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TOPICAL REVIEW

Negative emissions—Part 2: Costs, potentials and side effects

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Abstract

The most recent IPCC assessment has shown an important role for negative emissions technologies (NETs) in limiting global warming to 2 °C cost-effectively. However, a bottom-up, systematic, reproducible, and transparent literature assessment of the different options to remove CO_2 from the atmosphere is currently missing. In part 1 of this three-part review on NETs, we assemble a comprehensive set of the relevant literature so far published, focusing on seven technologies: bioenergy with carbon capture and storage (BECCS), afforestation and reforestation, direct air carbon capture and storage (DACCS), enhanced weathering, ocean fertilisation, biochar, and soil carbon sequestration. In this part, part 2 of the review, we present estimates of costs, potentials, and side-effects for these technologies, and qualify them with the authors' assessment. Part 3 reviews the innovation and scaling challenges that must be addressed to realise NETs deployment as a viable climate mitigation strategy. Based on a systematic review of the literature, our best estimates for sustainable global NET potentials in 2050 are 0.5–3.6 $GtCO_2\ yr^{-1}$ for afforestation and reforestation, 0.5–5 $GtCO_2\ yr^{-1}$ for BECCS, 0.5–2 $GtCO_2\ yr^{-1}$ for biochar, 2–4 $GtCO_2\ yr^{-1}$ for enhanced weathering, 0.5–5 $GtCO_2\ yr^{-1}$ for DACCS, and up to 5 $GtCO_2\ yr^{-1}$ for soil carbon sequestration. Costs vary widely across the technologies, as do their permanency and cumulative potentials beyond 2050. It is unlikely that a single NET will be able to sustainably meet the rates of carbon uptake described in integrated assessment pathways consistent with 1.5 °C of global warming.

1. Introduction

The Paris goal of holding global warming 'well below 2 °C' and to 'pursue efforts' to limit it to 1.5 °C imply a starkly limited remaining CO_2 budget (IPCC 2013, 2014b, Rogelj *et al* 2016). Considering the lack of deep, near-term decarbonisation, negative emission technologies (hereafter referred to as NETs) will evidently

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need to play a progressively more important role in climate stabilization strategies (Rogelj *et al* 2015a, Luderer *et al* 2013).

Studies applying global Integrated Assessment Models (IAMs) have highlighted the strategic and long-term importance of CDR for cost-effectively limiting global warming to 2 °C (Kriegler *et al* 2014), the key technology being Bioenergy with Carbon Capture and Storage[12] (BECCS) (Fuss *et al* 2014, Clarke *et al* 2014)[13]. Rogelj *et al* (2018) analyse the most recent and comprehensive set of 1.5 °C scenarios, which remove about 15 $GtCO_2\,yr^{-1}$ (median, 3–31 full range) by 2100 through BECCS. This corresponds to 175 (median, 54–404 full range) $EJ\,yr^{-1}$ of bioenergy. Such large amounts of bioenergy can however imply trade-offs with other land-based policy goals such as biodiversity conservation and food production (e.g. Kraxner *et al* (2013), see Creutzig (2016) for a discussion of the associated views). Recently, afforestation and reforestation have been added to many of the IAMs, which explicitly model the land use sector or are coupled to large-scale, geographically explicit land use models (e.g. Humpenöder *et al* 2014, Calvin *et al* 2014).

However, in order to perform a high-quality integrated assessment of NETs, a characterization of the different options is needed. A variety of reviews on NET technologies have taken on this task over the years (Smith *et al* 2016a, National Academy of Sciences 2015, Caldecott *et al* 2015, Lenton 2014, 2010, McGlashan *et al* 2012, McLaren 2012, Vaughan and Lenton 2011, The Royal Society 2009). From the approximately 3000 articles on NET technologies and measures identified by Minx *et al* (2017), more than 200 are classified as review articles. However, the available assessments have three shortcomings: first, they insufficiently bridge the divide between strategic evidence from long-term climate change mitigation models and the technological and institutional bottom-up evidence from the engineering and social science disciplines (Minx *et al* 2018). Second, the assessment of the entire NETs portfolio has been very fragmented so far, with only one publication assessing a full set of options (Friends of the Earth 2011), and other important efforts missing out technologies such as biochar and soil carbon sequestration (National Academy of Sciences 2015). Third, none of the available NETs and geoengineering assessments provide a systematic, comprehensive and transparent analysis rooted in a formal review methodology.

As in the two companion papers to this piece (Nemet *et al* 2018, Minx *et al* 2018), our review is formalized according to standard systematic review procedures (such as those more frequently employed in the medical and social sciences): (1) a search query is defined for each NET to transparently identify the relevant literature; (2) studies are then individually excluded according to pre-defined eligibility criteria; (3) qualitative and quantitative evidence is extracted and synthesized from the final document set (see the supporting information (SI) available at stacks.iop.org/ERL/13/063002/mmedia for the full protocol). Such a procedure is necessary to ensure reproducibility, avoid systematic omissions or biases in literature selection and to deal with a rapidly expanding base of knowledge (Minx *et al* 2017).

This paper is divided into two main parts. The first section proceeds with a review of low-stabilization scenarios from the IAM literature, examining the role of negative emissions in the mitigation portfolio and the magnitudes of CO_2 that would be removed from the atmosphere. The second part comprises our bottom-up review of individual NETs technologies and options, with a particular focus on magnitudes, costs and side-effects—both negative (e.g. competition for land, biodiversity loss or increased ocean acidification) and positive (e.g. health benefits from reduced air pollution, reduced ocean acidification, energy access—particularly off-grid). While the scenario literature in the past has mostly incorporated negative emissions in the form of BECCS and afforestation and reforestation, we here consider a larger range of negative emissions options, including biochar, enhanced weathering, ocean fertilization, direct air carbon capture and storage, soil carbon sequestration and some further options with smaller literature bases.

2. Scenario evidence on the role of negative emissions

The IPCC's Fifth Assessment report highlighted a potentially important role for NETs in keeping global temperature rise below 2 °C with a probability greater than 66% (IPCC 2014a, Clarke *et al* 2014). More recently the ambition of the Paris Agreement not only to keep warming well below 2 °C, but to pursue further efforts to limit warming to below 1.5 °C (UNFCCC 2015) has pushed NETs into the spotlight of discussions on viable mitigation pathways (Hulme 2016, Peters 2016, Rogelj *et al* 2015a, Hallegatte *et al* 2016, Luderer *et al* 2013). A series of high level commentaries and recent articles further elevated the issue and emphasized the controversial nature of NETs deployments featured in long-term mitigation scenarios (Geden 2015, Anderson 2015, Anderson and Peters 2016, Gasser *et al* 2015, Peters and Geden 2017, Lomax *et al* 2015, Williamson 2016, Parson 2017, Field and Mach 2017). We engage with this discussion directly, including its ethical foundations, in part 1 of the review series (Minx *et al* 2018).

[12] Although the term storage might imply accumulation for future use, we use it here interchangeably with the term 'sequestration' in accordance with the literature reviewed.

[13] Notable exceptions are Marcucci *et al* (2017), Chen and Tavoni (2013) and Strefler *et al* (2018b) for DACCS and Strefler *et al* (2018a) for terrestrial enhanced weathering. Strefler *et al* (2018b) combined three NETs (AR, BECCS and DACCS) for the first time.

In this section we review publicly available data from multi-model inter comparison studies[14] in order to understand the role of NETs in climate change mitigation (Riahi *et al* 2015, Kriegler *et al* 2015, GEA 2012, Riahi *et al* 2017, van Vuuren *et al* 2017a, Kriegler *et al* 2013b, 2016b). We supplement this data with further scenario evidence on the 1.5 °C limit (Luderer *et al* 2013, Rogelj *et al* 2015a, 2013a, 2013b, 2018). Hence the comprehensiveness and transparency of our review in this section is related to pooling the available data from recent studies. While many of the recent IAM scenarios include negative emissions, we only systematically review the literature that give sufficient importance to NETs, i.e. where NETs are mentioned in abstract, keywords or title. Importantly, the vast majority of mitigation scenarios considered here only features negative emissions via bioenergy with carbon capture and storage (BECCS). We interpret this evidence as a lower-bound estimate of negative emission potentials in these models, since the introduction of additional NETs seems to consistently increase cumulative NETs deployment (Chen and Tavoni 2013, Humpenöder *et al* 2014, Marcucci *et al* 2017).

2.1. Understanding the role of negative emissions for achieving alternative long-term climate goals

The carbon budget has been established in IPCC AR5 as a fundamental concept to understand human-induced (long-term) warming. It is defined as the cumulative amount of net CO_2 emissions that can be released while still limiting warming with a specific minimum probability to below a given temperature threshold (IPCC 2013, 2014b, Rogelj *et al* 2016). In principle, gross CO_2 emissions can be larger than the carbon budget as long as they are simultaneously compensated by negative emissions (figure 1) (Kriegler *et al* 2014, Riahi *et al* 2015, Eom *et al* 2015, van Vuuren *et al* 2013, van Vuuren and Riahi 2011, van Vuuren *et al* 2007, Azar *et al* 2006, 2010). Yet the geophysical limits of negative emissions are currently not well understood (Rogelj and Knutti 2016), although they are starting to be explored more rigorously (Keller *et al* 2018). A recent study asserts that the carbon budgets associated with the Paris Agreement temperature goals can be revised upwards from AR5 estimates (Millar *et al* 2017). This discussion is still new and unresolved. In the absence of a broader body of evidence we maintain the estimates from the IPCC AR5 (IPCC 2014b).

Looking across the available scenario evidence, two major purposes of negative emissions in climate change mitigation can be identified: first, NETs are deployed in scenarios for biophysical reasons, because the carbon budget consistent with a given temperature target is exceeded (van Vuuren *et al* 2007, van Vuuren and Riahi 2011, Clarke *et al* 2014). The 'payback' for this temporary exceedance is the required amount of cumulative net negative emissions, i.e. the total global net removal of carbon dioxide from the atmosphere towards the end of the 21st century when NETs draw global emission levels below zero (Blanford *et al* 2014, Kriegler *et al* 2013a). Compensation of excess positive emissions by negative emissions can come with a penalty (or 'interest'), because the cooling from net negative anthropogenic emissions may only offset part of the warming from earlier positive emissions (Zickfeld *et al* 2016). Second, negative emissions are deployed in scenarios for intersectoral compensation, i.e. to offset residual emissions that are difficult to mitigate, such as transportation—especially emissions from aircraft—and industrial emissions (Rogelj *et al* 2015a), or non-CO_2 GHGs from agriculture (Gernaat *et al* 2015). This occurs particularly in the second half of the 21st century when high carbon prices are realized in integrated assessment models. In figure 2 this can be observed when the total removal of CO_2 by NETs—henceforth referred to as gross negative emissions—is much larger than cumulative net negative emissions (Kriegler *et al* 2013a, van Vuuren and Riahi 2011, Krey *et al* 2014a, van Vuuren *et al* 2013). It is important to note that in some scenarios NETs are predominantly deployed because they are economically attractive (Azar *et al* 2006, Luckow *et al* 2010, Lemoine *et al* 2012), while in others they are biophysically required. For instance, some scenarios show that with immediate strengthening of climate policies it is still possible to limit warming to below 2 °C without NETs (Kriegler *et al* 2014). However, further delay of action or the tighter 1.5 °C climate goal renders NETs indispensable in the currently available scenarios.

Figure 3 provides an overview of emission pathways for achieving alternative climate targets and the role of negative emissions therein (Panel A). Scenario evidence available on the 1.5 °C warming limit remains comparatively limited. For IPCC AR5, evidence from only two models was available (Luderer *et al* 2013, Rogelj *et al* 2015a, 2013a, 2013b). We complement these studies with more recent 1.5 °C scenarios that span a variety of socio-economic conditions (Rogelj *et al* 2018).

Temperature overshoot is a typical feature in available 1.5 °C scenarios although the current scenario literature has not specifically focused on avoiding it[15]. All available scenarios hence show net negative cumulative emissions budgets for the second half of the 21st century (2050–2100) (Rogelj *et al* 2015a, 2018) or even in the longer run until 2300 (Akimoto *et al* 2017).

[14] LIMITS (https://tntcat.iiasa.ac.at/LIMITSDB/), AMPERE (https://tntcat.iiasa.ac.at/AMPEREDB/), RoSE (www.rose-project.org/database) provide results for hundreds of scenarios from roughly a dozen of models in the absence of explicit information on NETs in the even larger IPCC scenario database (https://tntcat.iiasa.ac.at/AR5DB/). We also include the SSP scenarios (https://tntcat.iiasa.ac.at/SspDb/). A description of the models that produced the scenarios analysed in this section is available in the SI.

[15] Azar *et al* (2013) reported that their IAM is unable to produce a 1.5 °C scenario without overshoot. A working paper by Holz *et al* (2017) suggests that it could be possible although they operate a system dynamics model that allows for very rapid decarbonisation and use a climate model that allows for a large carbon budget.

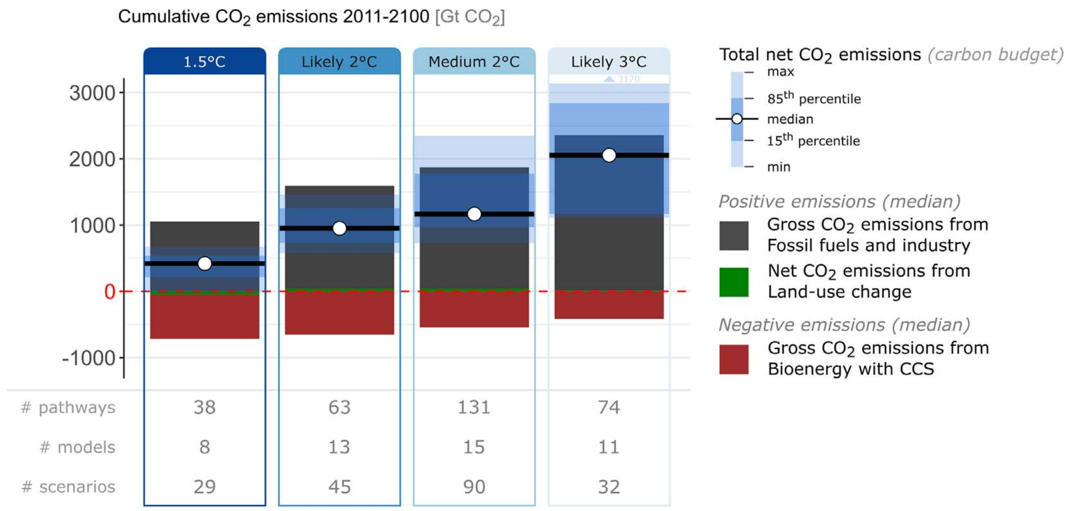

Figure 1. Positive and negative CO_2 emission components for reaching alternative temperature goals. Basic descriptive statistics of the underlying data is provided under the bar plot; more detailed data is available in the SI. Values in the row labelled 'pathways' indicate the number of available individual pathways. Those in the rows 'models' and 'scenarios' indicate the number of available individual models (see SI for model description) and scenarios. Important note: median values for gross negative CO_2 emissions can be considerably lower when a larger ensemble of scenarios is considered, as can be seen in figure 3. Yet not all emission categories were available from all modelling teams (e.g. gross positive emissions from fossil fuels and industry and net land-use change), so we had to take a smaller sample (see table S16 in SI). In the following paragraphs of this section on scenarios however, we focus on negative emissions and so we use the more complete dataset from figure 3.

