (flux)		Potential (cumulative)		Costs	Notes	Source
1				\$20–40		McLaren 2012
	0.7–3.67			\$33–578	No date for cost	Smith *et al* 2016l
	0.73–3.67					Fuss *et al* 2016l
2.5–11					Estimate covers land and ocean	Lenton 2014
Ocean fertilization (OF)						
			55–1027			IPCC 2013
			78–234		Iron fertilization only	Royal Society 2009
	1–4		90–300	\$500	Iron fertilization only	NAS 2015
2				~\$50		Friends of the Earth 2011
0.2–1				na	Over two technologies (Iron and macronutrients)	McLaren 2012
Ocean liming (OL)						
						IPCC 2013
	1		~100	\$50–100		NAS 2015
multiple Gt CO_2				\$30–60		Friends of the Earth 2011
1 multiple Gt CO_2				\$51–180	Over two technologies	McLaren 2012
			84->260	\$72–159		Caldecott *et al* 2015
0.99						Lenton 2014
	1					Vaughan and Lenton 2011
Soil carbon sequestration (SCS)						
2.3				\$20		Friends of the Earth 2011
	1.47–2.57					Fuss *et al* 2016
			104–130	\$<0–100		Caldecott *et al* 2015
		~605			Assumes a reversal of cumulative land-use changes	Vaughan and Lenton 2011

identified using a transparent search query in literature databases; (3) documents are manually checked for relevance, according to pre-defined criteria; (4) evidence is extracted and synthesized for review. Such a methodology has the advantage of greater transparency and reproducibility, but suffers from the obvious problem of increased time commitment. Nonetheless, formalizing reviews in this manner is arguably a necessary step to rigorously examining contentious science-policy issues (Minx *et al* 2017a), of which NETs are a signal example.

In this project we aim to assess the global CO_2 removal potential, costs and relevant side effects of major groups of NETs. We cover afforestation and reforestation (AR), biochar (BC), soil carbon sequestration (SCS), enhanced weathering on land and in oceans (EW), ocean fertilization (OF), bioenergy combined with carbon capture and storage (BECCS), and direct air capture and storage (DACCS). There are other CO_2 removal technologies such as blue carbon (Johannessen and Macdonald 2016) as well as a wider set of non-CO_2 greenhouse gas removal technologies that are not considered here in any depth (de Richter *et al* 2017, Richter *et al* 2013, Lomax *et al* 2015b, Stolaroff *et al* 2012, Ming *et al* 2016). For selected technologies we perform a scoping review, a type of rapid systematic review that aims to provide a comprehensive overview of developments within a field, but does not try to quantitatively assess the drivers of observed variation in available estimates. Instead, we only qualitatively discuss possible sources of variation. Prior to embarking on the review, we gathered teams of experts for each technology, then developed a project protocol to guide the review procedure (figure 3).

The first step of the protocol is to define and iterate a set of search queries for the Web of Science and Scopus. Prior work had already outlined a set of NETs queries (Minx *et al* 2017c), which were then further refined with each technology team. At a minimum, these search queries aim to capture a set of documents that: (1) refer to at least one technology in question; and (2) refer to the removal of CO_2 in some regard. For example, a study on afforestation would only be captured by the search query if it also contained some reference to carbon sequestration. This strategy focuses the core of our review on mitigation-related studies, although it undoubtedly misses work that could be relevant for a more specific NETs assessment (e.g. publications on afforestation and biodiversity).

Having compiled a set of broadly relevant documents, the second stage of the scoping review is to manually exclude irrelevant articles (2.1). The exclusion criteria were broadly as follows: if a paper did not report global sequestration potentials,

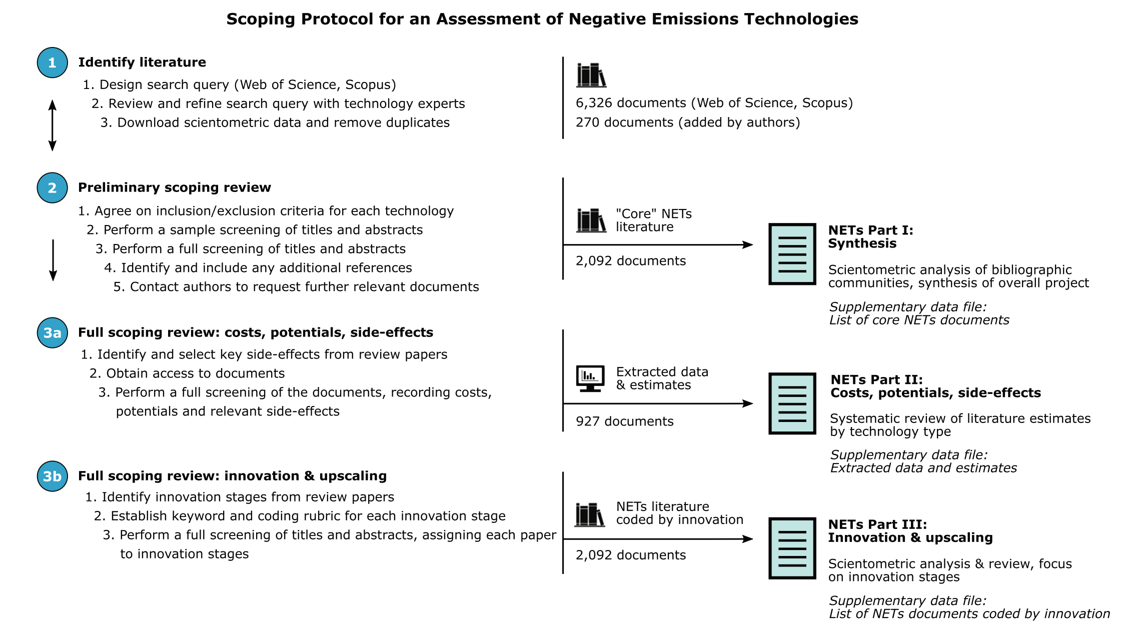

Figure 3. Search and scoping strategy applied in this systematic review.

sequestration costs, or discuss the side-effects of deployment, it was excluded. Deviations from this general rule by technology were necessary, these were therefore discussed and agreed upon in each team (e.g. species-specific sequestration potentials are very common in the land-use NETs, but have to be excluded as they cannot be meaningfully aggregated in our study). Similarly, 'side-effects' is open to broad interpretation, but typically involves such issues as competition for land and food production (BECCS), albedo change (afforestation and reforestation), or ecosystem impacts (ocean fertilization). The exclusion criteria are discussed in more detail in the Supporting Information of Fuss *et al* (2018). In order to ensure consistency in applying the criteria, random samples of papers were screened and cross-checked within the technology teams until a good level of agreement was reached among the experts (90%). The full screening of abstracts could then proceed (note: after the sample screening, abstracts were divided among members of each technology team, hence each abstract was read once). If, during this process (and in later stages of the review), additional relevant articles were discovered, these were added manually.

The initial search query yielded 6284 papers in Web of Science and Scopus (once duplicates were removed). The preliminary scoping review in stage 2 reduced this set to 1984 NETs documents that focus on costs, potentials and side-effects. We retrieved contact information for all corresponding authors from these documents. To each author, we sent an email with a list of her references in our database asking for a complete list of her publications on NETs. In case of gaps, additional documents could be forwarded via email or uploaded to our project website. Overall, we sent emails to 1256 authors during November and December 2017. 564 of the links in these emails were clicked on, and 419 documents were added. 270 of these documents were not already in our database, and these documents underwent the same preliminary scoping review (stage 2), adding another 147 relevant documents. Overall, stage 2 yielded a total of 2093 core documents on NETs, which we use in section 4 of this paper to describe the relevant research landscape.

For reviews #2 (Fuss *et al* 2018) and #3 (Nemet *et al* 2018), the core set of NETs documents was refined further. In the first case (Fuss *et al* 2018) this was via a more comprehensive screening of documents looking at full texts to examine and extract data. In the latter case (Nemet *et al* 2018) each document was coded by the innovation stages discussed in the abstract. These procedures are described in the respective manuscripts.