Box 1. Defining climate policy scenarios in terms of warming limits.

We analyze the role of negative emissions for keeping temperature rise below alternative warming thresholds—namely 1.5 °C, 2 °C and 3 °C. For this purpose we define scenarios in terms of a minimum probability (usually 66%; sometimes 50%) for temperature rise not to exceed a certain warming threshold (Rogelj *et al* 2016), as conventionally done in the literature (Rogelj *et al* 2015a, Luderer *et al* 2013, Rogelj *et al* 2011, Clarke *et al* 2014):

• **1.5 °C scenarios**: Scenarios with a probability greater than 50% of reverting warming below 1.5 °C by 2100.
• **Likely 2 °C scenarios**: Scenarios that keep warming below 2 °C with a greater than 66% probability throughout the 21st century.
• **Medium 2 °C scenarios**: Scenarios that keep warming below 2 °C with a greater than 50% probability throughout the 21st century. Most of the scenarios that meet this criterion introduce adequate climate policies after an initial delay (delayed action scenarios).
• **Likely 3 °C scenarios**: Scenarios that keep warming below 3 °C with a greater than 66% probability throughout the 21st century.

For most scenario studies the reduced-form carbon-cycle and climate model MAGICC was used in a probabilistic setup to determine implied warming levels (Meinshausen *et al* 2011, Rogelj *et al* 2012, Schaeffer *et al* 2015). While some of these scenario categories are more in line with the Paris Agreement long-term temperature goal, they do not represent a formal interpretation of the UNFCCC temperature goal.

All these 1.5 °C scenarios are fundamentally dependent on the global-scale availability of NETs (figure 3). Scenarios that restrict[16] the availability of NETs substantially often result in model infeasibility (Luderer *et al* 2013). However, recent structured explorations of various socioeconomic contexts, the so-called Shared Socioeconomic Pathways (SSPs) (Riahi *et al* 2017, O'Neill *et al* 2017), have shown that NETs use can be restricted to some degree in 1.5 °C scenarios if specific socioeconomic conditions are met, such as low energy demand, sustainable consumption patterns and high crop yield improvements (SSP1) (Rogelj *et al* 2018).

Transition pathways limiting climate change to 1.5 °C are consistently characterized by sharp immediate reductions of net CO_2 emissions (3%–7% yr^{-1} on average between 2030 and 2050, taking 2030 as a reference) that lead to a fully decarbonized world (net zero emissions globally) between 2046 and 2056 (15th and 85th percentiles), with a sustained period of annual net negative emissions[17] ranging between 1.3–29 $GtCO_2\ yr^{-1}$ during the second half of the century. In general, NETs deployment throughout this period is large-scale in currently available scenarios. By 2050 NETs deployment is already between 5 $GtCO_2\ yr^{-1}$ and 15 $GtCO_2\ yr^{-1}$ in most scenarios. The associated scale-up of NETs between 2030 and 2050 therefore takes place much more swiftly than in most 2 °C scenarios, removing an additional 0.1–0.8 $GtCO_2$ every year on average. Total NETs deployment across the 21st century is associated with a cumulative removal of carbon of 150–1180 $GtCO_2$.

[16] Typical restrictions imposed are the unavailability of CCS and a restriction of the annual bioenergy potential to 100 EJ (Krey *et al* 2014b, Luderer *et al* 2013, Clarke *et al* 2014).
[17] Please note that this analysis only considers gross negative emissions from BECCS as those from AR are not available in the datasets.

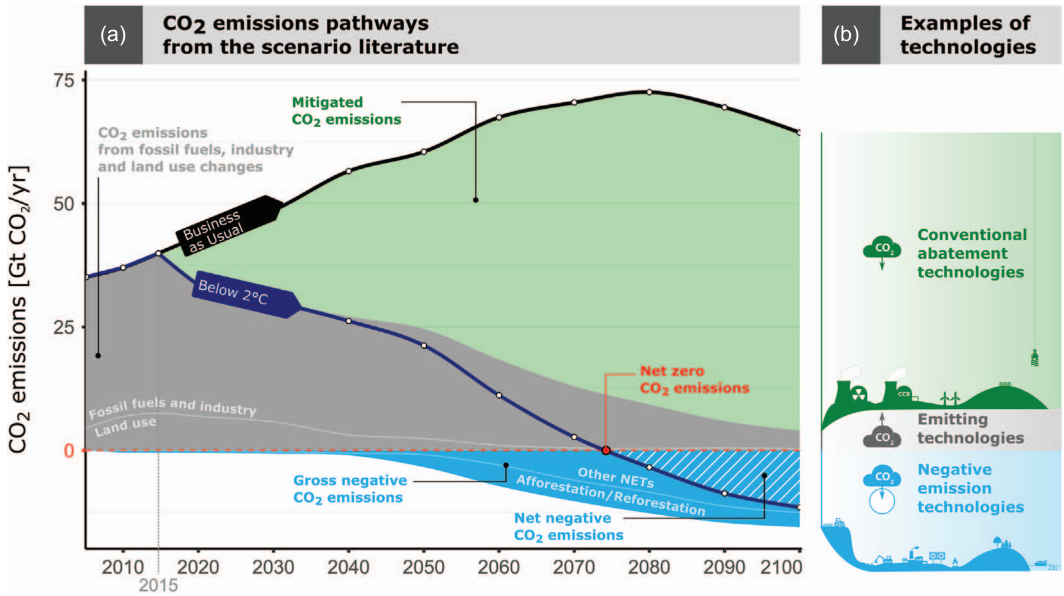

Figure 2. The role of negative emissions in climate change mitigation. The graph juxtaposes emission reductions from conventional mitigation technologies (panel A) with the removal of carbon dioxide via negative emissions technologies (panel B) in an exemplary scenario consistent with a 66% chance of keeping warming below 2 °C relative to a baseline scenario. Global emission levels turn net negative towards (hatched blue area) the end of the century to compensate for earlier carbon budget overshoot. Cumulative gross negative emissions represented by the entire blue area. The exemplary scenarios 'business as usual' and 'below 2 °C' were constructed using data from the LIMITS database (https://tntcat.iiasa.ac.at/LIMITSDB/). They correspond to the LIMITS-RefPol and LIMITS-RefPol-450 scenarios produced with the MESSAGE model. Gross positive and negative CO_2 emissions from land-use changes labelled as 'land use' (bottom grey shaded area) and 'afforestation/reforestation' (bottom blue shaded area) were inferred from net land-use changes emissions by using data in figure SI13 in Popp *et al* (2017). This manual edit was done to account for current afforestation and reforestation efforts and differentiate between negative emissions from land-use changes and other NETs.

Our ranges describe the statistics of an ensemble of opportunity, which has not been designed to span all possible outcomes in terms of NETs deployment. It mostly represents dynamics that are considered cost-effective by models in absence of particular societal preferences. The ranges thus represent characteristics of the currently available literature. Additional research needs to confirm that these can also be interpreted as requirements in a more formal sense.

Compared to 1.5 °C scenarios, the literature on the role of NETs in 2 °C scenarios is much more mature and rooted in a series of inter-model comparison exercises (Riahi *et al* 2015, Kriegler *et al* 2013b, Krey *et al* 2014b, Kriegler *et al* 2016b, 2016a, 2014, Fuss *et al* 2014, Tavoni and Socolow 2013, Kriegler *et al* 2013a, van Vuuren *et al* 2013). These have been summarized in IPCC AR5 (Clarke *et al* 2014). In 2 °C scenarios NETs are primarily deployed for limiting overshoot in atmospheric concentrations rather than temperatures (Riahi *et al* 2015, Blanford *et al* 2014, Tavoni and Socolow 2013, van Vuuren *et al* 2013). While this still leads to a significant reduction in the probability of reaching the long-term climate goal (Schaeffer *et al* 2015, Riahi *et al* 2015, Eom *et al* 2015), temperature overshoot carries additional risks associated with higher levels of warming and the resulting impacts and climate feedbacks that could occur (van Vuuren *et al* 2013, Solomon *et al* 2009, Friedlingstein *et al* 2006, Clarke *et al* 2014).

In general, 2 °C scenarios feature much more flexibility in NETs deployment, covering a wide range from zero to levels comparable with higher bound deployments in 1.5 °C scenarios. Hence, it is important to highlight that while many 2 °C scenarios deploy NETs at large scale, there are also scenarios that do not deploy NETs at all, or at very low levels (e.g. Eom *et al* 2015, Kriegler *et al* 2014, Luderer *et al* 2013, Riahi *et al* 2015, Rogelj *et al* 2013a)—an aspect that is often sidelined in discussions but is crucial for understanding the policy option space (Edenhofer and Kowarsch 2015, Minx *et al* 2017). For 2 °C scenarios featuring NETs deployment, it also points towards a strong economic rationale within models, as towards the end of the 21st century NETs become economically attractive if a temporary overshoot of the CO_2 budget is allowed, or if residual GHG emissions from other sectors are highly expensive to mitigate (Kriegler *et al* 2013b, Krey *et al* 2014a, Kriegler *et al* 2014).

In the 2 °C scenarios[18] with immediate implementation of climate policy and no additional technological constraints, net CO_2 emission reductions between 2030 and 2050 take place at an average rate of 1%–4% per year (Riahi *et al* 2015). After 2080 more than two thirds of these 2 °C scenarios have completed the decarbonisation of the world economy, i.e. they

[18] Here we account for both likely 2 °C and medium 2 °C scenarios.

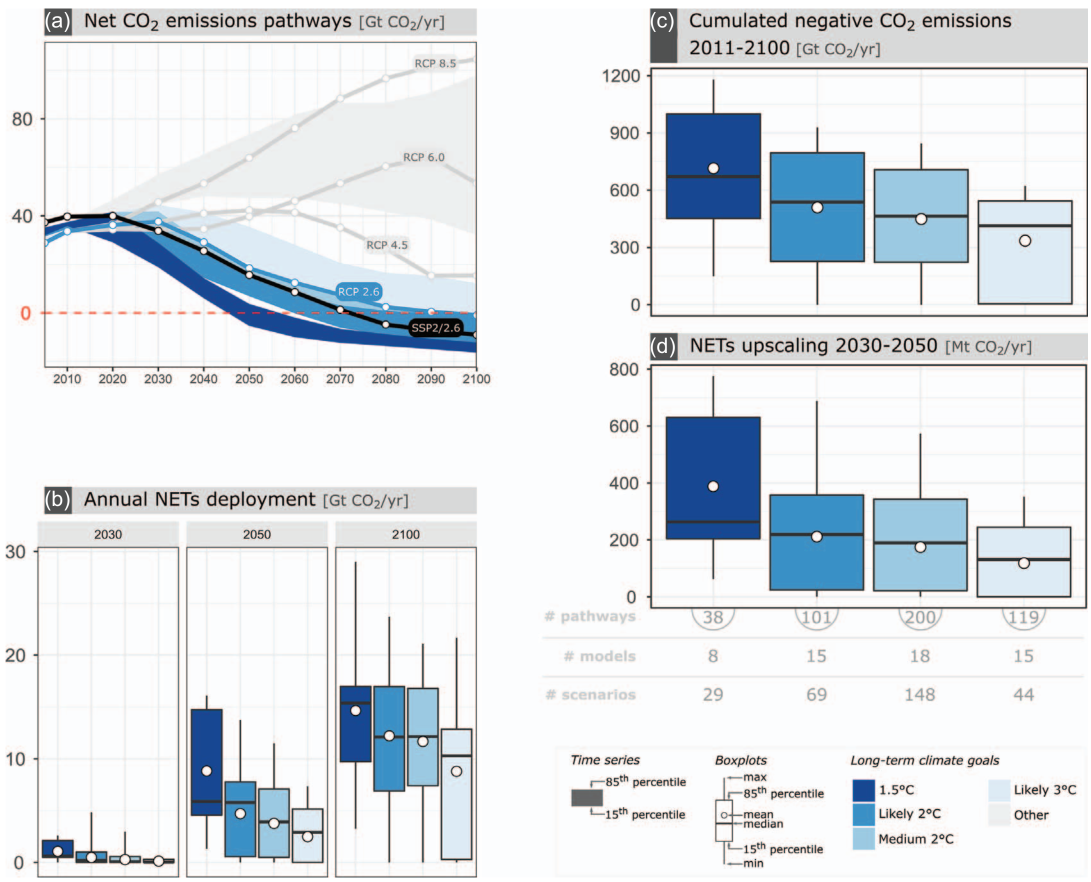

Figure 3. The role of negative emissions for achieving alternative long-term climate goals. Climate goals are indicated with blue shades. The more stringent the climate goal, the darker the blue colour. Net CO_2 emissions are displayed in panel (*a*) (top-left). Ribbons indicate the 15th and 85th percentiles for each climate goal. The original RCPs and the SSP2–2.6 marker scenarios are provided for orientation purposes. The boxplots in panels (*b*)–(*d*) provide the same statistics. The range between the minimum and maximum values is indicated with a vertical solid line. The range between the 15th and 85th percentiles is indicated by a blue-filled rectangle. The median is shown with a solid horizontal line whereas the mean is indicated by a white point. NETs deployments in 2030, 2050 and 2100 are shown in panel (*b*). Cumulative gross negative CO_2 emissions between 2011 and 2100 are shown in panel (*c*). Annually averaged gross negative CO_2 emissions between 2030 and 2050 are displayed in panel (*d*). Descriptive statistics of the underlying data are provided under panel (*d*) and more detailed data is available in the SI. Statistical differences between figures 1 and 3 arise because a few modelling teams did not report all variables necessary to plot figure 1 (i.e. gross positive emissions from fossil fuel and industry, net land-use emissions). A description of the models is provided in the SI.

transition from net positive to net negative CO_2 emissions (Rogelj *et al* 2015b). While there are some scenarios available without net negative emissions at the end of the century, most scenarios feature considerable NETs deployment ranging from 5 $GtCO_2\,yr^{-1}$ to 21 $GtCO_2\,yr^{-1}$ at the end of the 21st century. These annual deployment ranges are therefore not much lower than for 1.5 °C scenarios. In 2 °C scenarios with limited or no negative emissions (labelled with 'limited bioenergy' or 'no CCS/BECCS'), decarbonisation (including fossil fuel phase-out) occurs more rapidly than in the most cost-efficient 2 °C scenarios (full portfolio), but at a higher overall cost (Kriegler *et al* 2014, Krey *et al* 2014a, Riahi *et al* 2015, Luderer *et al* 2014). For instance, Luderer *et al* (2013)—based on the REMIND model—show that mitigation costs defined as the ratio of discounted[19] and aggregated consumption losses over discounted and aggregated GDP increase from 1.4% to 1.9% if BECCS (as the only explicit NETs option in the model) is limited, and to 2.3% in the absence of BECCS in 2 °C scenarios. Limiting BECCS in 1.5 °C scenarios increases costs from 2.3%–4.1%, while the absence of BECCS makes the scenarios infeasible. Similarly, multi-model results from EMF27 highlight the most significant cost mark-up for imposed technology constraints when CCS remains absent and bioenergy is limited to 100EJ (Kriegler *et al* 2014). One key reason for the larger cost mark-ups could be the constraints imposed on the NETs deployment potentials in the scenarios. Klein *et al* (2014) show that the negative emissions value of biomass tends to dominate over its energy value in low stabilization scenarios.