The landscape of negative emissions research

The upper panel of figure 4 shows that the body of publications dedicated to NETs is fast growing, but remains still at a reasonable size with a total number of about 2000 studies (see SI available at stacks.iop.org/ERL/13/063001/mmedia for a list). This number differs from results presented in (Minx *et al* 2017c): we not only include publications dedicated to NETs in a hand-selection process, but search a wider range of results by including also the Scopus database and publications we manually added ourselves. We further note that there is a considerably wider literature on individual NETs, but we restricted our original search to documents that deal with atmospheric carbon removal in order to keep the study focused

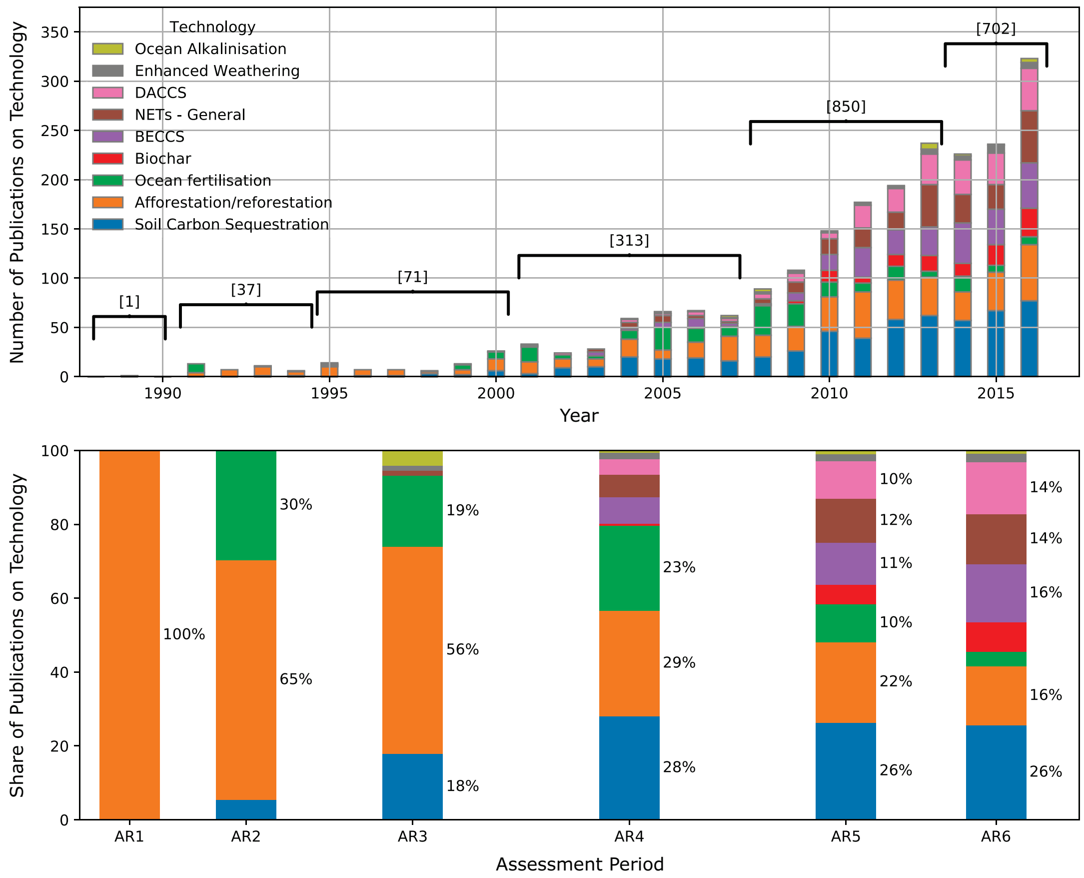

Figure 4. Total number of studies on NETs by year and IPCC assessment period. Bars on the top panel show the total number of papers mentioning each technology (note that some papers may reference more than one technology period). The bottom bars show the share of the literature in each assessment period that mentions each technology. 'NETs—General' denotes studies that mention negative emissions, but not a specific technology.

and the task at hand manageable and reproducible. Growth has been larger than for the scientific enterprise as a whole as well as for the entire climate change literature (Minx *et al* 2017c). This matches our expectations as NETs form a more recent discourse within climate change mitigation.

Considering the timeline of NETs publications, studies falling between the first two IPCC assessments (AR1 and AR2) mainly focused on afforestation and reforestation with some discussions around OF in AR2[16]. This is a good reflection of the very limited available literature at the time. The third IPCC assessment cycle witnessed the phase-in of scientific publications on SCS, alongside a broader discussion of biological sink enhancement in AR3 (Kauppi *et al* 2001). By AR4, the first studies on all major NETs had emerged, but with no attempts towards a systematic discussion—probably due to the immaturity of the field. Yet, negative emissions as a key issue for achieving very stringent mitigation goals were highlighted in AR4 (Barker *et al* 2007) paving the way for a more comprehensive treatment in AR5 (Clarke *et al* 2014). For AR6 there are already about 680 additional publications available during the first three years of the cycle, with a substantial number of studies for most technologies.

In terms of the individual NETs discourses, figure 4 shows that some discussions on NETs are long-standing, while others are rather recent. Early discussions in the field started with AR and OF, followed by SCS in the late 1990s. Most other NETs enter the debate firmly after 2005. A more general discourse on negative emissions only emerged after the publication of IPCC-AR4 in 2007. Moreover, NETs discourses show a steady increase across all technologies, with the exception of OF, which peaked between 2005 and 2010 and declined thereafter over concerns on adverse side-effect, effectiveness and legal issues (Rayfuse *et al* 2008, Lukacs 2012, Güssow *et al* 2010). Recent growth (2011–2016) in publications has been strongest for BC (33%) followed by the general discussion of NETs (21%), SCS (15%) and DAC (12%). Finally, the largest number of studies has been accumulated for SCS (550) and AR (490). There are more than 200 publications for most other options except (EW and BC).

Figure 5 shows a bibliographic coupling network of our corpus of relevant negative emissions literature

[16] 'Biofuels'—i.e. the BE part of BECCS was discussed as a potential mitigation measure (for fossil fuel offsets) in all ARs.

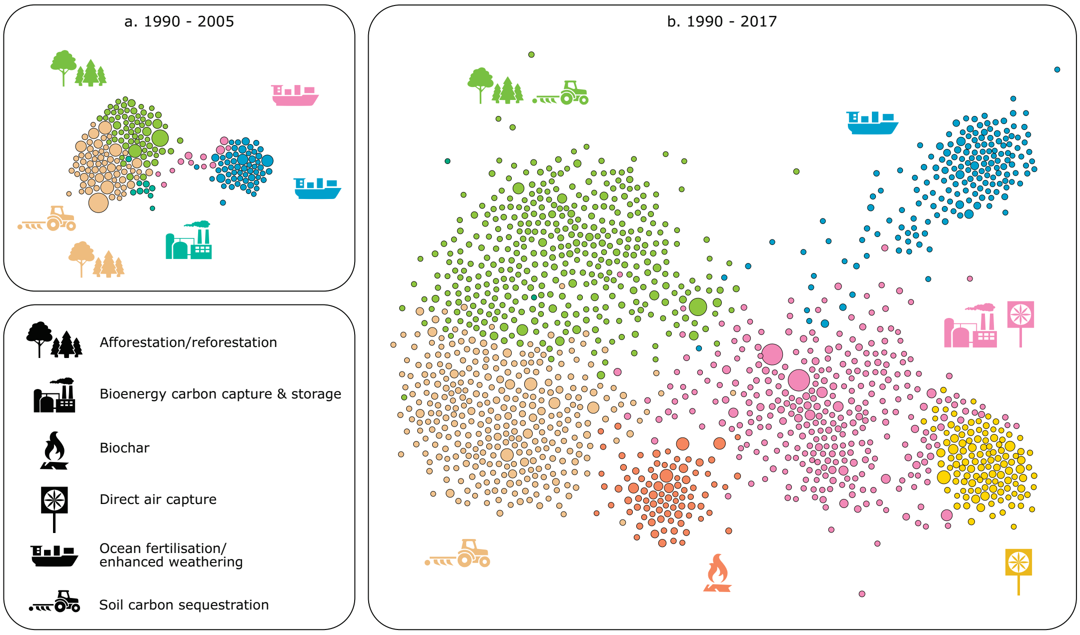

Figure 5. Bibliographic coupling network of negative emissions publications. The nodes in (*a*) and (*b*) represent articles, scaled by citations (normalized across years and scientific fields). Proximity between nodes indicates strong bibliographic coupling—a shared set of cited references—with the layout determined by the force-directed algorithm ForceAtlas2. Clusters were identified using a community detection algorithm, separately in each time period. Individual papers were already marked up by technology in the scoping review, clusters are therefore labelled by the technology types that exceed a proportion of 10% in each grouping (where a paper had two technologies, each had a weighting of one). On manual inspection, some clusters in figures (*a*) and (*b*) approximately match, and are colored accordingly. The network centrality scores for (*a*) and (*b*) are *x* and *y*, respectively, indicating a denser network of citations as the last decade of publications are added. Note that enhanced weathering of the ocean and ocean fertilization have been grouped together by the algorithm. Yet, they mark distinct options with very different characteristics and side-effects.

for the time periods 1990–2005 (small panel) and 1990–2017, generated in VOSviewer (van Eck and Waltman 2010). In each plot, the proximity of publications is based on their number of shared references. Publications are clustered into distinct technology communities identified by colors. Figure 5 shows that between 1990 and 2005, two distinct discourses dominated—one focused mainly on OF and a much larger one essentially about the various options for enhancing natural carbon sinks (AR, SCS) except BC. For each of these NETs already distinct bodies of research have emerged and, in fact, most of the seminal work have already been published. For other NETs, though some literature has begun to be published, distinct communities are yet to emerge.

By 2017 the breadth of the discussion has fully unfolded and all major NETs have developed into distinct research fields including BECCS, BC and DACCS. BECCS studies, which figure 5 shows begin to emerge from 2005, form a central part of the complete network. The pink cluster in figure 6 is composed mainly of BECCS studies, along with broader discussions on NETs (which we describe as 'NETs - general' in our database). This cluster reflects both the scenario literature where BECCS studies initially gained prominence, as well more general discussions of negative emissions where scenarios are often used as a starting point (Smith *et al* 2016, Anderson 2015, Anderson and Peters 2016, Fuss *et al* 2014, 2016, Gasser *et al* 2015, Geden 2015). This materializes in the network: of all the clusters, the BECCS cluster displays the highest average betweenness centrality—meaning that BECCS papers occur most frequently on the shortest paths between other papers (Freeman 1978).