Low energy demand trajectories (low energy intensity) with more aggressive energy savings are an important option for providing further flexibility in 2 °C scenarios for achieving the climate goal with lower negative emissions deployments (figure 4)

[19] Luderer *et al* (2013) applied a discount rate of 5% to both consumption losses and GDP.

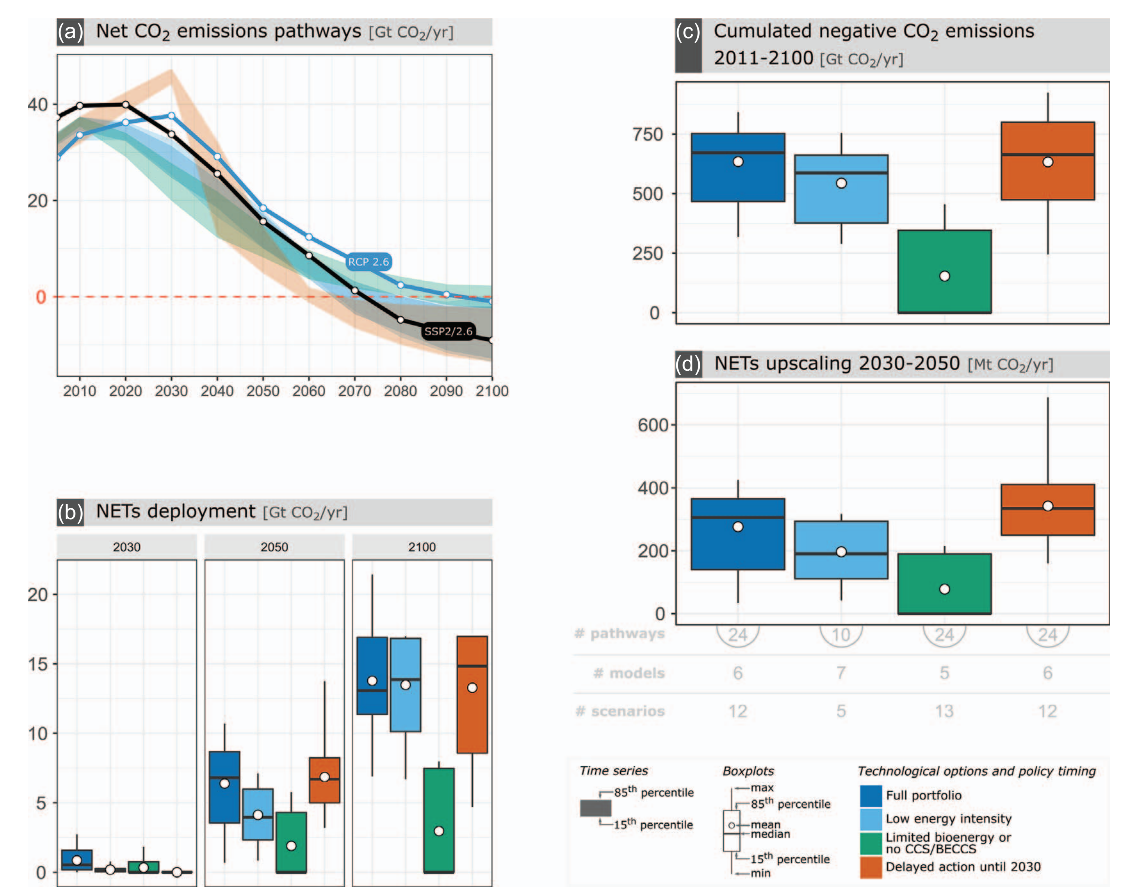

Figure 4. Negative emissions have a distinct role in 2 °C scenarios depending on the technological options and policy timing. Technological options and policy timing are indicated with various colours (dark blue for full technological portfolio, light blue for low energy intensity, green for limited biomass and no CCS/BECCS, and red for delay action until 2030). The cases full portfolio, low energy intensity and limited biomass or no CCS/BECCS assume climate action from 2010 onward. Net CO_2 emissions are displayed in panel (*a*) (top-left). Ribbons indicate the 15th and 85th percentiles for each pathway category. The original RCP-2.6 (also called RCP-3PD) and the SSP2–2.6 marker scenarios are provided for orientation purposes. The boxplots in panels (*b*)–(*d*) provide the same statistics. The range between the minimum and maximum values is indicated with a vertical solid line. The range between the 15th and 85th percentiles is indicated by a blue-filled rectangle. The median is shown with a solid horizontal line whereas the mean is indicated by a white point. NETs deployments in 2030, 2050 and 2100 are shown in panel (*b*). Cumulative gross negative CO_2 emissions between 2011 and 2100 are shown in panel (*c*). Annually averaged gross negative CO_2 emissions between 2030 and 2050 are displayed in panel (*d*). Basic descriptive statistics of the underlying data are provided under panel (*d*), and more detailed data is available in the SI. 2 °C scenarios include both likely 2.0 °C and medium 2.0 °C scenarios. A description of the models is provided in the SI.

(Rogelj *et al* 2013b, Krey *et al* 2014a, Eom *et al* 2015). In particular, gross cumulative negative emissions deployment (290–760 $GtCO_2$) tends to be lower in these scenarios driven by lower deployment rates (0–7 $GtCO_2\ yr^{-1}$) and upscaling (0–0.3 of additional $GtCO_2\ yr^{-1}$) between 2030 and 2050. Further delay in adequate global climate action swiftly locks 2 °C pathways with NETs in, including delayed action until 2030 (as implied by current NDC ambitions). Like most 1.5 °C scenarios, these 2 °C pathways can no longer be achieved without any or even limited amounts of NETs (figure 5) (Luderer *et al* 2013, Riahi *et al* 2015). Deployment and upscaling rates also increasingly mirror those seen in the available 1.5 °C scenarios.

The CO_2 removal ranges presented in this review are much wider than those reported in (Clarke *et al* 2014) and (Rogelj *et al* 2015a). The underlying scenarios are almost exclusively assuming middle-of-the-road and do not consider systematically socio-economic variations in future conditions. Here, such variations are considered via the new shared socio-economic pathways (SSPs) (Riahi *et al* 2017, O'Neill *et al* 2017, Rogelj *et al* 2018). One important insight from this new evidence is that the role and importance of NETs in climate change mitigation scenarios depends crucially on socio-economic developments (Riahi *et al* 2017, Bauer *et al* 2017, Popp *et al* 2017, van Vuuren *et al* 2017b, Rogelj *et al* 2018). For optimistic storylines following a sustainability narrative (SSP1). NETs requirements can be substantially lower than in middle of the road scenarios (SSP2) (Riahi *et al* 2017, Rogelj *et al* 2018). Conversely, the dependence on NETs increases in scenarios characterized by high energy demand and a strong preference for using fossil fuels (SSP5). For instance, to keep global warming below 1.5 °C the required cumulative removal of carbon over the 21st century can decrease by up to 67% in an SSP1 scenario, but increase by up to 32% in an SSP5 scenario (both compared to SSP2 scenarios). Likewise, scenarios characterized by strong regional rivalries across the world

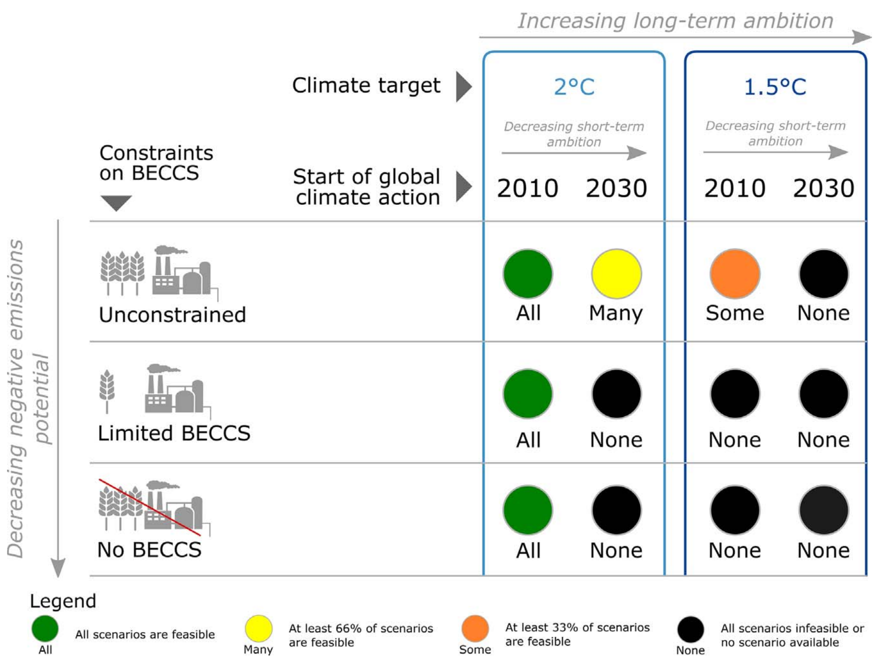

Figure 5. Model feasibility for different climate policy scenarios. Scenarios differ with respect to the climate policy ambition, the timing of climate policy and the assumptions of the available technology portfolio. All scenarios share the same exogenous socio-economic assumptions for GDP, population and energy demand. 'Many' means that less than 50% of the model runs were feasible whereas 'some' means that less than 33% of the model runs were feasible. Data come from REMIND model runs (Luderer *et al* 2013). 2 °C scenarios include both likely 2 °C and medium 2 °C scenarios.

(SSP3), or strong inequality within and between world regions (SSP4), would feature different NETs requirements. Beyond discussions of how to organize climate and energy policies with regard to negative emissions (Peters and Geden 2017), it is therefore also crucial to start a discussion on how the general development trajectory affecting consumption patterns, energy demand and international cooperation can be changed in light of its impact on NETs reliance to achieve stringent climate objectives.

While the vast majority of studies feature BECCS as the only explicit NET in the portfolio, a number of studies examine the role other NETs, often in small portfolios of two NETs that include BECCS. These studies looked at afforestation and reforestation (AR) (Humpenöder *et al* 2014, Kreidenweis *et al* 2016, Tavoni *et al* 2007, Edmonds *et al* 2013, Reilly *et al* 2012, Popp *et al* 2017, Rose *et al* 2012, Calvin *et al* 2014), enhanced weathering (EW) and direct air carbon capture and storage (DACCS) (Marcucci *et al* 2017, Chen and Tavoni 2013, Strefler *et al* 2018b). The IAM community is currently investigating the role of larger NETs portfolios including AR, BECCS, DACCS and EW.

The IAM literature on AR has now become substantial. It shows an average cumulative potential for AR over the 21st century and across models ranging from 200–860 $GtCO_2$ (Humpenöder *et al* 2014, Kreidenweis *et al* 2016, Rao and Riahi 2006, Calvin *et al* 2014, Tavoni *et al* 2007, Edmonds *et al* 2013, Reilly *et al* 2012). The upper end of the range is computed by models that include endogenous technological change (Humpenöder *et al* 2014, Kreidenweis *et al* 2016, Edmonds *et al* 2013). Yet it is interesting to note that a model that does not consider this effect, but includes the impacts of climate change on crop yields, still reports estimates up to 650 $GtCO_2$ (Reilly *et al* 2012). The lower end of the range of results is associated with modelling constraints (e.g. limits on bioenergy production or the availability of BECCS). Maximum annual deployments over the 21st century range between 0.5–10 $GtCO_2$ (Humpenöder *et al* 2014, Popp *et al* 2017, Reilly *et al* 2012). A common finding to all the selected studies is the low cost of implementing AR compared to that of other NETs. For instance, Strengers *et al* (2008) estimated that about 50% of the potential would be available at costs below 55 US$/$tCO_2$, while Humpenöder *et al* (2014) note that AR starts at carbon price as low as 6 US$/$tCO_2$. In terms of policy costs, AR can decrease the costs of mitigating climate change by about US$3 trillion (Tavoni *et al* 2007).

Chen and Tavoni (2013), Marcucci *et al* (2017) and Strefler *et al* (2018b) provide the only assessments of DACCS in a full-fledged integrated assessment model. They find that DACCS may only be profitable for very stringent climate policies. DACCS is only phased in after 2065, but then scales up rapidly to annual removal rates of 35–40 $GtCO_2\,yr^{-1}$ by the end of the century. The availability of DACCS in model runs eliminates sharp emission reductions in the short-term and compensates these delayed reductions via large amounts of net negative emissions towards the end of the century. Despite the relatively short application period the cumulative removal is large-scale, up to about 500 $GtCO_2$, and hence is associated with a sharp decline of atmospheric CO_2 concentrations. Uncertainty surrounding the development and implementation costs of this technology currently remains a major barrier (see section 3.3). Finally, Strefler *et al* (2018a) assess the techno-economic potential for land-based enhanced weathering at about 5 $GtCO_2$ for both basalt and fosterite. Adding it to the technology portfolio reduces the carbon price (Strefler *et al* 2018a). Because EW does not compete with BECCS, this technology might be particularly valuable if other NETs options are limited.