At the network level, betweenness centrality is lower in the 1990–2017 network. This shows the increasing distance between more distinctive research fields. For example, the two clusters between which average shortest path lengths are the greatest are SCS and OF. These clusters share few common references, and are only indirectly linked through papers in more central clusters, like that on BECCS. This decentralizing trend lies in contrast to an increase in degree centrality, which measures the number of connections each paper has (normalized according to the number of papers in the graph). In the full network, papers are more densely connected, reflecting the growing body of shared references in each subfield. This is exemplified in the AR cluster, which, as the most mature technology field, displays the greatest average degree centrality. In short, the research landscape is diversifying and developing into epistemic niches, but against a countertrend of increasing connectivity, suggesting a growing awareness of other efforts in the field and emerging common discourses.

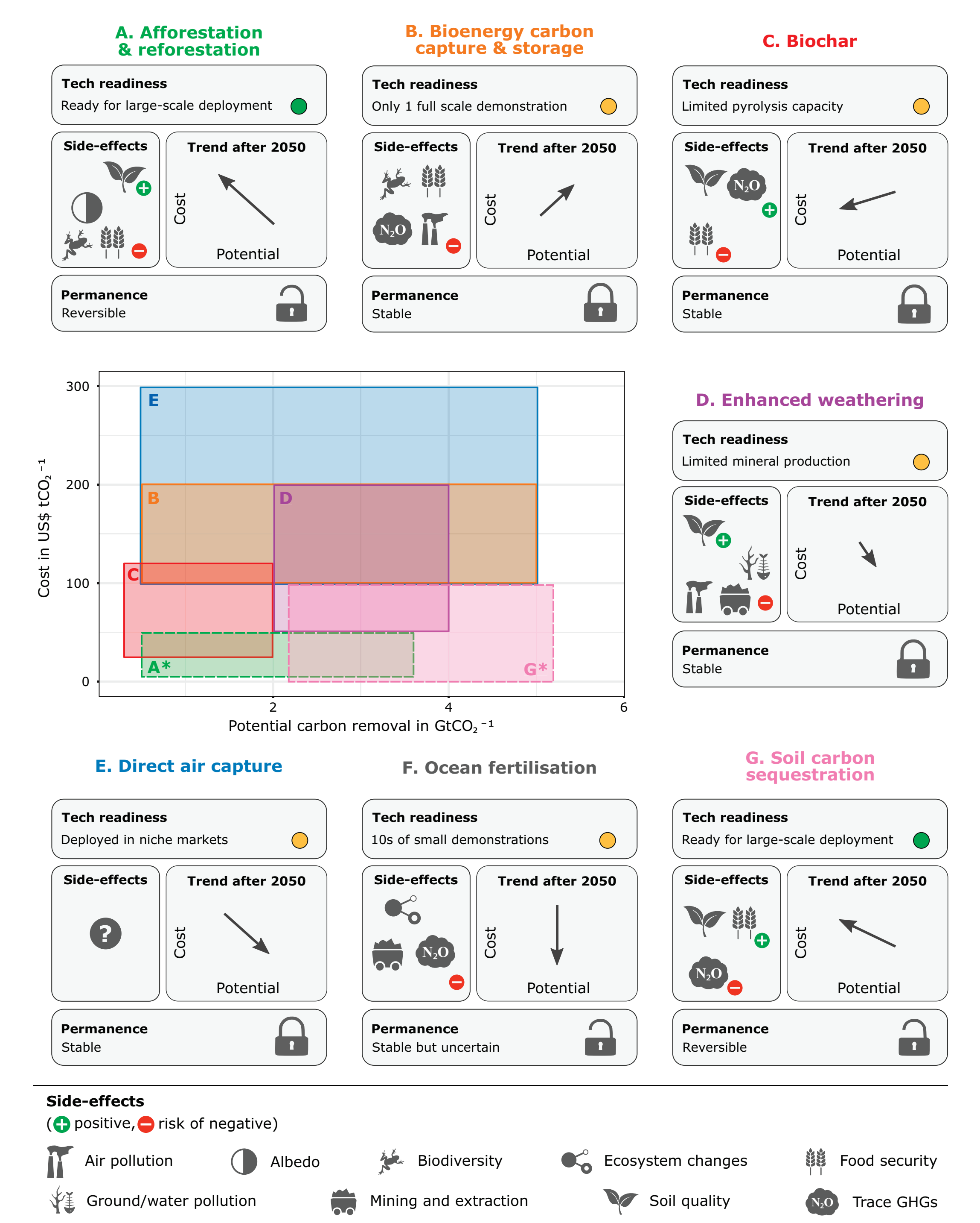

Figure 6. Synthesis of NETs costs, potentials and key side-effects. Central panel gives an expert judgment for 2050 potentials and costs. All ranges result from assessments of these individual technologies and are not additive as technologies compete for limited geological storage, land and biomass feedstocks. The full ranges found in the literature are shown in table 3 and discussed in Part 2 of this review in depth (Fuss *et al* 2018). As annual deployments of soil carbon sequestration and afforestation cannot be sustained as long as other technologies (due to rapid sink saturation) we represent these technologies as dashed boxes in the central figure with an asterix*. Side panels A–G show expected future trends in costs and potentials after 2050 as judged by the author team based on the respective assessment of the individual technologies (Fuss *et al* 2018). Key side effects are indicated by icons underneath. Note that risks of negative side effects are often contingent on implementation, e.g. large-scale afforestation with mono-cultures versus agroforestry projects, or biochar from dedicated crops versus residues. A more comprehensive list is side effects provided in table 3. A comprehensive discussion of costs, potentials and side-effects can be found in Fuss *et al* (2018). An assessment of the literature on innovation and upscaling is provided in Nemet *et al* (2018).

Synthesis—what we know about negative emissions

This section integrates and condenses the findings from all three parts of this review to summarize the current status of knowledge on negative emissions. In particular, table 3 brings together some crucial insights. This section stays at a high level to focus on what we consider to be the key points, while more details including a wealth of additional references can be found in the respective sections of the three publications (Fuss *et al* 2018, Nemet *et al* 2018).

Given important differences between NETs and SRM approaches, we argue in this review that neither should be lumped together under climate- or geo-engineering. SRM and NETs both describe human interventions that take place after the release of CO_2 to the active biosphere. Yet, by reducing atmospheric CO_2 concentrations NETs still address the root cause of climate change, as with mitigation options. SRM approaches seek to temporarily limit some of the worst impacts of climate change. Other important differences refer to the novel global risks imposed by SRM, the different time scales at which these interventions work, or distinct governance challenges (National Research Council 2015). We do not advocate presenting NETs as another mitigation option, but argue that it should not be lumped together with SRM. We therefore support a four-fold classification of human response options to climate change that consists of mitigation, adaptation, NETs and SRM—with the last two strictly distinguished from each other.

Over the past decade, NETs have moved from the periphery towards the core in climate policy discussions. This change is in part due to the growing cognitive dissonance between increasing long-term ambition in international climate policy—most recently manifested in the Paris Agreement—and the very limited success in achieving short-term emission reductions across the globe. In fact, global GHG emissions will continue to grow until 2030 unless short-term ambition is ratcheted up by many countries (Rogelj *et al* 2016a, Meinshausen *et al* 2015, Schleussner *et al* 2016).

The introduction of NETs in cost-optimizing mitigation scenarios reduces the costs of long-term mitigation but impedes early emissions reductions (see also figure 8). The resulting budget overshoot is 'paid back' towards the end of the century during a sustained period of net negative emissions, i.e. a global net removal of carbon dioxide from the atmosphere. However, gross negative emissions in scenarios that offset residual CO_2 emissions which are difficult to mitigate tend to be much larger, pointing towards the economic attractiveness of NETs in many scenarios.

Scenario evidence suggests the need for large-scale NETs deployment in 1.5 °C scenarios. We define 1.5 °C scenarios as those with a greater than 50% probability to keep global mean temperature increase below 1.5 °C in 2100 and an at least 66% probability of keeping warming below 2 °C throughout the 21st century. The dependence on negative emissions is due to the very limited carbon budget—the remaining net cumulative anthropogenic CO_2 emissions of 0–200 $GtCO_2$ that can still be emitted throughout the 21st century in order to keep the climate goals (Rogelj *et al* 2016b, 2018, 2015)[17]. These scenarios are typically characterized by large amounts of gross negative emissions across the 21st century (150−1180 $GtCO_2$) initiated by rapid patterns of upscaling NETs (0.06–0.8 $GtCO_2$ per year between 2030 and 2050 to 1−16 $GtCO_2 yr^{-1}$ by 2050).

The dependence on NETs can be limited to a large degree for 2 °C scenarios—defined as scenarios with a larger than 66% (likely 2 °C scenarios) and 50% (medium 2 °C scenarios) probability of keeping temperature rise below 2 °C throughout the 21st century. 2 °C scenarios without any additional constraints on the technology portfolio or policy timing deploy negative emissions at similar scales to 1.5 °C scenarios (320−840 $GtCO_2$), but scale-up is slower (0.03−0.4 $GtCO_2$ per year between 2030 and 2050) and 2050 deployment levels are lower (1−11 $GtCO_2$) for most scenarios. Therefore, many commentators implicitly or explicitly suggest a large-scale dependence on negative emissions for 2 °C scenarios (Lackner *et al* 2016, Williamson 2016, Gasser *et al* 2015, Anderson and Peters 2016, Peters and Geden 2017). Yet, among the 2 °C pathways there are scenarios without any substantial NETs deployment. This implies that the large NETs deployment observed in many 2 °C scenarios assuming immediate and comprehensive mitigation action is mainly rooted in their competitiveness (economic attractiveness) and could be largely avoided. In fact, 2 °C scenarios do not yet fundamentally depend on negative emissions at large scale.