In sum, a common picture of NET portfolios seems to emerge from the integrated assessment evidence. Adding a second NET to the mitigation portfolio increases the negative emission potentials while reducing mitigation costs. In scenarios produced by inter-temporal optimization frameworks that have perfect knowledge of future technological availability and costs, these benefits accrue at the expense of weakened incentives for short-term emission reductions. We address the issue of potential moral hazard in paper 1 of this series (Minx *et al* 2017a). Additionally, these results suggest that expanding the NETs portfolio can hedge against risks associated with the large-scale deployment of BECCS (e.g. biodiversity loss and food price increase). Finally, the levels and timing of NETs deployments differs across technologies, as would be expected.

3. Potentials, costs and implications of large-scale NET deployment

Whether NETs perform at the levels of deployment envisioned in integrated assessment scenarios depends on three crucial features: their biophysical potentials for carbon sequestration (including storage and its permanence), their economic costs, and the social, economic, and environmental side-effects of their deployment—which in turn may pose limitations on potentials and costs[20]. Existing assessments suggest that NETs range widely along these dimensions (Royal Society 2009, National Academy of Sciences 2015) and that large-scale deployment will indeed have non-trivial impacts on water use, land footprints and nutrient use (Smith *et al* 2016a). In this section we proceed with an exhaustive review of the bottom-up literature on seven NETs. We aim to be transparent and comprehensive in our selection of literature (see SI). Where global deployment potentials or costs exist for a given NET, they are reported in the text and transcribed into the SI. This data is used to present ranges visually, and forms the basis of our synthetic comparison between different technology options. A variety of drivers may explain differences between reported ranges, including study methodology (e.g. empirical research, modelling), scope (technology type, system boundaries), and constraints (e.g. social, environmental). Where possible we group costs and potentials by these drivers, thereby explaining the wide differences that can be observed between studies. Finally, each NET is assessed by a subset of authors with the corresponding expertise. They make an overall judgement of a cost and potential range for each technology, taking into account our current understanding of the literature and social, economic and environmental constraints to deployment[21].

3.1. Bioenergy with carbon capture and storage (BECCS)

The concept of BECCS rests on the premise that bioenergy can be provided with zero or at least low carbon emissions, i.e. about as much additional CO_2 is sequestered above baseline when growing additional biomass as feedstock, as is released during its combustion or other energy conversion processes. If the latter emissions are then also captured and stored (e.g. in geological formations), it is effectively taken out of the carbon cycle and the system generates negative emissions (Creutzig 2016, Creutzig *et al* 2015, Smith *et al* 2013, 2014). As section 2 has shown, BECCS features prominently in the IAM scenario literature and has been subject to considerable scrutiny since the IPCC's Fifth Assessment Report (AR5) in 2014 (Fuss *et al* 2014, Anderson and Peters 2016). In this section, we provide a comprehensive overview of the literature on global potentials and costs, and some key side-effects of BECCS are considered.

In this assessment, we focus on bioenergy as well as geological storage potentials as limiting factors and consider costs and additional aspects from the literature on the entire BECCS chain in order to keep this multi-technology review manageable. There is a lot of additional literature, for example, relevant to the CCS component of BECCS. This covers many specific technological aspects related to the capture, transportation and storage components. A recent comprehensive review of this literature is provided in Bui *et al* (2018).

Global bioenergy potentials: The availability of biomass and land is seen as the fundamental limiting factor, structuring discussions about BECCS

[20] Evidently, for any niche technology to achieve wide-scale adoption, basic research and development needs to take place, and a specific set of political and institutional conditions must exist to generate demand. We review NETs along these lines in paper 3 of this series (Nemet *et al* 2018).

[21] Cost estimates come in a variety of different forms, including (1) establishment or capital costs (e.g. the cost of converting land use to forestry, or installing a direct air capture unit); (2) opportunity costs (e.g. the lost revenue from competing land uses, principally agriculture); (3) the carbon price required to deploy a NET at a given scale; (4) the normalized average carbon price required to sequester a unit of carbon for a given NET. Clearly (4) is the most desirable cost unit for technology comparison, but it is rarely reported and often derived from widely varying assumptions. In the following, we will make sure to highlight which cost type we are putting forth in order to avoid inducing inappropriate comparisons.

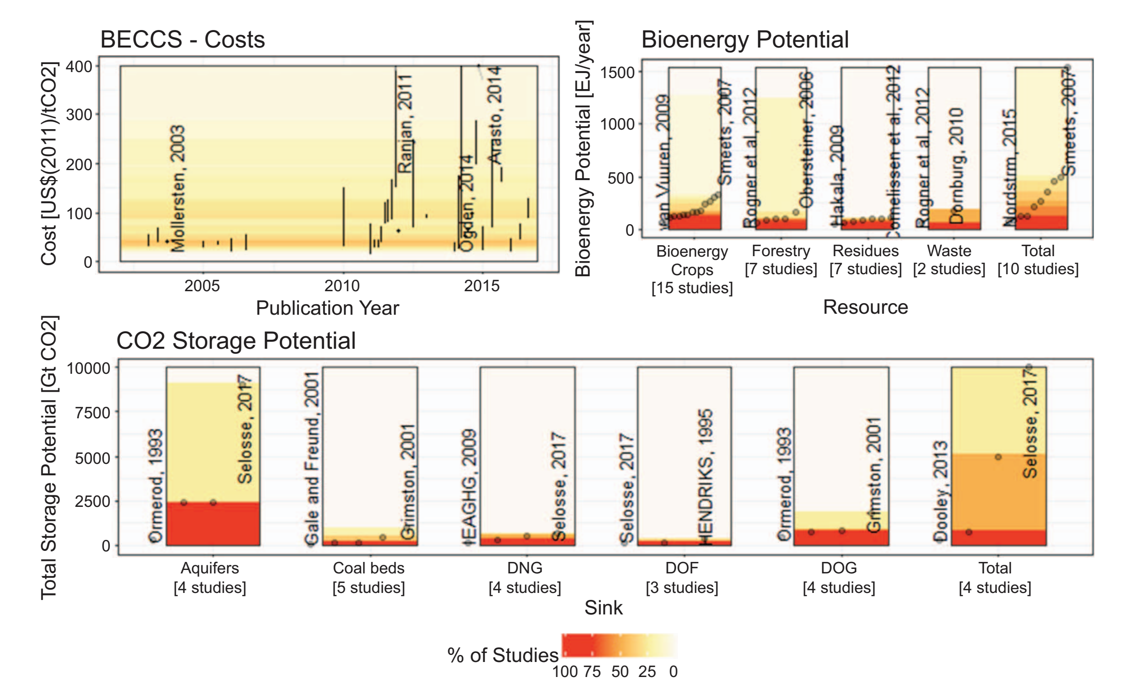

Figure 6. Costs and potentials for BECCS. The heat bar panel for costs is shaded according to the proportion of the ranges overlapping at each cost value (studies are depicted as lines plotted by the year of publication, or as dots where only a single estimate was available). The heat bar panels depicting negative emissions potentials are shaded according to the proportion of studies whose maximum estimate (depicted as dots) is greater or equal to each potential value. Where no maximum estimate was available, the estimate was taken. For BECCS, we show bioenergy potentials categorised by feedstock, and storage potentials by sink (DNG: Depleted natural gas fields, DOG: Depleted oil fields, DOG: Depleted oil and gas). Estimates and ranges at the top and bottom end of the distribution are labelled; the data can be further explored in our online supporting material available at https://mcc-apsis.github.io/NETs-review/.

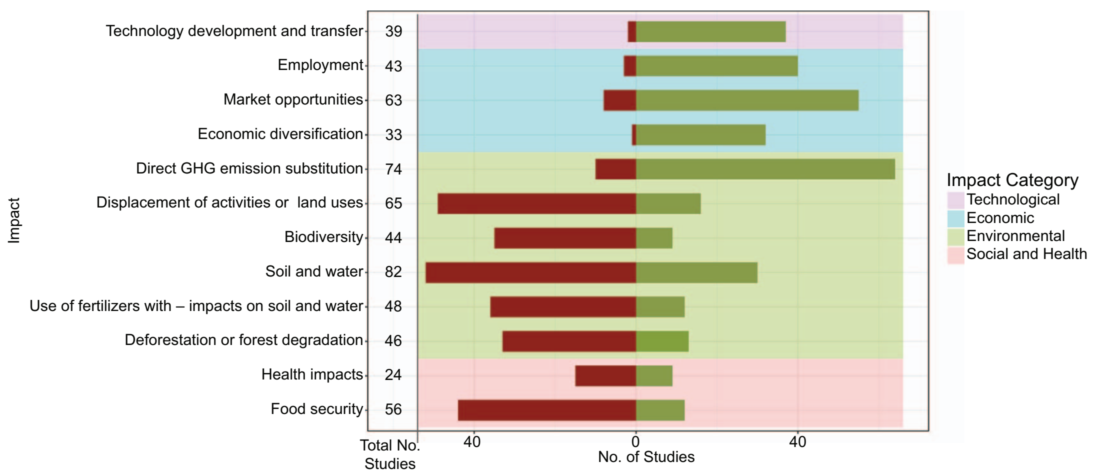

Figure 7. Distribution studies discussing negative and positive impacts for key side-effects. Adapted from Robledo-Abad *et al* (2017).

potentials (Krey *et al* 2014a, Smith *et al* 2016a, Creutzig *et al* 2015). 1 EJ of biomass typically yields around 0.02–0.05 $GtCO_2$ worth of negative emissions.

Total bioenergy potential estimates for 2050 range from 60–1548 EJ yr^{-1}. Estimates at the lower-end of this range (Kraxner and Nordström 2015, Searle and Malins 2015, Smith *et al* 2012) all provide minimum estimates of around 60 EJ yr^{-1}. Bioenergy crop deployment is limited by land allocation for natural parks (Kraxner and Nordström 2015, Field *et al* 2008 (a 2030 estimate)), or when deployed only on degraded (Wicke *et al* 2011, Nijsen *et al* 2012) or marginal land (Searle and Malins 2015), which will lead to lower yields. Other conservative estimates for 2050 consider only residues, either immediately available (Smith *et al* 2012) or in line with 2050 estimates (Tokimatsu *et al* 2017).

Potentials increase as deployment constraints are relaxed to include more productive land, with minimum potentials of 130 and 160 EJ yr^{-1} and maximum estimates of 216 and 267 EJ yr^{-1} (Beringer *et al* 2011, Rogner *et al* 2012) and similar estimates for 2055 (Popp *et al* 2014, Klein *et al* 2014). Higher estimates are characterized by more limited cropland expansion and lower nature conservation criteria.

The group of optimistic estimates start at around 350 EJ yr^{-1} (Cornelissen *et al* 2012, Fischer and Schrattenholzer 2001, Smeets *et al* 2007). Although Cornelissen's calculations are limited to rain-fed agriculture, and apply a food-first principle, they still estimate 340 EJ available/yr by 2050. This is partly due to their inclusion of algae as a feedstock, which contributes 90 EJ yr^{-1} to their estimate and the use of fertilizers over a relatively large deployment area (673 Mha). Fischer and Schrattenholzer (2001) assume limited agricultural land expansion due to increasing yields. Bioenergy crops here are deployed on grassland rather than constrained to marginal or degraded lands as in the more conservative estimates above. Smeets *et al* (2007) provide the most optimistic estimates between 370–1500 EJ yr^{-1}. Much of this potential (215–1272 EJ yr^{-1}) comes from dedicated bioenergy crops and the wide range reported reflects different factor yield increases (2.9 vs 4.6), area available for deployment (729 Mha and 3585 Mha respectively) and rainfed vs irrigated agriculture. Smith (2012) provides an estimate of biospheric capacity of 727.5 EJ yr^{-1} over all vegetated land (11 000 Mha). Rogner *et al* (2012) assess a theoretical bioenergy potential of 793 EJ yr^{-1} if all aboveground net primary production (NPP) that is not used for food, feed or fiber is devoted to bioenergy production.

Bioenergy estimates from dedicated crops offer wide discrepancies, from conservative estimates of approximately 20 EJ yr^{-1} (Erb *et al* 2012a, Thrän *et al* 2010, Hakala *et al* 2008, Nijsen *et al* 2012, Beringer *et al* 2011), to middle ranges of 70–180 (Erb *et al* 2012b, Yamamoto *et al* 2000, Hoogwijk *et al* 2009, Cornelissen *et al* 2012, Beringer *et al* 2011, Thrän *et al* 2010, Rogner *et al* 2012) to high estimates above 200 EJ yr^{-1} (Hoogwijk *et al* 2005, Smeets *et al* 2007, Cornelissen *et al* 2012). Variance depends largely on available land and yields (Dornburg *et al* 2010, Boysen *et al* 2017), which in turn can be driven by assumptions regarding future population and diet (Haberl *et al* 2011, Hakala *et al* 2008), biodiversity and conservation restrictions (Erb *et al* 2012a, Beringer *et al* 2011, Popp *et al* 2011), or land quality and technology improvements (Smeets *et al* 2007). Hakala's low estimates use current global statistics rather than projected yields to account for social and institutional conditions, and they further reduce their estimates when considering global affluent diets (Hakala *et al* 2008). High estimates are derived from scenarios of large-scale deployment on abandoned agricultural land, where yield factor increases are far higher than on marginal lands (Smeets *et al* 2007, Hoogwijk *et al* 2009). Higher estimates are commonly grounded in economic analysis, involving factors such as technological change to improve yields, whereas lower estimates focus on ecological and biophysical concerns and natural limits to sustainable bioenergy deployment (Creutzig 2016).

Estimates for forestry-sourced bioenergy range from 38–165 EJ yr^{-1} (Smeets and Faaij 2007, Lauri *et al* 2014, Smeets *et al* 2007, Cornelissen *et al* 2012, Rogner *et al* 2012). The only estimate above 200 EJ yr^{-1} comes from an aggressive deployment of afforestation and reforestation activities. Smeets' central estimate sees forests being deployed on 292 Mha of land, while Obersteiner *et al* (2006)'s lower deployment scenario starts at 290 Mha and goes up to 660 Mha for the extreme estimate of 1250 EJ yr^{-1}. By contrast, the lowest estimate comes from the application of strict sustainability criteria that excludes consideration of protected, inaccessible and undisturbed forests, as well as non-commercial species and traditional-use biomass resources (Cornelissen *et al* 2012).

Although not fully assessed here, algae has been proposed as an alternative source of biomass for BECCS. Due to its high photosynthetic efficiency and high yields (Moreira and Pires 2016), its capacity to co-produce protein and its potential to decrease land competition (Beal *et al* 2018), algae may address some of the sustainability concerns raised by BECCS.