If near-term emission reductions follow the pathways suggested by current NDCs there will be a fundamental dependence on negative emissions by 2030 in 2 °C scenarios. 2 °C scenarios that delay adequate mitigation action in the short-term along the current NDC trajectory show similar features to 1.5 °C scenarios today: no available scenarios without NETs, large scale deployment of NETs throughout the 21st century (250−920 $GtCO_2$) and rapid upscaling of NETs between 2030 and 2050 (0.2–0.7 $GtCO_2$ per year) to 3−14 $GtCO_2$. Following low energy demand trajectories throughout the 21st century increases the flexibility in NETs deployments across all scenarios.

The introduction of multiple (more than one) NETs leads to an increased total deployment of NETs, but for each NET at decreasing scales relative to the single NETs case. The level of substitutive effects depends on the composition of the NETs portfolio. Initial evidence suggests that they are stronger for NETs competing for land (e.g. AR and BECCS) (Humpenöder *et al* 2014) and less strong for NETs competing for storage (BECCS and DACCS) (Marcucci *et al* 2017, Chen and Tavoni 2013). The increases in total NETs deployments are accompanied by further obstructions to short term emissions reductions as well as further reduced long-term policy costs.

Most recent evidence suggests that future socio-economic conditions are decisive for the level of future

[17] Estimation of carbon budget depends on temperature data used, and various methodological assumptions. A recent estimate suggests a more generous CO_2 budget for the 1.5 °C limit (Millar *et al* 2017).

Table 3. Summary of insights on costs, potentials, side-effects, upscaling and innovation as assessed based on Fuss *et al* (2018) and Nemet *et al* (2018). All ranges result from assessments of these individual technologies and are not additive as technologies compete for limited geological storage, land and biomass feedstocks. Annual deployments of soil carbon sequestration and afforestation cannot be sustained as long as other technologies due to rapid sink saturation.

Group	Option	NETs deployment levels in IAMs (in $GtCO_2yr^{-1}$ in 2050 [2100], full range)				Potential (in $GtCO_2yr^{-1}$)	Costs (in $/$tCO_2$)	Side effects		Permanence and saturation	Development status of technology	Remaining barriers to development, deployment and upscaling
		1.5°C	*2°C*	*2°C delay*	*3°C*	Author judgment [full range]	Author judgment [full range]	positive	negative			
Geological storage	*DACCS*	0 [40]	0 [11–40]	n/a	n/a	0.5–5 [limited by upscaling and costs]	100–300 [25–1000]	Business opportunities; specific applications could improve indoor air quality	CO_2 penalty if high (thermal) energy demand satisfied by fossil fuels; currently high front - up capital costs; mostly insufficiently studied; material/waste implications not known but cannot be excluded; some spatial requirements	High permanency for adequate geological storage; possible storage limitations but flexible co-location with storage possible	Deployed in small niche markets; costs unknown	Costs; mass production; leakage concerns; ensure governance that renders DACCS a CO_2 sequestration rather CO_2 utilization technology
	BECCS	1–16 [3–29]	0–14 [0–24]	3–14 [5–17]	0–7 [0–22]	0.5–5 [1–85]	100–200 [15–400]	Market opportunities; economic diversification; energy independence; technology development and transfer; GHG emissions substitution	Direct and indirect LUC; food security; biodiversity losses; deforestation and forest degradation; health impacts; impacts on soil and water; albedo change; CO_2 leakage	High permanency for adequate geological storage; possible storage limitations; limits on rates of bioenergy production and carbon sequestration	~1 full scale demonstration plant worldwide.	Costs; land use competition; leakage concerns
Ocean storage	*Ocean fertilization*	n/a	n/a	n/a	n/a	Extremely limited [0.5–44]	No expert judgement due to limited potential [0–460]	Potential increase in fish catches; enhanced biological production	Unknown impacts on marine biology and food web structure; changes to nutrient balance; anoxia in surface ocean; probable enhanced production of N_2O and CH_4	Fragile saturation of oceans; permanence from millennia to months/days	~10s of small scale demonstrations	Efficiency of method; scale up; incentives for adoption; impacts on ocean and marine life

Table 3. *Continued.*

Group	Option	NETs deployment levels in IAMs (in $GtCO_2 yr^{-1}$ in 2050 [2100], full range)				Potential (in $GtCO_2 yr^{-1}$)	Costs (in $/t$CO_2$)	Side effects		Permanence and saturation	Development status of technology	Remaining barriers to development, deployment and upscaling
		1.5°C	*2°C*	*2°C delay*	*3°C*	Author judgment [full range]	Author judgment [full range]	positive	negative			
Storage in terre - strial bio-sphere	*AR*	n/a	0–3 [1–4]	n/a	0–2 [0–5]	0.5–3.6 [0.5–7]	5–50 [0–240]	Implementation dependent benefits for soil carbon, soil quality, biodiversity, livelihoods, water retention, employment	Direct and indirect LUC; net-positive warming in high latitudes due to albedo effect; risks for biodiversity and food security.	Saturation within a period of decades to centuries; vulnerable to natural and human - induced disturbances; requires on-going management to maintain sinks	Available at large scale	Lack of incentives for widespread adoption; competing land uses; concerns about offsetting temperature effect from albedo changes
	SCS	n/a	n/a	n/a	n/a	2–5 [0.5–11]	0–100 [−45–100]	Improved soil resilience and improved agricultural production; negative cost options; reduced pollution and improved soil quality; positive impacts on soil, water and air quality	Possible increase in N_2O emissions and N and P; need for addition of N and P to maintain stoichiometry of soil organic matter	Soil sinks saturate and are reversible when the management practice promoting SCS ceases	Available at large scale	Incentives for widespread adoption; concerns about permanence
	Biochar	n/a	n/a	n/a	n/a	0.5–2 [1–35]	30–120 [10–345]	Increased crop yields and reduced drought; reduced CH4 and N2O emissions from soils; improved soil carbon, nutrient and water cycling impacts	Competition for biomass resources; direct and indirect LUC; potential increase plant vulnerability against insects, pathogens, and drought; albedo change partly offsetting mitigation effect	Residence times of biochars range between decades to centuries depending on soil type, management, and environmental conditions	Pyrolysis capacity limited at present	Incentives for widespread adoption; costs of pyrolysis

Table 3. *Continued.*

Group	Option	NETs deployment levels in IAMs (in $GtCO_2 yr^{-1}$ in 2050 [2100], full range)				Potential (in $GtCO_2 yr^{-1}$)	Costs (in $\$/tCO_2$)	Side effects		Permanence and saturation	Development status of technology	Remaining barriers to development, deployment and upscaling
		1.5°C	*2°C*	*2°C delay*	*3°C*	Author judgment [full range]	Author judgment [full range]	positive	negative			
	EW	n/a	[3]	n/a	n/a	2–4 [0–100]	50–200 [5–3460]	Increase in crop yields; improved plant nutrition; improved soil fertility, nutrient and moisture; increase in soil pH; increasing cation exchange capacity in depleted soils	Human health risks associated to fine grained material; ecological impacts of mineral extraction and transport; potential heavy metal release; changes in soil hydraulic properties	Saturation of soil; residence time from months to geological time scale	Tailored mineral production limited at present due to unknown optimal parameterization of products.	Incentives for widespread adoption; costs of mineral production and distribution

dependence on NETs in both 1.5 °C and 2 °C scenarios. While the scenario evidence for AR5 lacked larger variations of socio-economic baseline conditions, this evidence has become available in the meantime (Popp *et al* 2017, Bauer *et al* 2017, van Vuuren *et al* 2017, Riahi *et al* 2017, Rogelj *et al* 2018). As expected, the ranges observed in NETs deployment both for 1.5 °C and 2 °C scenarios expand at both ends once more or less favorable socio-economic conditions are assumed. For example, NETs deployments are much lower in a world that unfolds along a sustainability narrative with higher levels of education and urbanization, lower population levels and less inequality within and between countries compared to a world that is fundamentally characterized by fossil-fuel reliant development (see O'Neill *et al* (2017) for a detailed outline of five alternative socio-economic narratives). Hence, the socio-economic futures assumed in models themselves substantially impact the economically optimal deployment of NETs and the dependence of individual scenarios on them (Riahi *et al* 2017, Rogelj *et al* 2018). It is therefore crucially important not only to think about how climate policies can reduce GHG emissions given a set of baseline conditions, but also how non-climate policies could help to transition between alternative future worlds.

There are bio-physical and socio-economic limits for all individual NETs, but we identify relevant deployment potentials that could be realized in the mid-term (2050) for all NETs except ocean fertilization. In other words, NETs are, in principle, feasible at variable costs and with at least partially proven technology but not at unlimited scale, and often with high uncertainties on impact. Yet the potentials for different NETs identified in this review (see table 3) are not additive as different technologies compete, for example, for land, biomass resources and safe geological storage. Moreover, lifting any of these potentials will require reliable institutions that incentivize good governance and practice across the globe. Particularly for land-based options such as AR, BECCS or SCS reaching the higher end of the deployment ranges could be challenging due to the large number of actors involved. Moreover, those technologies which are still at relatively early stages of development such as BECCS or DACCS would require stable and structured incentives across the innovation cycle.