Global storage potentials. The second major factor that could restrict BECCS deployment is the availability of storage. There is little doubt in the literature that there is, in principle, sufficient potential available across the globe to geologically store vast amounts of CO_2 permanently, as required by many 1.5 °C and 2 °C scenarios (Dooley 2013). Yet in individual regions there could be storage bottlenecks that would limit the BECCS potential in that region (Calvin *et al* 2009, Edmonds *et al* 2007, Dooley 2013).

Global estimates of total storage potential span a massive range—from 320 (Koide *et al* 1993) to 50 000 $GtCO_2$ (Hendriks and Blok 1995). Global estimates using top down approaches grow as more storage options are considered. The low estimate of 320 $GtCO_2$ conservatively assumes that 1% of all sedimentary basins might be suitable for storage (Koide *et al* 1993). This more than doubles (to 777 $GtCO_2$) when proven depleted oil and gas reserves are included (Ormerod *et al* 1993), then roughly doubles again to 2065 $GtCO_2$ (Hendriks and Blok 1995) when considering undiscovered oil and gas reserves. The assessment increases dramatically to over 50 000 $GtCO_2$ when other trapping mechanisms allow storage to occur in aquifers without a structural trap (Hendriks and Blok 1995). Later estimates make use of more detailed information from regional and national studies to generate global estimates (Selosse and Ricci 2017, Dooley 2013). Dooley's estimate of theoretical capacity is in the same order of magnitude (35 000 $GtCO_2$), but is significantly reduced by physical and practical constraints to 13 500, 3900 and 290 $GtCO_2$ of effective, practical, and matched potential worldwide, respectively[22]. The effective capacity estimate is in line with estimates reached by integrating global IEA GHG data with data from national and site specific estimates, and other sources such as Total Petroleum System and the United States Geological Survey for a total potential of 10 000 $GtCO_2$ (Selosse and Ricci 2017).

Global estimates for depleted oil and gas fields range from 458 (Ormerod *et al* 1993) to 923 $GtCO_2$ (IEA Greenhouse Gas R&D Programme 2000) (IEA Greenhouse Gas R&D Programme 2000). This relatively narrow range likely results from thorough documentation of structures during exploration and extraction. Despite wide differences in total potentials, the broad studies with breakdowns provide a narrower range of 458–801 for oil and gas fields (Hendriks and Blok 1995, Selosse and Ricci 2017, Ormerod *et al* 1993). IEA GHG estimates are based on a detailed database of 155 geological provinces (IEA Greenhouse Gas R&D Programme 2000). Regional assessments provide insight into the geographical distribution of resources. North American estimates range from 40 (Dooley *et al* 2005) to 136 $GtCO_2$ (Wright *et al* 2013). The low estimate only considers the CO_2 sequestration potential of depleted gas fields and oil fields with enhanced oil recovery (EOR). European estimates range from the effective capacity evaluated by the GeoCapacity project of 20 $GtCO_2$ (Vangkilde-Pedersen *et al* 2008) to 280 $GtCO_2$ (Hendriks and Blok 1995). The latter estimate can likely be attributed to the former Soviet Union nations, which Selosse and Ricci (2017) estimate have 277 $GtCO_2$ of capacity. Estimates that exclude this region cluster are between 20 and 60 $GtCO_2$ (Vangkilde-Pedersen *et al* 2008, 2009, IEA GHG 2005, Selosse and Ricci 2017). Lower estimates exclude some countries and present effective capacities with site-specific information. Middle Eastern estimates range from 208 (Selosse and Ricci 2017) to 250 $GtCO_2$ (Hendriks and Blok 1995), but only EOR estimates were found at national or site specific levels (Jaju *et al* 2016, Movagharnejad *et al* 2012, Mortensen *et al* 2016, Hassani *et al* 2016).

Estimates of the storage potential of coal beds range from 60 (Gale and Freund 2001, Gale 2004) to 700 $GtCO_2$ (Kuuskraa *et al* 1992). Lower estimates consider the economic constraints (Dooley *et al* 2005) of 10 high potential countries, while a more comprehensive assessment of 24 countries expands the potential to 487 $GtCO_2$ (Godec *et al* 2014). Kuuskraa *et al* (1992)'s estimate appears to be based on theoretical analysis by the authors leading to a higher range. The early estimate of 150 $GtCO_2$ considers few countries and subsequent regional estimates have revised this upward. In North America, estimates have increased from 47 $GtCO_2$ (IEA GHG 1998, Gale 2004) to 65–120 $GtCO_2$ (Godec *et al* 2014, Dooley *et al* 2005, Wright *et al* 2013). Lower-end estimates tend to consider specific basins with high potential and favorable market conditions while higher estimates reflect theoretical global potentials.

Most of the potential and variability in estimates comes from estimates of potentials in aquifers. Hendrik's broad estimate of 200–50 000 $GtCO_2$ covers all other estimates in the literature. The lower-end considers aquifers only with a structural trap, while the high end integrates other trapping mechanisms allowing much wider deployment[23]. Early estimates are explicitly conservative, but it is unclear whether they are considering structural traps in their constraints (Koide *et al* 1993). Although the 50 000 estimate is explicitly theoretical, regional estimates have provided support to it. High potentials have been estimated for North America (Dooley *et al* 2005, Wright *et al* 2013), China (Li *et al* 2009) and OECD Europe (IEA GHG 2005).

Costs. Cost estimates through the entire literature range from US\$15–400/tCO_2. Estimates that cover BECCS generally estimate prices of between US\$30 and 400/tCO_2 (Luckow *et al* 2010, Koornneef *et al* 2012, Arasto *et al* 2014). However, most sources focus on a specific source for CO_2 capture. Many papers explore the potential of capture from ethanol fermentation and find ranges of US\$20 to 175/tCO_2 (de Visser *et al* 2011, Fabbri *et al* 2011, Fornell *et al* 2013, Laude *et al* 2011, Möllersten *et al* 2004, Johnson *et al* 2014, Rochedo *et al* 2016). Low values within the studies represent deployment in the most suitable plants with easy access to abundant biomass and short distances to storage sites. Capturing CO_2 emissions from both ethanol fermentation and cogeneration units increases costs (US\$40–120 vs US\$180–200/tCO_2 avoided) but also increases avoidance potential (Laude *et al* 2011). Combustion BECCS has higher costs ranging from US\$88 to US\$288/tCO_2 (Akgul *et al* 2014, Al-Qayim *et al* 2015, Kärki *et al* 2013). Low estimates in combustion come from utilizing oxy-fuel technologies (Al-Qayim *et al* 2015, Kärki *et al* 2013). The lowest estimate for this technology group (US\$14–77/tCO_2 avoided) comes from a variation of oxy-fuel combustion that is still unproven (Abanades *et al* 2011). Biomass gasification technologies are estimated between US\$30 to US\$6/tCO_2 (Gough and Upham 2011, Rhodes and Keith 2005, Sanchez and Callaway 2016). However, Ranjan provides much more pessimistic estimates of US\$150–400/tCO_2 avoided, but these might be due to extremely large land requirements for the production of biomass. The cost

[22] The types of potential correspond to estimates of capacity increasingly constrained by physical (theoretical), technical (effective), regulatory, economic (practical) barriers as well as detailed matching with large CO_2 sources (matched) (Bradshaw *et al* 2007, Bachu *et al* 2007).

[23] Structural traps refer to geological structures capable of retaining hydrocarbons, sealed structurally by a fault or fold (IPCC 2005). For an overview of trapping mechanisms see (Bradshaw *et al* 2007).

of CO_2 avoidance via BECCS utilizing black liquor produced by pulp and paper mills has been estimated to range between US$20 and US$70/tCO_2 when using recovery boilers (Onarheim *et al* 2015, Möllersten *et al* 2004) and US$20–55 when using gasification technologies (Möllersten *et al* 2006, 2004). Other technologies have been estimated at US$86–167/t$CO_2$ avoided (Carbo *et al* 2011) and US$20–40/t$CO_2$ (Johnson *et al* 2014) for BioSNG and biomass FT diesel, respectively.

Low cost estimates typically start with a coal-CCS configuration and assume biomass fuel costs lower than those of coal, as at least partially available, e.g. in the US-Midwest. Transport costs of biomass are included in some (e.g. Sanchez and Callaway 2016) but not all studies. Importantly, biomass is nearly always assumed to be produced at zero life-cycle emissions. But life-cycle emissions related to direct or indirect land use pose a 10%–30% efficiency penalty on carbon abatement, and hence on costs of negative emissions, even in the optimistic cases where biomass is derived from cellulosic sources or dedicated bioenergy crops. It may also be relevant to price in indirect externalities, mediated via land markets, e.g. on food markets, ecosystem services, and livelihoods (see below). This is a contentious exercise with little agreement and large parameter uncertainties.

Side effects. Side effects can be broadly categorized into climate effects induced by biomass provision, resource needs, and broader environmental and sustainability effects transmitted via the coupled land-energy system (Creutzig *et al* 2015, Robledo-Abad *et al* 2017). An exhaustive and comprehensive literature review of 1175 publications on side effects and sustainable development contributions of bioenergy published in a recent study revealed that side effects can be in general both positive and negative; however, negative effects are more often observed in the literature in social and environmental dimensions, whereas positive effects are more often observed in economic and technological dimensions (Robledo-Abad *et al* 2017).

Climate effects belong to the categories of direct land use change, indirect land use change, and albedo effects. Land use change emissions include those from change in previous use, such as deforestation, and changes in global land use induced by economic markets. These are generally high for first-generation biofuels, such as corn ethanol, which are derived from food markets; while overall emissions are still relevant but in lower ranges for bioenergy from cellulosic or woody sources, and from food waste and forest residues (Plevin *et al* 2010, Smith *et al* 2016a)[24]. (Some specific albeit relatively low-yield choices can generate carbon-negative bioenergy, see Tilman *et al* 2006). Low emissions also translate into a significant efficiency loss in bioenergy for climate mitigation or for BECCS as negative emissions technologies. Calculation of indirect land use effects is subject to parameter and structural model choice rather than accounting only and leads to considerable uncertainty in estimates and abatement effects (Plevin *et al* 2010, 2014).

The global albedo effects of cultivating biomass for bioenergy are also relevant and vary with geographical location. Higher latitudes, where biomass might replace reflective snow cover, are more prone to an albedo effect that offsets climate mitigation (Bright *et al* 2015). Land use and land cover change forcing ranges from -0.06 to $-0.29\,\mathrm{W\,m^{-2}}$ by 2070 depending on assumptions regarding future crop yield growth and whether climate policy favors afforestation or bioenergy crops (Jones *et al* 2015).

Required resources may include fertilizer use (which in turn lead to GHG emissions and must be factored in) and water use. If 170 EJ $\mathrm{yr^{-1}}$ were produced by a 2 °C-compliant BECCS infrastructure by 2100, the water footprint would amount to 59.5 $\mathrm{km^3}$/GtCO_2 by 2100 (Smith 2016), which corresponds to 1.5% of global yearly freshwater withdrawals.

Bioenergy is confronted with substantial concerns regarding competition for land, including impact on food prices, biodiversity, water and nutrients (Williamson 2016, Smith *et al* 2013, Haberl 2015, Robledo-Abad *et al* 2017, Edenhofer *et al* 2013). A major concern is the effect that large-scale deployment poses on food security. Although many studies apply a food-first principle to limit deployment, increased land competition could lead to increased global food prices (Popp *et al* 2011, Reilly *et al* 2012) and regional resource shortages (Müller *et al* 2008). Some biofuels (such as corn ethanol) impact food prices, but others that do not directly compete with food (such as sugarcane) have a lower impact—yet often these price impacts are dwarfed by exogenous factors like economic growth (Zilberman *et al* 2013, Roberts and Schlenker 2010, Timilsina *et al* 2012). These concerns can be alleviated by limiting deployment to marginal land, but this is often associated with detrimental impacts on biodiversity (Dale *et al* 2010, Wiens *et al* 2011). Conversely, deployment on degraded lands could contribute to protection from erosion and soil restoration (Lemus and Lal 2005).

More than 1 billion small-holder farmers could also be directly or indirectly subjected to changing agricultural practices and bioenergy systems, both positively and negatively (Mutopo *et al* 2011, Creutzig *et al* 2013). BECCS has the potential to increase and diversify rural income, but also at the risk of displacing small-holders or exposing them to the volatility of world markets (Buck 2016). Current practice is commonly not concurrent with livelihood concerns; instead research points to the global commodification of

[24] Although achievable scales are not clear yet, there is also research on third-generation biofuels, derived from algal biomass (Brennan and Owende 2010) with the potential to enhance yields by improving microalgal biology through genetic or metabolic engineering (Tandon and Jin 2017).

a local energy supplement and the consolidation of corporate power in agribusiness and energy sectors (Borras and Franco 2010, Rist et al 2010). Case study analyses demonstrate that while some local actors are likely to profit from bioenergy deployment schemes, others, often starting from an institutionally disadvantaged position, can lose out (Creutzig et al 2013, Schoneveld et al 2010). Distributional issues are hence a crucial dimension in designing the governance of bioenergy (Hunsberger et al 2014).

CCS poses its own set of risks. Overpressure could lead to the pollution of potable water, to seismic activity or to leaks, which could not only rapidly reverse positive mitigation effects, but cause environmental and health damage at the leakage sites (Holloway 2009, National Academy of Sciences 2015, Smith et al 2016a, Bruckner et al 2014).

Permanence and saturation. In principle, once the CO_2 removed from the atmosphere via BECCS is geologically stored, it is one of the NET options that is less vulnerable to reversal. Most importantly, stored CO_2 is not subject to further management decisions like other land-based NETs. While leakage can be an issue, it is not widely perceived as a major hurdle to safe and permanent storage. Moreover, there is significant research on monitoring and verification as well as on leak detection and remediation (Bui et al 2018). However, considerable concerns with BECCS are associated with its level of effectiveness, which can be compromised by significant amounts of emissions from indirect land-use change (Plevin et al 2010).

Authors' assessment. Overall, by 2050 we see BECCS at costs of US\$100–200/tCO_2 that accrue inter alia from the necessity to guarantee limited sustainability and land-use carbon cycle effects, and which will require high management intensity on a case-by-case basis. Our estimate of 2050 potentials ranges is 0.5–5 GtCO_2 (considering here a technological potential that remains cognizant of other sustainability aims). As for all land-intensive options, we remain conservative in our suggested values as they refer to mid-century where population pressures are highest according to recent projections (Samir and Lutz 2017). A range of 5GtCO_2 and possibly higher requires global land governance, integrating multiple land use concerns for the global common good.