It will be difficult to achieve NETs deployment ranges as currently suggested by mitigation scenarios with a single NET. Available scenarios achieve large-scale removal of carbon dioxide from the atmosphere almost exclusively with BECCS. There is great skepticism in the technology literature that modelled annual deployment levels of 10–20 $GtCO_2$ towards the end of the 21st century can actually be achieved by BECCS alone, or by any other individual NET (Anderson and Peters 2016, Anderson 2015, Geden 2015)[18]. There are two important implications: first, rather than betting on the large-scale availability of a single NET in the future, it seems crucial in the light of the prevailing uncertainties surrounding all NETs to keep the dependence on NETs for achieving the climate targets as small as possible. Second, it appears prudent to plan for the deployment of a wider set of NETs than BECCS. Such a discussion of NET portfolios, with a variety of technologies contributing potentially at more modest scales is important, but often absent from the NETs discussion. Importantly, this allows some hedging of risks associated with deploying individual NETs at large-scales.

There is an asymmetry across NETs in terms of immediate availability, safe storage and effectiveness, as well as costs and potentials. Some of the land-based NETs—in particular, SCS and AR—are readily available today for widespread implementation. In fact, they also tend to be among the cheapest available options—in the case of SCS there is a limited potential available at negative private costs and with a string of co-benefits (table 3). Yet, the cheapest options and largest potentials are often available in regions with weak institutions. Furthermore, biophysical impacts can partially offset temperature reductions. For example, AR measures in the North are often not very effective due to changes in the albedo (Wang *et al* 2014, Anderson *et al* 2011). Moreover, there are large uncertainties involved with regard to the confidence we can have that a certain NET has actually permanently removed a ton of carbon (effectiveness). Equally, storage is subject to saturation, is highly reversible (especially under climate change), depends heavily on future management decisions and is therefore highly dependent on future institutional and political conditions. BECCS and DACCS tend to have larger overall potentials and provide much more reliable long-term storage, but show substantially higher costs and are still further down in the innovation chain. Nevertheless, this might suggest a natural deployment succession that starts with land-based NETs in the near future and moves towards geological storage options when larger deployment scales need to be reached.

Despite the focus of the NETs discussion on the very long-run, there is an immediate urgency to upscaling NETs that is largely under-appreciated both in science and policy. 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 for introducing and upscaling NETs is between 2030 and 2050. For example, scaling-up NETs to the extent described in many 1.5 °C and 2 °C scenarios requires adding several hundred BECCS or DACCS plants every year during that period. The urgency mainly derives from the generally long time periods required for the development, scaling-up and

[18] Note that bioenergy is a very versatile technology that has multiple, important uses in climate change mitigation scenarios. Even if BECCS remains unavailable, demand for bioenergy remains almost as high as additional bioenergy is used by other sectors (Rose *et al* 2014).

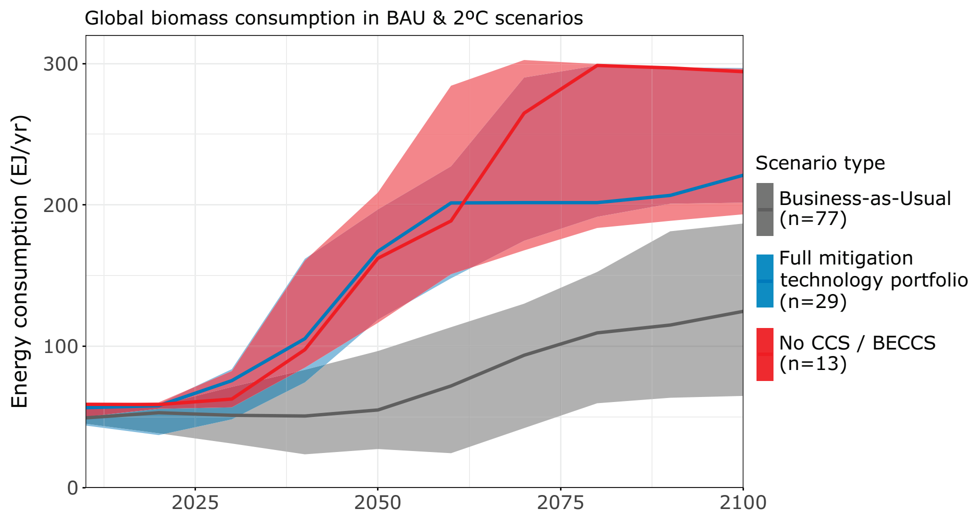

Figure 7. Bioenergy deployment in likely and medium 2 °C scenarios unfolds at similar levels over the 21st century regardless of the availability of BECCS. Bioenergy deployment corresponds here to the total amount of primary energy biomass consumption in exajoules per year (EJ yr^{-1}). It is provided for three scenario types: business-as-usual scenarios (grey) and likely 2 °C scenarios with (blue) and without BECCS. Data sources: LIMITS (Kriegler *et al* 2013c), RoSE (Kriegler *et al* 2013b), AMPERE (Riahi *et al* 2015).

diffusion of technologies to attain widespread adoption. This challenge is exacerbated by the thousands to millions of actors that potentially need to adopt these technologies for them to achieve the required planetary scale. If NETs are to be required at the scales currently discussed, the resulting urgency of implementation is neither reflected in the scientific literature, nor in contemporary policy discussions, nor in policy itself.

Our analysis of the innovation literature on NETs suggests that, overall, the discussion is still at an early stage. Almost 60% of the literature still deals with 'research and development' (R&D)—the earliest stages of the innovation process. More than 80% of the literature deals with supply side issues of the innovation process (R&D, demonstrations, scale-up), while crucial demand-side issues (demand pull, niche markets, public acceptance) are still substantially under-developed.

Ethical aspects

Despite their increasing prominence in mitigation scenarios, ethical analysis of NETs remains comparatively rare. This is in sharp contrast to the ethics of SRM, about which three volumes of essays (Preston 2012, Burns and Strauss 2013, Clingerman and O'Brien 2016) and numerous articles have already been produced. While the relative neglect of NETs among ethicists appears to be changing (Shue 2017, Morrow and Svoboda 2016, Preston 2016), it remains conventional to view NETs as less ethically problematic than SRM. In their influential report, the Royal Society claimed that NETs were ethically preferable to SRM since they could contribute to long-term decarbonisation, with 'fewer uncertainties and risks' (Shepherd *et al* 2009)[19]. Whether this assessment is correct will depend on which techniques are adopted, and how these are implemented. Given the differences between SRM and NETs, framing both under the umbrella term 'geoengineering' could be problematic for developing distinctive ethical arguments. We therefore prefer typologies which clearly distinguish SRM from NETs, and both from conventional mitigation and adaptation (Heyward 2013). In his review, Preston (2013) identified thirteen ethical issues raised by SRM and NETs, encompassing research, implementation, and finally cessation. However, many of these concerns are SRM-specific, and the extent to which they apply to NETs is unclear. Ethical analyses are required which adequately reflect the differences between SRM and NETs, and between particular techniques (Baatz *et al* 2016, Preston 2013).

Distributive justice and ethical permissibility

Within the normative literature on global justice and climate change, harms to basic life conditions of the kind that would undermine human rights or basic capabilities are of particular importance (Gardiner *et al* 2010). Assessing potential benefits and burdens of climate policy requires an integrated perspective on climate justice, sustainable development and global justice (Caney 2012). For instance, a global implementation of BECCS raises questions concerning differentiated national responsibilities, along with challenges of ensuring institutional arrangements across a global supply chain that credibly incentivise and monitor biomass production, energy generation, and carbon storage (Peters and Geden 2017). Shue (2017) has argued that relying on large-scale BECCS would

[19] While seeming to share the Royal Society's verdict, Gardiner argued that this was not adequately justified by the report itself (Gardiner 2011).

be seriously unjust because this could undermine food security, disproportionately harming the poorest. However, the variation among implementation effects (see table 3, figure 6) shows that NETs can be a very mixed ethical proposition. Thus, Shue may be correct under some implementation assumptions, but not under others.

In fact, food security concerns are not specific to BECCS, but are related to bioenergy more generally. Concerns have been expressed about the sustainability and justice implications of large-scale bioenergy production (Gamborg *et al* 2012). Shrader-Frechette (2015) has argued that it would be impermissible to view biofuels as substitutes for fossil fuels, objecting to claims that they are safe, sustainable, and low-carbon, while (Gomiero *et al* 2010) have claimed that large-scale biofuel reliance would be unacceptable in light of existing appropriation of ecosystem services. The increasing land competition on global scale would likely be exacerbated by NETs. As such, Creutzig (2017) points to the need for global coordination and governance of land as a precondition for large-scale bioenergy uses. But it is equally important to note the differences between biofuels in assessing these implications.