3.2. Afforestation and reforestation (AR)

Afforestation refers to planting trees on land that has not been afforested in recent history (a reference value of at least 50 years is commonly used). Reforestation, on the other hand, refers to the replanting of trees on more recently deforested land (IPCC 2000). Negative emissions can arise from both practices, as the growth of additional biomass sequesters CO_2 from the atmosphere. The distinction between afforestation and reforestation is often not clean in the literature and we therefore categorize them jointly.

Global sequestration potentials and costs. Out of 12 previous assessments of different NETs, seven offer yearly potentials at either mid-century or 2100. The 2050 range is 0.5–7 GtCO_2 yr^{-1} (Lenton 2014), which encompasses the ranges given in earlier assessments (Friends of the Earth 2011, McLaren 2012, Lenton 2010). In 2100, this range widens to 1–12 GtCO_2 yr^{-1}, covering the ranges given by Smith et al (2016a), the National Academy of Sciences (2015) and Lenton (2010, 2014). In addition, some assessments give potentials in cumulative terms with the lowest 2100 estimate of 80 GtCO_2 coming from the Oxford University's Stranded Assets Programme (Caldecott et al 2015) and the highest estimate being the upper end of the IPCC AR5 range with 260 GtCO_2 (IPCC 2014a). There is high agreement on the maximal costs of AR being around US\$ 100/ton of sequestered CO_2 and less agreement on the lower-end of the range, with the National Academy of Sciences (2015) quoting US\$1 and the rest being in a range of US\$18–20/ton CO_2. The Royal Society Report (2009) does acknowledge AR as an option to remove carbon, but does not give potentials. Their assessment points to 'low costs' as well.

Taking the systematically scoped literature (see section 3.2.1) into account, the upper end of the 2100 sequestration potential remains at just above 12 GtCO_2 yr^{-1} in 2100. The lower-end is slightly more conservative at 0.54 GtCO_2 yr^{-1} (Liu et al 2016)[25]. New estimates from Integrated Assessment Modeling combined with more detailed bottom-up land use models give a range of 5.83–9.56 GtCO_2 yr^{-1} in 2100 when 2580 Mha are afforested (Kreidenweis et al 2016), with a lower potential of 3.53 GtCO_2 yr^{-1} for afforestation of 1489 Mha at a carbon price of US\$24/tCO_2 (Humpenöder et al 2014). Earth System Modeling mimicking the afforestation rates in an RCP4.5 pathway finds 6.64 GtCO_2 yr^{-1} in 2100 (Sonntag et al 2016). Houghton et al (2015) estimate that about 500 Mha could be available for the re-establishment of the world's tropical forests on lands previously forested but not currently used productively. This would sequester at least 3.7 GtCO_2 annually for decades, even though they raise the important caveat that forests need both time to grow and will eventually suffer from saturation and thus assume a linear decline in productivity from 3.7 GtCO_2 in 2065 to 0 by 2095. Earlier estimates lie in between 0.47 and 4.88 GtCO_2 yr^{-1} by 2100 (Sohngen and Mendelsohn 2003, Cannell 2002, Canadell and Raupach 2008, Strengers et al 2008, van Minnen et al 2008, Thomson et al 2008) with estimates depending on various assumptions, most notably the amount of land available. For example, many studies assume that only abandoned or low-productivity land can be used for AR. For example, Thomson et al (2008) use an area of 120 Mha of unproductive land

[25] Assuming that Liu et al (2016) provide a 2100 potential, which seems likely, but the main body of their article is in Chinese.

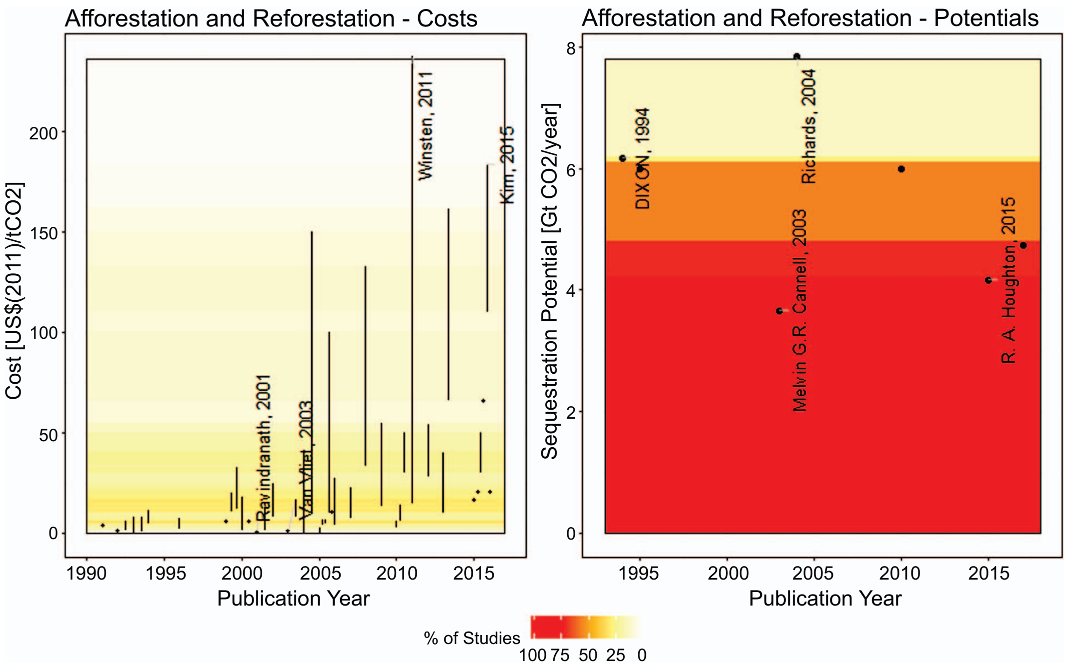

Figure 8. Costs and potentials for afforestation. The heatbar distribution of literature estimates in each panel are calculated as in figure 6, with individual publication cost ranges represented by lines (costs panel); and maximum estimates of negative emissions potential plotted by publication year (potentials panel). Afforestation potentials are constrained to global studies for the year 2050 (or proximate to 2050, e.g. Houghton *et al* 2015). Cost estimates include both regional and global studies. Estimates and ranges at the top and bottom end of the distribution are labelled; the data can be further explored in our online supporting material available at https://mcc-apsis.github.io/NETs-review/.

arriving at a maximum potential of 1.14 $GtCO_2\ yr^{-1}$ by 2100, while van Minnen *et al* (2008) start from abandoned land of 831 Mha thus also having higher maximum potentials (4.88 $GtCO_2\ yr^{-1}$ by 2100). 2050 potentials range from 0.44 $GtCO_2\ yr^{-1}$ (van Minnen *et al* 2008) to 6.16 $GtCO_2\ yr^{-1}$ (Dixon *et al* 1994). A number of publications using different methodologies fall in between those (Brown *et al* 1995, Kaiser 2000, Karnosky *et al* 2003, Nilsson and Schopfhauser 1995, Thomson *et al* 2008). Benítez *et al* (2007) use a 20 year time frame to arrive at a sequestration potential of 1.3 $GtCO_2\ yr^{-1}$. (Richards and Stokes 2004) review older literature and find that more than 7 $GtCO_2$ could be sequestered yearly for decades (IPCC 2000, Nordhaus 1991, Sedjo and Solomon 1991, Sohngen and Mendelsohn 2003). Griscom *et al* (2017) assess a wider set of conservation, restoration, and improved land management actions that increase carbon storage and/or avoid GHG emissions across global forests, wetlands, grasslands, and agricultural lands. The maximum potential of the AR component of these actions is 17.9 $GtCO_2$, where all grazing land in forested ecoregions is reforested—however this would require substantial global dietary shifts away from grass-fed beef. Note that it is not possible from the studies identified to conclude whether different modeling and estimation techniques lead to systematically higher or lower potentials.

Global costs range between US\$2 and US\$150/tCO_2 for the scoped articles (Humpenöder *et al* 2014, Richards and Stokes 2004, Sohngen and Mendelsohn 2003, Brown *et al* 1995). This range includes almost no estimates from the Integrated Assessment Modeling literature for 2100 and is mostly based on bottom-up estimates and establishment costs. As more IAM literature becomes available for sequestration through AR (as is happening now), the upper range can be expected to shift upwards. In addition, conserving forests as long-term sinks will still require management after the actual afforestation process, an additional cost that is often not taken into account in the reviewed estimates.

Richards and Stokes (2004) provide an overview of AR cost studies from the 1990s and early 2000s, identifying substantially lower costs in developing compared to industrialized countries. This is in line with our observations from the scoped literature: most of the cost studies originate in the USA, Australia, Canada, or are global studies. There are only few cost studies in Latin America, two for India, none for Southeast Asia and none for Africa. Out of the full sample of the scoped literature, 17% present cost estimates. Multiple factors may drive differences in cost-effectiveness between regions, such as yield rates, land prices, transaction costs, and reporting differences. Many more studies based in developing countries would be needed to clarify these differences. In addition, estimates differ in methodology and scope. For instance they may be the (exogenous) prices at which a potential was calculated, or the bottom-up establishment costs for a pre-specified sequestration target, or the cost at which AR becomes profitable, or a combination of these. This has to be borne in mind as a major caveat when examining the cost ranges across regions. For those studies that follow an optimization approach, the cost range is US\$10–237/tCO_2. Bottom-up studies relying on the valuation of the different cost components range from US\$0.1–15/tCO_2. Those that use opportunity costs correspond to a range of US\$3–160, but are obviously very location-specific. Studies relying on reviews of previous literature, where it is impossible to track down the type of costs surveyed, lie between US\$7.50 and 50.

Side effects. A wide variety of biophysical, social and economic side-effects are considered in the AR literature. One of the most prominent issues from a climate perspective is albedo change, which finds significant attention particularly in global studies (Anderson *et al* 2011, Arora and Montenegro 2011, Betts *et al* 2007, Jackson *et al* 2008, Wang *et al* 2014). There is high agreement that the low albedo of boreal forests renders AR in high latitudes counterproductive, accelerating local warming and speeding ice and snow cover loss; similarly, temperate AR has uncertain or net neutral benefits for global temperature reduction, particularly if substituting for relatively high albedo agricultural land uses. Tropical AR, due to higher productivity, moderate albedo effects, and its potential to generate evaporative cooling, i.e. the local cooling effect resulting from evapotranspiration, holds the greatest potential for net temperature reduction—up to three times that of boreal forests per unit of land area, according to Arora and Montenegro (2011). A second major consideration is the association between AR and biodiversity. The literature is currently lacking a comprehensive review on this topic, which is predominantly investigated on a case study basis, with ensuing variety in terms of local system conditions. Nonetheless, afforestation using native species is generally regarded as superior compared to plantations for habitat quality and species diversity (Hall *et al* 2012, McKinley *et al* 2011); and although they may perform less well in terms of carbon sequestration, diverse afforestation plots are less vulnerable to climatic perturbations (Locatelli *et al* 2015) and provide a greater variety of subsistence products and services, enhancing local management and acceptability (Díaz *et al* 2009, Locatelli *et al* 2015, Venter *et al* 2012).

Other issues addressed were local livelihoods, particularly for developing and middle-income regions (which are inevitably matters of design, ownership and appropriate payments in afforestation schemes) (Greve *et al* 2013, Locatelli *et al* 2015, Renner *et al* 2008); AR effects on soil organic carbon, for which Laganiere *et al* (2010) provide a meta-analysis of varying species and site conditions; and questions of broader resource limits to large-scale AR schemes, including nutrient cycling and water consumption (Deng *et al* 2017, Jackson *et al* 2005, Smith and Torn 2013).

Permanence and saturation. Biogenic CO_2 storage has a much shorter permanence than CO_2 stored in geological formations. Forest sinks saturate within a period of decades to centuries, compared to thousands of years for geological storage (Smith *et al* 2016b); forests are also subject to natural and human disturbances, e.g. drought, forest fires and pests (potentially exacerbated by climate change), or sudden reversals in land use. These issues require careful forest management long after the actual afforestation process, making AR a less attractive NETs option over time. Ultimately, total long-term afforestation (storage) potential is constrained by land area, so new land will need to be freed up for additional negative emissions in the 22nd century, for instance by shifting global diets away from meat products (Röös *et al* 2017, Griscom *et al* 2017).

Upscaling. Although AR does not involve ramping up large infrastructures like BECCS (see section 3.1) and DACCS (see section 3.3), the pace at which removal will be taking place will still be slow, as forests need to grow to their full potential. Upscaling and diffusion will be analyzed and discussed in more detail in Nemet *et al* (2018).

Authors' assessment. Albedo effectively constrains afforestation as a mitigation strategy to the tropics—and within these regions it will have to compete with agriculture and other sectors for land (particularly under a portfolio of NETs). The estimate by Houghton *et al* (2015) for a total area of 500 Mha of marginal land in the tropics is therefore a feasible, yet ambitious boundary limit for global afforestation. Note that an earlier study by Zomer *et al* (2008) found only 760 Mha of globally available land that satisfied UNFCCC accounting conditions. The 500 Mha constraint constitutes approximately 3.6 GtCO_2 yr^{-1} of carbon removal by 2050, albeit declining to 0 by the end of the century (Houghton *et al* 2015). Under these conditions (marginal land in the global South), costs will tend towards the lower-end of the global range, likely not exceeding US\$5–50/tCO_2, with the caveat that very few cost studies exist for tropical countries in the past decade (Benítez and Obersteiner 2006, Torres *et al* 2010).

3.3. Direct air carbon capture and storage (DACCS)

Direct air CO_2 capture and storage, also known as CO_2 capture from ambient air, comprises several distinct technologies to remove dilute CO_2 from the surrounding atmosphere.

There is a plethora of different materials and processes under investigation. Most attempts have focused on hydroxide sorbents, such as calcium hydroxide. More recently a stream of research on solid materials has emerged, mostly involving amines. Engineering problems involve enlarging the contact surface to increase CO_2 withdrawal and dealing with moisture. A key issue is the energy needed. This includes the energy for releasing CO_2 from the sorbent, regenerating the sorbent, for fans and pumping, as well as for pressurizing the CO_2 for transportation. For example, temperatures greater than 700 °C are required to separate CO_2 from the calcium compound and to

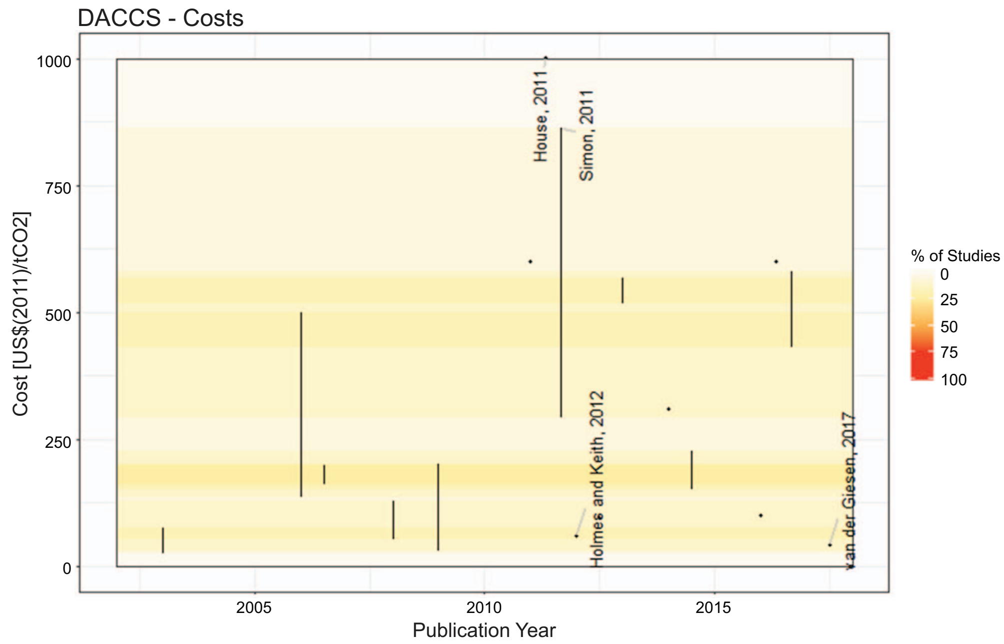

Figure 9. Costs for direct air capture. The heatbar distribution of literature estimates are calculated as in figure 6 for costs only, with individual publication cost ranges represented by lines. No literature estimates for potentials exist, but are often implicitly assumed to be unlimited. Estimates and ranges at the top and bottom end of the distribution are labelled; the data can be further explored in our online supporting material available at https://mcc-apsis.github.io/NETs-review/.

regenerate calcium hydroxide. Readers interested in the specific processes, materials and options are referred to (Sanz-Pérez *et al* 2016, Barkakaty *et al* 2017).

Potential and costs. Generally, potentials remain largely ignored, in part because they are implicitly assumed to be unlimited. Yet, many of the available NETs assessment have provided estimates—most ranging somewhere between 10–15 $GtCO_2$ annually in 2100 (Fuss 2017, Smith *et al* 2016a, McLaren 2012, National Academy of Sciences 2015) with some seeing much higher potentials beyond 40 $GtCO_2$ (Lenton 2014). The limited evidence from long-term mitigation scenarios are at the higher end of this range (i.e. 40 $GtCO_2$) by end of the century (Chen and Tavoni 2013). However, potentials have not been systematically investigated, and some critical perspectives voice doubts on the scalability of DACCS (Pritchard *et al* 2015).

Most of the discussion around DACCS potential has been dominated by cost considerations as the key parameter determining the viability of the technology. A recent study by Sanz-Pérez *et al* (2016) has reviewed the available literature comprehensively and provides much of the basis associated with the DACCS costs presented here.

Costs of DACCS incur mainly from (1) capital investment, (2) energy costs of capture and operation, (3) energy costs of regeneration, (4) sorbent loss and maintenance. Additional costs occur for CO_2 compression, transportation and storage and are similar to those studied in the CCS literature. However, a main difference is that DACCS can be deployed proximate to storage facilities, and can be co-located with attractive sites for renewable energy, thus minimizing transport and grid costs (Goldberg *et al* 2013). Depending on location and grid demand, there may exist opportunities where renewable energy is abundant and cost-competitive and accessed directly thereby circumventing the grid. Given the energy requirements of DACCS, coupling these plants with cheap renewable energy could be a method of bringing down the operating costs of the plant. It is important to note that if DACCS is powered with coal, the CO_2 emissions from fueling the plant would be greater than the CO_2 captured (National Academy of Sciences 2015).

As shown in table 1, in general, cost estimates range from US$30-$1000/tCO_2 (Sanz-Pérez *et al* 2016), see also figure 9. It is difficult to compare the costs of DAC reported in the literature due to their differing boundary conditions in addition to the fact that many of the reported estimates are the costs of CO_2 capture and not the costs of capturing the avoided CO_2. More specifically, a significant amount of thermal energy is often required for DAC due to the requirement of strong binding of the capture material because of the extreme dilution of atmospheric CO_2. The use of natural gas to provide the thermal requirements for regenerating the capture material, results in CO_2 emitted into the atmosphere. Hence, if a DAC plant is designed to capture on the order of 1 Mt CO_2 yr^{-1}, it may ultimately avoid only a fraction of this due to the emissions generated from the use of natural gas to provide energy to the plant. The use of renewable energy or in the case of Climeworks, low-grade waste heat—provided the separation process allows, for DAC will lead to the greatest impacts since the maximum amount of CO_2 will be captured and avoided. For example, House *et al* 2007

Table 1. Cost estimates of complete[26] DACCS systems reported in the literature, concentrated from 400 ppm to 98+% purity[27].

Cost [US$(2011)/t$CO_2$]	Assumptions	References
< 140	• 1/3 cost capital and maintenance • 2/3 cost carbon-neutral electricity + natural gas • Sodium hydroxide solvent approach followed by causticization and calcination • Efficient heat exchange • Contactor design based on cooling tower technology	Keith *et al* 2006
~ 600	• Modeling Carbon Engineering's approach • Potassium hydroxide solvent approach followed by causticization and calcination • Conventional contactor design based on postcombustion CO_2 capture	APS Report 2011
~ 1000	• Theoretical estimate based upon minimum work calculations combing with second-law efficiencies ranging between 2%–5% and energy cost estimates ranging between 80–103 $/MWh for natural gas, excluding capital costs	House *et al* 2011
< 500	• 2nd-law efficiency of 10% • Contactor design based on cooling tower technology • Inexpensive contactors, i.e. $0.5 M to capture 1t$CO_2$/day	Simon *et al* 2011
~ 300	• Contactor design based on cooling tower technology • Plastics in place of stainless steel for contactor packing	Zeman 2014
60–190	• Capture based on solid sorbents rather than solvents for CO_2 capture • Estimate does not include compression for transport • Temperature vacuum swing adsorption process	Sinha *et al* 2017
600	• Capture based on solid sorbents rather than solvents for CO_2 capture • Amine-functionalized solid sorbents • Temperature and vacuum swing adsorption process	Climeworks www.climeworks.com/
n/a	• Capture based on solid sorbents rather than solvents for CO_2 capture • Humidity swing adsorption process • Concentrating to 3%–5% purity only	Lackner 2009

provide a range of energy required for DAC between 500–800 kJ molCO_2. For many processes, this consists of a combination of electricity for fans and pumps and thermal energy for regeneration of the capture material. Based on a carbon intensity of 490 g CO_2 per kWh for natural gas, leads to emissions of 0.7–1.2 MtCO_2 yr^{-1}, resulting in CO_2 avoided of 0.3 MtCO_2 per year in the best case and net emissions of 0.2 MtCO_2 yr^{-1} in the worst-case scenario. If the cost of CO_2 capture is $200/t$CO_2$, this scenario would lead to a lower-bound avoided costs of CO_2 capture of $600/t$CO_2$. Therefore, depending on how one chooses to provide energy to the DAC plant will ultimately determine the cost of avoiding CO_2 in the atmosphere.

Low-cost estimates tend to come from sources closer to industry (Ishimoto *et al* 2017), but they also often do not include all cost components and are therefore difficult to compare. The upper range estimate of US$1000/t$CO_2$ is derived from thermodynamic considerations without an explicit consideration of a particular technology. For instance, Ranjan and Herzog (2011) argue that such thermodynamic considerations rule out estimates below US$500. These calculations include costs for capture and regeneration. Some judge such high cost estimates as more reliable (Socolow *et al* 2011); they are also proposed more frequently as outcomes in the available scientific assessments(National Academy of Sciences 2015, Smith *et al* 2016a, Caldecott *et al* 2015, McLaren 2012).

Socolow and colleagues (Socolow *et al* 2011) used a simplified factored estimation approach consisting of the dominant pieces of equipment used in a solvent-based separation process. They focused on a two-loop hydroxide-carbonate system, similar to that which has been proposed by the first DACCS study by (Lackner *et al* 1999), and relying on processes also used in the pulp industry. Under optimistic technological assumptions for this process they obtain costs of US$600/t$CO_2$. They also point out that in the early stages of deployment costs are likely to be substantially higher. About 30% of the costs originate from a CO_2-penalty as the process is heated by natural gas combustion. This a key source for efficiency improvement and cost reduction.

Using the APS estimate as benchmark, a number of options might reduce costs. Mazzotti *et al* (2013) investigate optimization at the front-end that amongst other effects increase the fraction of CO_2 captured. That could reduce costs by 10%–20% down to around US$520/t$CO_2$. Another study by Zeman (2014) further optimized the design by APS and Mazzotti

[26] Complete indicates, contactor, regeneration, and compression, ready for pipeline transport; approximate cost of CO_2 transportation via pipeline is US$2.2-$8.9/tonne CO_2 per 250 km of dedicated pipeline, range capturing a capacity of 3–10 MtCO_2 yr^{-1} for onshore and offshore pipelines. (IPCC 2005); storage costs range due to the heterogeneity of the reservoir, 7–13 2011 USD/tCO_2 (USDOE 2014).

[27] With the exception of Lackner *et al* (1999) where the end product is 3%–5% for algae cultivation applications.

(e.g. substituting certain stainless steel components for plastics), to obtain about US\$310/tCO_2.

Holmes and Keith (2012), associated with the air capture company Carbon Engineering, suggested a cooling tower design, where air flows orthogonal to a downward flowing hydroxide solution. Holmes *et al* (2013) presented then a prototype with >1000 hours of operation, validating the cross-flow contactor design. However, the authors and their company did not disclose the costs and energy requirements of regeneration, which are estimated to be substantial. As a comparison, APS calculations would result in ca. US\$230/tCO_2 (neglecting CO_2-penalties if heated by natural gas, and neglecting storage costs).

An alternative design is based on solid sorbents (specifically: anionic-exchange resin) (Lackner 2009). Solid sorbent systems might be cheaper as less energy is required for regeneration. A preliminary calculation yields estimates of US\$200/tCO_2, costs that could decrease down to US\$30/tCO_2 with technological development. It is important to note that the desired CO_2 application requires very low purity CO_2, i.e. 3%–5%, which means the capture technology may be weakly binding with an elegant regeneration approach such as humidity swing. In the situations in which high-purity (i.e. 95%) CO_2 is required as a chemical feedstock, a weak-binding low-cost approach would likely not be feasible. An alternate solid sorbent system based on amines with porous oxide supports found US\$95/tCO_2 but excluding capital costs (Kulkarni and Sholl 2012). A similar approach, based on monolithic honeycombs finds similarly plausible costs of around US\$100/ tCO_2 (Sakwa-Novak *et al* 2016). Again, all of these costs are not taking into account the avoided emissions, but are reflective of only costs of capturing CO_2.

Wastewater treatment is being explored as a means to capture ambient CO_2. Huang *et al* (2016) demonstrated a moisture-driven capture process via an ion-exchange resin and subsequent microbial electrochemical carbon capture, capable of a capture efficiency of 0.40 g CO_2 g^{-1} of chemical oxygen demand (COD) or biochemical oxygen demand (BOD). Assuming an average BOD of 0.35 and 0.5 g L^{-1} for domestic and industrial wastewater, respectively, global potential for CO_2 storage via wastewater treatment is estimated at 220 MtCO_2 per year (Sato *et al* 2013). This figure is based on numbers reported for wastewater treated in 55 of 181 countries, including the North America, South America, most European nations, China, Japan, India, South Korea, and the Russian Federation. This figure does not reflect the amount of wastewater generated, and it is estimated that while high-income countries treat 70% of the wastewater generated, this drops to 28%–38% for middle-income countries and as low as 8% for low-income countries. Further, only 37% of the data reported could be considered recent (2008–2012). Thus, though the global estimate provided above is non-conservative and defines a theoretical upper-limit based on best-available current wastewater treatment data, the amount of *treatable* wastewater is expected to be much larger, resulting in a greater theoretical global capacity. Yet, this greater upper-bound remains limited by the financial constraints.

Within the field of Industrial ecology there is support to capture and store CO_2 in materials, such as polymers, rather than underground (Meylan *et al* 2015, Barbarossa *et al* 2014, Bringezu 2014). A significant breakthrough was the proof that CO_2 from ambient air can be converted to methanol (Kothandaraman *et al* 2016). However if methanol is used as a fuel, this process is at best carbon neutral, not carbon negative. Concerns are that above ground storage of CO_2 in polymers may be substantially less than that of CO_2 underground in addition to the potential nature of shorter timescales of CO_2 storage in materials.

In a modeling study with mass production and technological learning, cost floor estimates of US\$60/ tCO_2 were found for 2029, and possibly even lower with time (Nemet and Brandt 2012).

Side effects. The literature has so far not discussed side-effects systematically. While the physical scale would be impressive if DACCS were deployed at relevant GtCO_2 scales, limited land resources are not much of a concern (Keith 2009, Lackner *et al* 2012) nor is storage capacity (de Coninck and Benson 2014) (see section on BECCS). However, geological storage is associated with a string of side-effects, as described in the section on BECCS. In the case of solvent-based separation for DACCS, the use of potassium hydroxide (Holmes and Keith 2012) is well-studied and have been used for industrial applications (e.g. pulp and paper industry) for decades with minimal wastewater produced. Solid waste build-up in the recovery cycles of these separation processes will have similar environmental implications and disposal guidelines as the reclaimer waste in conventional amine scrubbing operations.

Permanence and saturation. The implicit understanding of the literature is that DACCS can be scaled-up solely subject to technological learning but not subject to biophysical constraints. DACCS has, with the exception of one small plant (Magill 2017), not been deployed, and hence has yet to receive the same level of scrutiny as other technologies. Currently its biggest stated drawback is the cost; there is a wide range of estimates with several important publications emphasizing the high end. A plethora of more cost-effective and more conventional options exist; however, the examples of photovoltaics and batteries (Kittner *et al* 2017, Creutzig *et al* 2017) have demonstrated that an order of magnitude in costs can be bridged within one or two decades via manufacturing scale; and DACCS potentially could also be produced at high volumes.