Hence, for any targeted ethical inquiry related to BECCS, it is fundamental to ask whether the risks of large-scale bioenergy production are related to BECCS deployment or not. This requires the comparison of bioenergy uptake in scenarios that allow for BECCS with the uptake in scenarios without this option. Doing so highlights that in ambitious mitigation scenarios where the BECCS option is not allowed for, the uptake of bioenergy is not reduced at all. In fact, in many scenarios more bioenergy is used in those cases. The reason is that bioenergy is a versatile feedstock that has applications in many sectors that are particularly hard to decarbonize (e.g. like air but also passenger transport). In the absence of BECCS, bioenergy is applied in those sectors to cut fossil fuel related emissions further down towards zero with tight limits imposed on the ability for compensation via negative emissions. This essentially means that the ethical and policy discourses should primarily target bioenergy. If there are (ethical) concerns arising from large-scale bioenergy deployment, the discussion must be about limiting bioenergy use regardless of the particular application. In fact, the literature shows that temperature rise can be held below 2 °C even if bioenergy deployment is limited to no more than 100 EJ yr^{-1} (Kriegler *et al* 2013c, 2014, Krey *et al* 2014, Riahi *et al* 2015, Clarke *et al* 2014). Imposing such a restriction on bioenergy will automatically restrict the potential for BECCS deployment as well, but not necessarily of other NETs, like DACCS.

For techniques beyond BECCS, Hale and Dilling (2011) argue that ocean fertilization appears to be ethically impermissible because it involves additionally polluting the oceans in order to remediate the pollution of the atmosphere, thereby also shifting the planet to a new and unknown state. Concerns about public consultation and consent are especially daunting for techniques such as ocean fertilization, which affect global commons beyond the atmosphere. But techniques that involve large infrastructures for production, transportation and sequestration (e.g. BECCS and DAC) would also face procedural challenges. Adelman (2017) claims that the unforeseen, unintended and uncontrollable consequences of *both* SRM and NETs make them unacceptably risky to use, and impossible to gain consent for. However, this argument fails to even consider the potential benefits associated with achieving more stringent warming targets such as 1.5 °C, which may require large-scale NETs. Hale (2012a) argues DAC appears to be more permissible since its effects would be localised, and hence achieving consent would be feasible. A similar claim may be made for other forms of terrestrial NETs, particularly more benign or locally beneficial options such as soil carbon sequestration, biochar, or reforestation. Alternately, Preston (2016) argues that the desirability of a 'cessation requirement' may generally support NETs. Morrow and Svoboda (2016) have argued that *any* negative emissions technique could be morally permissible, provided that any wrongs are proportionately small in comparison to the gains of justice that would result, and that it compares favourably with any politically feasible alternatives. Of course, this comparison is likely to be fiercely contested.

The potential consequences of NETs implementation do not encompass all distributive concerns. This is especially clear in relation to intergenerational justice, a key theme of climate ethics. There is a danger that claims of historical responsibility will be 'framed out' via scenario design itself (McLaren 2016). There is also a danger of reproducing expert visions of technological futures, and thereby reducing questions of value to questions of quantified distribution or technological feasibility (Flegal and Gupta 2017).

Moral hazard, betting, and hubris

In our view, three issues in particular stand out in need of future ethical analysis (Lenzi 2018). These are first, that NETs might create a *moral hazard* against mitigation; second (and relatedly), that an implicit policy *bet* on NETs that are unproven at scale may lock in worse climate-related harms if they failed to deliver; and third, that the sheer scale of NETs deployment observed in mitigation scenarios is staggeringly *hubristic*.

The availability of NETs may create or exacerbate a mitigation moral hazard[20]. Moral hazard takes

[20] The label 'moral hazard' may be misleading, since there would not be a *moral* problem unless the behaviour incentivised is itself morally bad (Hale 2012b). The basic concern seems better expressed as *mitigation obstruction* (Betz and Cacean 2012, Morrow 2014), since it is precisely this which is ethically problematic.

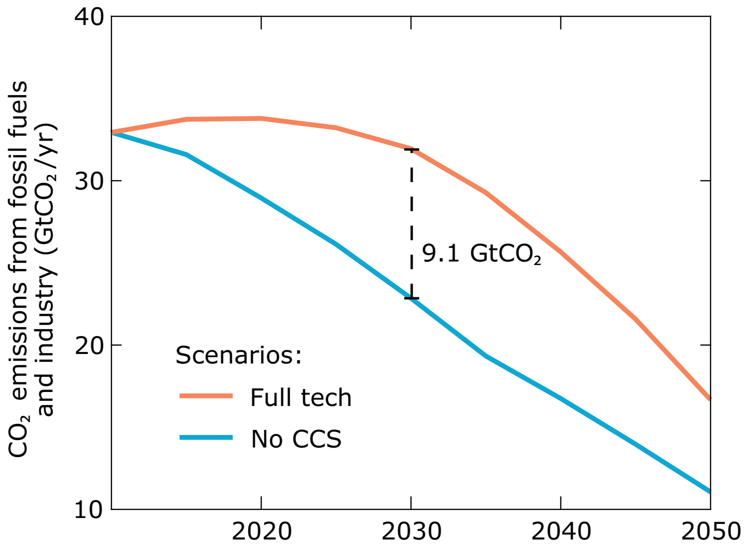

Figure 8. Moral hazard and negative emissions. Two REMIND scenarios are depicted, each with a greater 50% probability of keeping mean temperature rise below 2 °C throughout the 21st century. When negative emissions are constrained by not allowing for CCS, near-term CO_2 reductions are typically far steeper—in this example reaching a 9.1 $GtCO_2$ gap by 2030. Data source: AMPERE (Riahi *et al* 2015).

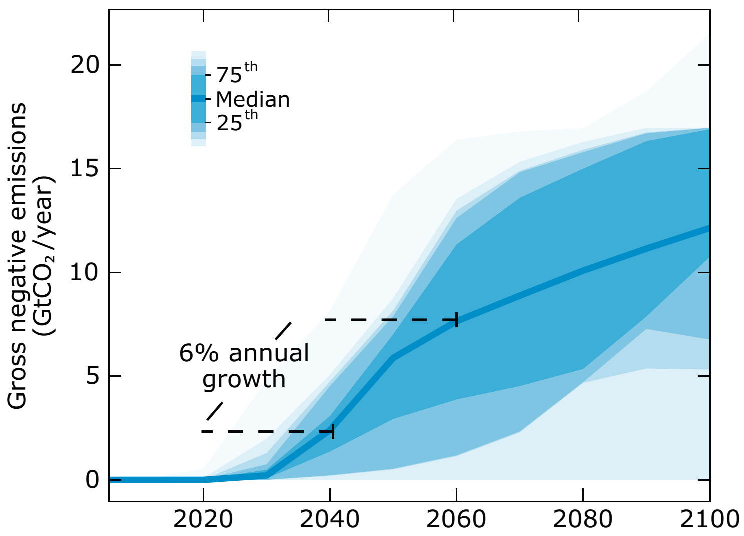

Figure 9. Betting on negative emissions. Gross negative emissions deployment ranges are depicted for an ensemble scenarios all with an at least 50% probability of keeping mean temperature rise below 2 °C throughout the 21st century. From a baseline of 0 in 2020, median annual growth rates of 6% would need to be sustained to meet ambitious median deployment levels by the mid-century. At the same time options are also available with significantly lower levels of gross negative emissions. Data sources: AMPERE (Riahi *et al* 2015), LIMITS (Kriegler *et al* 2013c), Rogelj *et al* 2015.

place when the assumed availability of large-scale NETs disincentivizes emissions reductions in the present. In fact, there are two distinct senses in which NETs might create a moral hazard. First, the availability of NETs within climate models displaces some mitigation. This effect is widely recognised (Calvin *et al* 2009, Kriegler *et al* 2013a, Azar *et al* 2006, Rao and Riahi 2006, Clarke *et al* 2009). The extent of mitigation obstructed by scenario design is potentially very large. In one comparison, near-term mitigation is greater by 9.1 $GtCO_2yr^{-1}$ by 2030 when NETs are excluded (Riahi *et al* 2015)[21]. The inclusion of NETs within scenarios thus raises ethical questions about appropriate research design. Research on NETs, like research on SRM, may create path-dependencies, locking in a requirement for NETs to meet climate goals (Jamieson 1996).

The second aspect is the extent to which NETs *actually* displace mitigation in practice. There is dispute about whether this has already occurred

[21] In this comparison, CCS is constrained, which limits both CCS-dependent BECCS and DACCS.

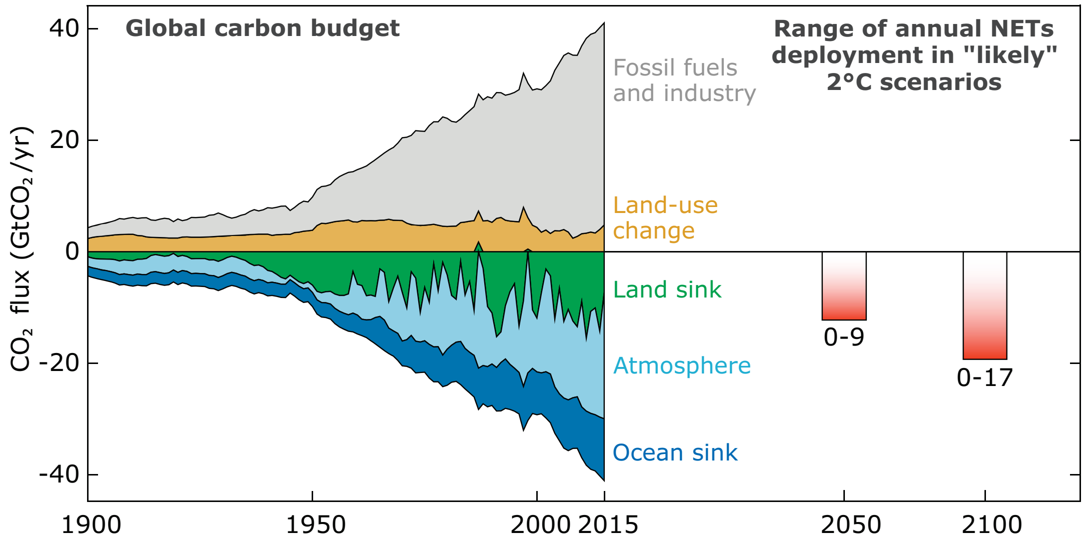

Figure 10. Hubris and negative emissions. Gross negative emissions deployment ranges for an ensemble of 450 ppm scenarios (also depicted in figure 2) with an at least 66% probability of limiting global mean temperature rise below 2 °C throughout the 21st century are shown beside the historical global carbon budget. The growing footprint of human activity on the land, atmosphere and ocean sink can be seen as hubristic; as can the expectation of extensive (planned) negative emissions in the future. At the upper-end of scenario estimates, NETs deployment levels for 2050 are approximately equivalent to the entire current natural land sink, and almost double it in 2100. Data and figure design of historic emissions (left panel) is from the Global Carbon Project (Le Quéré *et al* 2016). Scenario data from: (Riahi *et al* 2015, Kriegler *et al* 2013c, Rogelj *et al* 2015).

(Anderson and Peters 2016, Lackner *et al* 2016)[22]. But in any case, as Gardiner (2010) argues, current climate policy inertia coupled with incentives to 'pass the buck' continue to justify concerns with the deferral of mitigation in general. NETs may further disincentivise near-term mitigation by providing policy-makers with a convenient excuse for mitigating less now (Shue 2017). Nonetheless, this concern cuts both ways. The more stringent 1.5 °C target requires greater use of NETs, likely being unachievable via conventional mitigation alone. As such, NETs might result in less severe primary climate impacts, which would seem to be a gain of justice. Ignoring or side-lining NETs as a mitigation option would hinder future research on what may prove to be a vital means to achieve lower temperature targets, thus potentially decreasing climate risks. A policy of 'wise overshooting' is at least conceivable, in which short-term emissions primarily benefit developing countries by eliminating extreme poverty (Morrow and Svoboda 2016).

Relatedly, the deferral of mitigation may be encouraged by an implicit policy bet on the feasibility of NETs even though these technologies are largely unproven at large scale (Clarke *et al* 2014, IPCC 2014b). Creating a dependence on future large-scale NETs risks worse climate-related harms if they fail to deliver. Commentators have drawn attention to the risks inherent in this dynamic using the language of gambling (Anderson and Peters 2016). Although NETs are unproven at large-scales, recent modelling features them at very large, sometimes staggering scales. In the second half of the century, NETs (again typically BECCS) are often envisaged to remove between 10–20 $GtCO_2yr^{-1}$. There is considerable skepticism that such upscaling is possible (Anderson and Peters 2016, Anderson 2015, Geden 2015). Consider that there are already many renewables in operation, but there is at present only *one* functioning large-scale BECCS facility, and two commercial DAC plants. Similarly, the promise of other technologies such as EW techniques remains to be demonstrated at scale. From an ethical perspective, the key to any bet on NETs lies in determining whose interests are acting as collateral in the wager. As Shue (2017) points out, it is ethically significant that the potential losers of a failed gamble upon NETs are future generations, and especially the poorest among them, who would be most vulnerable if it failed, and who could not possibly consent.

Finally, planned large-scale NETs deployment as envisioned in many scenarios may greatly overestimate our collective ability to manage carbon cycle flows, thereby risking doing more harm than good. The hubris implied in such plans runs up against our ignorance of complex natural systems (Jamieson 1996). Hubris may also be accompanied by technological optimism, i.e. misplaced confidence in the efficacy of technological solutions to socially created problems (Preston 2013). There are historical precedents for both in attempts to manipulate weather (Fleming 2010). For NETs, hubris may be evident in overly neat assumptions of the reversibility of warming, reflecting a paradigm of carbon accounting that is not supported by our currently poor understanding of carbon cycle feedbacks and related earth system dynamics. Hubris concerns

[22] Hamilton (2013) argues that CCS has already displaced mitigation over the past decade.

create at most a 'presumptive argument' against great intervention in nature, rather than a strict impermissibility requirement (Preston 2011). Assessing hubris in relation to NETs also requires assessing the potential scale of implementation. According to scenario data, annual NETs deployment in the order of up to 20 $GtCO_2yr^{-1}$ (see figure 10)—and in extreme case around or even beyond 40 $GtCO_2yr^{-1}$ (Marcucci *et al* 2017, Chen and Tavoni 2013)—have been considered at the end of the 21st century, a figure that approximately doubles todays natural global land-emissions-sink. This implies a major perturbation of land-use and biogeochemical flows (Smith *et al* 2016) and does indeed appear hubristic in both senses of this term. Our review of the NETs 'side-effects' (Fuss *et al* 2018) highlights the manifold problems that would be expected with such large-scale deployments, from the albedo-dampening effects of temperate and boreal afforestation, to the changes in biodiversity resulting from land-use shifts and bioenergy production, and the mineral and fertiliser requirements of sustaining a high level of net primary production.

Of course, humans have already caused enormous changes to the Earth-system (Krausmann *et al* 2013). This raises additional questions about the ethics of large-scale NETs in the Anthropocene. While we may have unwittingly stumbled into this situation as a species, we now face the prospect of intentional intervention and management of the planet's carbon sinks.

Discussion and future research: what we need to know about negative emissions

With continued delays in achieving substantial and sustained CO_2 emissions reductions in the short-term, alongside increasingly ambitious long-term climate policy targets, negative emissions have rapidly moved into the spotlight of international climate policy discussions (Mach and Field 2017, Anderson and Peters 2016, Fuss *et al* 2014, Williamson 2016, Gasser *et al* 2015, Anderson 2015, Peters 2016, Lackner *et al* 2016). The topic is fundamental for the upcoming IPCC Special Report on 1.5 °C of global warming, because negative emissions have become a bio-physical requirement for limiting warming to below that level. Despite various assessments (Smith *et al* 2016, McLaren 2012, Fuss *et al* 2014, 2016, McGlashan *et al* 2012, Vaughan and Lenton 2011, Lenton 2014, National Research Council 2015, Friends of the Earth 2011, Lenton 2010, Shepherd 2012, Shepherd *et al* 2009, Caldecott *et al* 2015) and more emphasis in the most recent IPCC report (Clarke *et al* 2014, Ciais *et al* 2013), the current knowledge on NETs is still diffuse and incomplete. We argue that for making progress in our understanding of negative emissions, more systematic attempts are required to assess and aggregate currently available knowledge. Assessment bodies like the IPCC can only be effective if such synthetic evidence is provided by the research community (Minx *et al* 2017c, 2017a).

In this three part review, we assess the literature on negative emissions. Our focus is on mitigation and we therefore do not include most of the geophysical literature. Yet, within this scope, our assessment goes beyond the available literature by integrating the widely discussed issues of costs, potentials and side-effects of NETs (Fuss *et al* 2018) with a review of ethical issues involved (previous section) as well as an in-depth review of the literature on upscaling and innovation (Nemet *et al* 2018), which may well turn out the be the major bottleneck over the coming decades.

We designed our assessment to be systematic, comprehensive, transparent and reproducible (Petticrew and Roberts 2008, Ringquist 2013). Our motivation is to avoid bias in the selection of literature and unconsciously constraining the assessment qualitatively and quantitatively—a growing problem in times of exponential publication growth (Minx *et al* 2017c, 2017a). We search Web of Science and Scopus based on a transparent and reproducible search query. We acknowledge that these two databases do not cover the entire spectrum of relevant publications and include additional references known within the author team and from requested suggestions made by corresponding authors of all relevant NETs articles at our disposal. We screen the abstracts of almost 6000 resulting publications and hand-select about 2000 dedicated NETs publications based on a documented set of exclusions criteria. In order to achieve a high level of reproducibility, we always worked in teams in order to ensure high-levels of agreement across individual team members. Yet, despite our best efforts, we acknowledge potential limits in our documentation.

A way of assessing our success in covering the literature is to compare our results with existing assessments of NETs as undertaken by intergovernmental and international organizations such as the IPCC (Clarke *et al* 2014, Ciais *et al* 2013, IPCC 2011), by scientific academies (National Research Council 2015, Shepherd *et al* 2009), NGOs (Friends of the Earth 2011), government funded projects (Rickels *et al* 2011) as well as individual or groups of scholars (Fuss *et al* 2016, Smith *et al* 2016, Vaughan and Lenton 2011, McLaren 2012, McGlashan *et al* 2012, Lenton 2010, 2014, Caldecott *et al* 2015). We show that these assessments differ considerably in their coverage of the literature and also in their assessments of costs, potential and side-effects of individual NETs. Our results cover the entire range of estimates across all of these assessments (tables 2 and 3). We argue that expert judgements are a crucial component of assessment processes, but highlight the importance of transparently locating those within the wider literature and an assessment of uncertainty, wherever possible (Kowarsch *et al* 2017, 2016, Mach and Field 2017). As it is impossible to distinguish between publication bias and expert judgement retrospectively, we highlight the importance of establishing systematic review practices and the provision of transparent expert judgement during the assessment process.

Our assessment is systematic in search and selection of the literature as well as recording of the available quantitative evidence of global costs and potentials of individual NETs. We show the resulting ranges in a sequence of figures (Fuss *et al* 2018), but our assessment of the sources of variation remains qualitative, as in traditional literature reviews without a more formal methodological framework. In fact, it would be very interesting to formally analyze the variation across studies in meta-statistical models. This would be required to turn our analysis into a full-fledged systematic review (Higgins and Green 2008, Ringquist 2013, Petticrew and Roberts 2008).

There are multiple reasons why we did not attempt this here: first, this would have only been possible for individual NETs as only a few global estimates are available for several NETs under consideration. Second, the necessary data for a meaningful analysis of the drivers behind variation is often not provided in manuscripts as many variables of interest would directly relate to specific design aspects and parametrizations of models, which are usually not reported. Third, due to the resource intensity of the project, it would have been beyond the capacity of the team here to provide any further analysis. In fact, in the case of IAMs, NET deployment levels are determined by the emerging dynamics of the entire system, and therefore dedicated multi-year model comparison projects are required to disentangle variations. We therefore leave a formal systematic review to future research. Yet, the resources created by this research project provide an adequate starting point.

Our assessment points towards a series of knowledge gaps and future research avenues. The main ones are summarized in table 4. Here we only highlight a few. *First*, there is an urgent need to understand how cost developments and system understanding leads to different conclusions on required future NET deployment, which is crucial for informing policy debates. Initial work by Blanford (2013), for example, suggests that a disregard of near-term impacts in pure cost-effectiveness models leads to typical (Hotelling) carbon price trajectories that favor the omission of near-term emission reductions at the expense of large-scale deployment of NETs in the long-term. In a cost-benefit setting a more linear and flatter trajectory emerges (Golosov *et al* 2014) that suggest an optimal mitigation pathway with substantially less NETs deployment.

Second, our analysis highlights that even moderate NET targets in 2050 require immediate action. However, there is hardly any literature on short-term policies to foster NETs. There is obviously an important research and development component. In addition, research should attempt the identification of strategic niche markets, e.g. in collaboration with management schools. At the same time deployment pathways should be designed such that harmful path dependencies remain precluded.

Third, there is a lack of discussion on what might be termed the 'political economy and public finance' of negative emissions. On the one hand, for almost all NETs there is a requirement to better understand the barriers to implementation. Some of them might be institutional in nature and others may be related to distributional aspects associated with NETs deployment. Understanding who wins and who loses from large-scale deployments of NETs is key for designing policies that are more likely to succeed. On the other hand, both 1.5 °C and many 2 °C scenarios show sustained levels of global net negative emissions during the second half of the 21st century with very high annual deployments at the end when the temperature limit is met. There is no sound understanding of the challenges of financing such a net removal and what policy instruments would be most suitable for this purpose. Moreover, most of the available pathways may not be optimal as they could generate large stranded assets, as most of the NETs fleet would need to be decommissioned once no further removal is desired by society.

Fourth, since any upscaling of NETs implies great social changes, along with changes to the global economy, further research is always required to explore the broader ethical implications of NETs in the context of global justice and sustainable development. While there is currently very little ethical analysis of NETs, there is scope for future work to reflect on the climate futures produced by recent modelling, which imply very different ethical costs, risks and benefits.

Yet, one of the major findings of our assessment is that the major bottleneck for standing any chance of realizing even comparatively modest NETs trajectories is through upscaling and technology diffusion, not only by mid-century, but in the short- and mid-term. Due to the time lags involved in such processes there is a disconnect between requirements identified in the scenario literature and the state of development in the real world. This gives rise to a real urgency for NETs development that is largely under-appreciated in science and policy.

The deep uncertainties and scale-dependent risks associated with NETs cannot be easily resolved and exploratory scenarios are a necessary, but insufficient basis to design policy and deployment strategies. Many known unknowns remain, including risks, but possibly also opportunities. Climate policy needs to focus on limiting the dependence on NETs through aggressive mitigation. Yet, to the extent that reaching the international climate goals increasingly depends on the deployment of these potentially risky and uncertain technologies, policymakers need to change course and flank climate policies with adaptive and evolutionary strategies in research, development and deployment of NETs that focus on rapid learning.

Table 4. Overview of key research avenues for NETs from the entire assessment.

Option	Research avenue
Assessment	• Formal meta-analysis of costs and potentials from individual NETs and use of robust quantifications for parametrization of IAMs • Aggregation of local into global estimates for many land-based NETs • Assessing relevant trade-offs between NETs in an interactive stakeholder-based process • Further clarification of the major geophysical research gaps and integration with research on human response options • Systematic review on the prospects of carbon capture and utilization technologies
Cross-sectoral discussions	• Political economy, public finance and policy instrument choice of NETs • Governance of vulnerable and potentially impermanent carbon sinks
Mitigation scenarios	• Drivers of NETs deployments in IAMs: model design and parametrization • Need for integrated portfolios of NETs in IAMs; evaluation of interactions with other mitigation options; • Better understanding of geophysical constraints of negative emissions and implementation in IAMs • Analysis of NETs deployment dynamics in a risk management framework (decision under uncertainty) • Adverse side-effects of NETs for non-climate sustainable development goals. • The importance of socio-economic context for NETs dependence and deployment, and therefore also the role of non-climate policies for transitioning between future socioeconomic contexts
Ethics	• Co-design and evaluation of scenario evidence on NETs • Critical reflection upon ethical and political aspects of climate futures involving NETs • Clarify whether and how ethical arguments apply to specific NETs and how they compare to those raised in discussions on SRM • Better grounding ethical arguments in available quantitative evidence
Innovation and upscaling	• Shift frame of research agenda from 'deployment' to 'adoption' • Understand incentives potential adopters face • Funding mechanisms for high impact demonstration projects for each NET • Identify niche markets to enable early adoption • Reconcile need for long term adoption goals with urgency of near-term progress in innovation and upscaling
Afforestation and reforestation	• Understand balance of biophysical effects of different species composition for impacts of afforestation (e.g. albedo change, respiration) • Comprehensive assessment of impacts and reforestation on biodiversity • Systematic review of regional costs and potentials, accounting for climate feedbacks and positive side-effects • Review of institutional mechanisms to foster AR projects, in terms of effectiveness, permanence, and reproducibility
Enhanced weathering	• Field experiments that evaluate the full impact on biogeochemical cycles, and biomass and carbon stocks in soils and plants. • Quantification of the geogenic nutrient release effect on biomass increase under limitation conditions and the change in soil properties like hydrology, cation exchange capacity, or plant root-mineral surface interactions due to the fresh rock products to enable case management plans for optimizing CO_2 sequestration. • Databases for possible application scenarios for combinations of rock products, soil conditions, climate and targeted plant systems.
Soil carbon sequestration	• Economic costs (and benefits) of real world deployment of SCS • Quantification of environmental, economic and social externalities associated with deployment of SCS • Better quantifying saturation timescales and reversibility risks • Understanding the barriers to implementation of SCS and how these can be overcome
BECCS	• Improved mapping of available land, especially marginal and degraded land (need for harmonized definitions). • Geographically explicit regional studies on potentials (and matching these bottom-up potentials with the global, top-down ones)
DAC	• Fine-grained, transparent, and complete (involving the complete DAC processing and storage) costing studies • Comprehensive estimation of environmental side effects (e.g. due to chemical usage at large scales), e.g. with life-cycle analysis methods • Innovation pathways via niche markets
Biochar	• Economic costs (and benefits) of real world deployment of biochar • Quantification of environmental, economic and social externalities associated with deployment of biochar, including land to provide feedstock • Better quantifying saturation timescales and reversibility risks • Understanding the barriers to implementation of biochar and how these can be overcome

To accelerate learning, the various NET options could be subjected to a portfolio approach. The approach is especially attractive as the current exploration of NET options suggests that each occupies different corners in the cost-risk-potential space. For example, BECCS has relatively high potential and medium costs, but is associated with high land use demand, water requirements and ensuing biophysical risks. DAC is deemed to be much more expensive but is less constrained by land use related risks. NETs may also change their cost-risk profile with scale of deployment and location. For example, afforestation in some locations might be a low cost, low risk option, but at higher scales could require high fertilizer and water input while competing with other land uses. Much of the literature also points to a lower effectiveness of afforestation in the North due to offsetting temperature effects from a changed albedo. Potentials, costs and risks of individual NET options may also be cross-fertilized by learning in related areas as time goes by. Institutional innovations and capacity building in regions with major gaps between biophysically feasible and realized yields such as in Sub-Saharan Africa, Ukraine or South-West Russia may contribute to closing the existing yield gap and by this take away pressure from land and enhance the prospects for land-intensive NET options such as BECCS or afforestation.

Dealing with uncertain and potentially risky NETs has important consequences for climate policy: from a risk management perspective there is a clear imperative to minimize the dependence on NETs and therefore to raise the level of short-term ambition as much as possible. A risk management perspective highlights the need for rapid learning in NETs and the importance of finding reasonable short-term entry points to ambitious climate policy at the same time. Limiting dependence on NETs and expanding knowledge and capabilities around them cannot be a contradiction in the real world.

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