Permanence and saturation is mostly subject to geological storage underground, similar to those noted in the section on BECCS. Building a DACCS plant that captures 1 MtCO_2 yr^{-1}, requires a significant surface

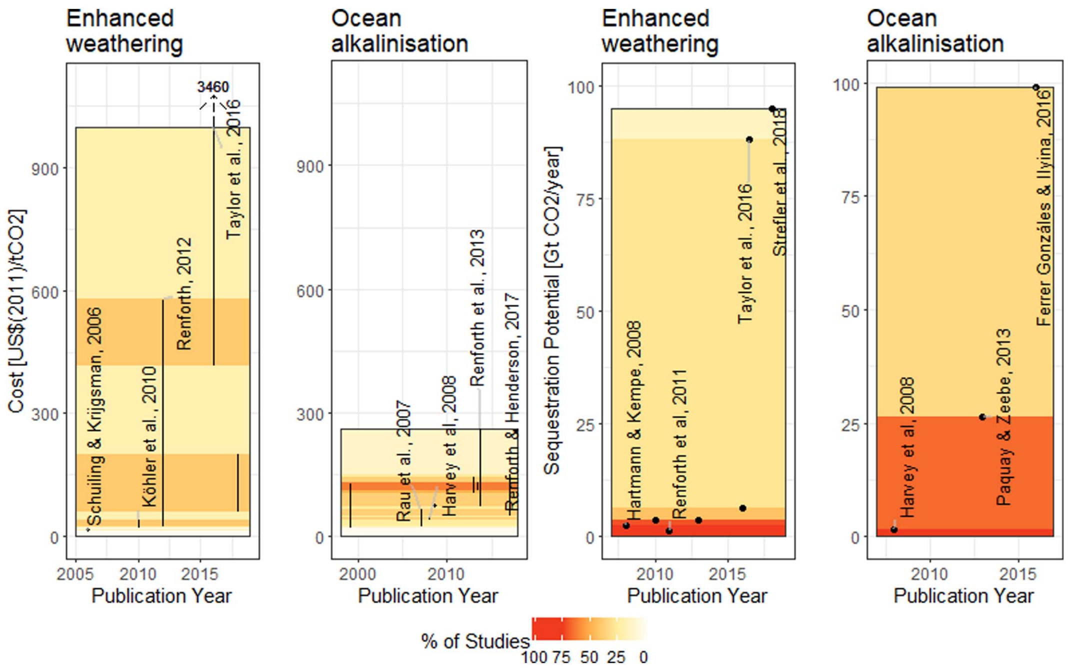

Figure 10. Costs and potentials for enhanced weathering and ocean alkalinisation. The heat-bar distribution of literature estimates in each panel are calculated as in figure 6, with individual publication cost ranges represented by lines (costs panels); and maximum estimates of negative emissions potential plotted by publication year (potentials panels). All estimates are global. Note that published numbers only consider inorganic sequestration effects, neglecting any additional potential of biomass production increase by improvement of soil conditions and provision of geogenic nutrients. This is an important and remaining information gap. Estimates and ranges at the top and bottom end of the distribution are labelled; the data can be further explored in our online supporting material available at https://mcc-apsis.github.io/NETs-review/.

area for the contactor alone—on the order of 38 000 m^2 for 75% capture. The materials and labor to build such an operation would be significant, making the siting of DACCS plants of significant scale in remote locations challenging. As discussed previously, the energy demands due to pressure drop considerations and material regeneration requirements, CO_2-free energy sources will be essential for DACCS to be considered a NET. Hence, a careful approach to the siting of DACCS plants is needed.

Authors' assessment. Based upon our literature review, it appears that a first-of-a-kind plant may be on the order of US\$600–1000/tCO_2 initially, but that as advances are recognized through the building of more plants, this cost may decrease to US\$100-300/tCO_2. For instance, Climeworks has built the first commercial-scale DACCS plant and suggests current costs on the order of US\$600/tCO_2 with anticipated costs of *n*th plants being on the order of US\$200/tCO_2[28]. Costs are initially high because of the up-front expenses of sourcing supply chains and resolving infrastructures issues, and because of lack of experience with the technology. It is also important to note that since the regeneration approach of Climeworks is based upon low-grade waste heat, the cost of CO_2 capture is similar to that of CO_2 avoided.

Our judgement on potential is 0.5–5 GtCO_2 yr^{-1} by 2050. Main constraints may be storage and unexpected environmental side-effects, as well as moderate land demand. However, if these constraints can be proven unjustified or can be overcome, potentials of up to 40 GtCO_2 may be possible by the end of the century.

3.4. Enhanced weathering (terrestrial and ocean)

Weathering is the natural process of rock decomposition via chemical and physical processes. It is controlled by temperature, reactive surface area, interactions with biota and water solution composition. Enhanced weathering (EW) aims to artificially stimulate one or more of these variables to speed up rock decomposition while increasing the cation release to produce alkalinity and geogenic nutrients. This purposeful acceleration of biogeochemical cycling transforms the process of weathering from geological to humanly relevant time scales by favoring chemical reactions that have the potential to sequester relevant amounts of atmospheric CO_2. This is done by grinding selected rock material into rock powder with a suitable grain size distribution to facilitate a maximum reactive surface area. In addition to the use of natural rocks, some authors report the use of other materials like mine waste material (Power *et al* 2013), concrete (Yamasaki *et al* 2002) or alkaline waste (Morales-Florez *et al* 2011).

Besides being a CDR strategy, EW can ameliorate soil and act as a long-term nutrients source (Leonardos *et al* 1987, Nkouathio *et al* 2008). Many tropical regions have nutrient poor soils, e.g. oxisols and ultisols and due to their high precipitation rates and

[28] www.climeworks.com/our-technology/.

temperature represent areas of high potential for EW implementation. Considering the world's oxisol area and an application rate of 900 t km^{-2}, similar to liming rates at Brazilian Cerrado (Lopes 1996), a total amount of 8 Gt of rock material would be needed to cover the world's oxisol area. For comparison, world lime production from 2005–2014 averaged 0.34 Gt yr^{-1} (Corathers 2015). According to Strefler *et al* (2018a) the annual application of 3 Gt yr^{-1} basalt might sequester 1 $GtCO_2$ yr^{-1}.

Ocean alkalinisation (or ocean liming) considers the addition of alkalinity, e.g. via $Ca(OH)_2$ to marine areas to locally increase the CO_2 buffering capacity of the ocean (González and Ilyina 2016, Renforth and Henderson 2017). While not strictly a weathering method, it is a further technology being incorporated in this section as similar geochemical principles apply.

Atmospheric carbon can be sequestered via EW in an inorganic or organic form. Inorganic C is sequestered through the production of alkalinity (bicarbonate and carbonate ions) while anions are counterbalanced by the release of cations from the rock products. If the solution is supersaturated with respect to a chemical element, precipitation of secondary minerals can occur, for example, in the form of carbonate minerals (Manning and Renforth 2013, Power *et al* 2013, Washbourne *et al* 2012). Organic C is sequestered when CO_2 is reduced and incorporated in biomass and additional carbon sequestration potential can be expected from the release of rock derived geogenic nutrients (i.e. potassium, phosphorus, several micronutrients) enhancing biomass production above previously limiting conditions (Hartmann *et al* 2013).

The method of EW can be applied to different Earth compartments like soils (and also mining waste rock) (Hartmann and Kempe 2008, Köhler *et al* 2010, Manning and Renforth 2013, Renforth 2012, Taylor *et al* 2016, ten Berge *et al* 2012, Wilson *et al* 2009), the open ocean (Hauck *et al* 2016, House *et al* 2007, Köhler *et al* 2013), and coastal zones (Hangx and Spiers 2009, Montserrat *et al* 2017). The chemical weathering of the rock powder material in different Earth compartments is conceptually the same and involves the release of cations, nutrients like phosphorus or silica, and production of alkalinity, for example as bicarbonate[29].

The largest research gap is missing field experiments that consider real scales, which evaluate the full impact of EW on biogeochemical cycles, biomass and carbon stocks in the soils, and the plants. Mineral dissolution kinetics in the soil-ecosystem of applied rock products containing fresh surface areas and a wide range of grain sizes should be included in studies. The field reaction kinetics will be different from laboratory studies, which may not consider all effects like the freshness of rock surfaces, topography, groundwater table variation, soil profile heterogeneity, grain size and unsaturated hydraulic conductivity variations. In addition, the grain surface evolution is essential, also with respect to clay mineral production or mineral-root interaction, to understand the element release patterns and potential for plants to utilize those released elements.

Areas in which biomass is under nutrient limitation conditions are the most attractive targets for implementing EW (Garcia *et al* 2018). Rock product weathering processes might supply nutrients to the environment, which potentially can increase biomass production (Anda *et al* 2015, 2012, d'Hotman and Villiers 1961, Hartmann *et al* 2013, Strefler *et al* 2018a). Nevertheless, studies quantifying the effects on biomass increase due extra geogenic nutrient input or soil amelioration by EW are scarce. Only a sufficient amount of field studies and data collection on nutrient application rates for certain climate-soil-plant conditions could enable the development of management plans to optimize CO_2 sequestration via additional biomass growth.

Sequestration potentials and costs. The reported sequestration potential considers theoretical (Hangx and Spiers 2009, Hartmann and Kempe 2008, Manning and Renforth 2013, Renforth 2012, Renforth *et al* 2011), and observational assessments (Morales-Florez *et al* 2011, Wilson *et al* 2009, House *et al* 2007), as well as regional to global scale model assessments (Hangx and Spiers 2009, Hauck *et al* 2016, House *et al* 2007, Köhler *et al* 2010, Taylor *et al* 2016, Köhler *et al* 2013, Strefler *et al* 2018a) and plot-scale experiments (Montserrat *et al* 2017, ten Berge *et al* 2012). Reported potentials range widely (see figure 10), depending on the compartment type assessed, such as local soils, coastal zones, or the open ocean. The highest reported regional sequestration potential is 88.1 $GtCO_2$ yr^{-1} for spreading pulverized rock over a very large surface area in the tropics (Taylor *et al* 2016). Considering cropland areas only, the potential carbon removal might be 95 $GtCO_2$ yr^{-1} for dunite and 4.9 $GtCO_2$ yr^{-1} for basalt (Strefler *et al* 2018a). Other assessments for land application range between these estimation approaches and are highly uncertain due to a variety of assumptions and unknown parameter ranges in the applied upscaling procedures, which still need to be verified by field experiments. A global CO_2 sequestration potential of organic biomass increase due to geogenic nutrient fertilization and improved soil conditions is not available, due to missing upscaling studies, and therefore are not represented in figure 8.

Costs are closely related to the chosen technology for rock grinding, material transport and the rock source (Hartmann *et al* 2013, Renforth 2012, Strefler *et al* 2018a). As costs are related to application site characteristics and purpose (for example, whether inorganic or organic sequestration is favored), most reported back of the envelope calculations found in

[29] A model reaction for the mineral Forsterite is: $Mg_2SiO_4 + 4CO_2 + 4\,H_2O \Rightarrow 2Mg^{2+} + 4\,HCO_3^- + H_4SiO_4$.

literature are highly uncertain. They range for inorganic CO_2 sequestration from US\$15–40/tCO_2 to US\$ 3460/tCO_2 (Köhler *et al* 2010, Schuiling and Krijgsman 2006, Taylor *et al* 2016). Renforth (2012) conducted a regional cost assessment for implementing inorganic EW in the UK, reporting operational costs applying mafic[30] rocks being US\$ 70–578/tCO_2 and for ultramafic[31] rocks being US\$ 24–123/tCO_2. These numbers can be taken as a reference for global application, considering the relative cost levels of regional economies. Variables like depth of rock extraction, technical, economic, socio-environmental drivers, and transport impact the costs of EW. Transportation costs depend on the means of transportation, with the cheapest costs for inland waterway and large ship distribution (US\$0.0016/t rock/km) and the most expensive for road transport done by heavy vehicles (US\$ 0.07936/t rock/km) (Renforth 2012). This highlights that infrastructural conditions are relevant for implementation and global cost estimates, which are normally not considered in global assessments.

A detailed global cost assessment (Strefler *et al* 2018a) points out that EW is a competitive option for carbon dioxide removal at US\$ 60/tCO_2^{-1} for dunite and US\$ 200/tCO_2^{-1} for basalt. The upper global limit of inorganic CO_2 sequestration including forested areas (Taylor *et al* 2016) might be only reached if very cost-intensive spreading by planes is considered. The potential of other more unconventional technologies like dirigibles or slurry pipelines were not studied so far. No study explicitly identifies the cost-effectiveness of sites globally and spatially-explicitly at a high spatial resolution. The costs change for different rock sources and for the considered region (Strefler *et al* 2018a), and estimates for organic CO_2 sequestration via the fertilization effect are missing for different types of biomass, as for example afforestation or bioenergy purposes, which demand optimization of the soil for the best sequestration potential.

The amount of rock products to be moved, given the above scenario of tropical soil in the introduction of this section (8 Gt rock/year) is comparable to the amount of coal mining and transport (IEA 2017) and appears to be low if compared to the 2010's global material consumption (biomass, fossils, and minerals) of 70 Gt per year (Krausmann *et al* 2017). A detailed spatially explicit global analysis suggests that in humid and tropical areas about 80% and 95% of the applicable crop areas for EW are within a distance of 300 km from potential source rocks, respectively (Strefler *et al* 2018a).

Application costs and potentials based on technological considerations of ocean liming, ocean EW or electrochemical weathering are less researched. A recent review suggests the potential for Ocean Alkalinization to be between 100 MtCO_2 yr^{-1} and 10 GtCO_2 yr^{-1} with costs ranging between US\$14 to more than US\$500/tCO_2 (Renforth and Henderson 2017).

Side effects. The assessment on side effects of EW is complex and challenging as they depend on exchanged matter between different compartments of the Earth System (Hartmann *et al* 2013, Taylor *et al* 2016, ten Berge *et al* 2012). The main factors controlling the side effects are: rock powder source, soil, ecosystem and climate characteristics. Application to soils alters the soil physical and chemistry properties, with impacts on groundwater, river water, and coastal zone water. In addition, the released material and changes in soil properties influence ecosystems and biomass carbon contents. Application in the coastal zone and the open ocean impacts the marine water chemistry and ecosystems.

The main side effects of land application are an increase in water pH (Köhler *et al* 2013, Taylor *et al* 2016), the release of heavy metals (e.g. Ni and Cr) in case of inappropriate material use, the release of plant nutrients like K, Ca, Mg, P, and Si (Hartmann *et al* 2013), as well as hydrological soil property changes, which could be designed to be favorable depending on the ecosystem. Respirable particle sizes which may contain asbestos-related minerals need to be avoided (Schuiling and Krijgsman 2006, Taylor *et al* 2016) by appropriate application procedures (e.g. water based slur application).

Köhler *et al* (2010) point out the complexity of predicting the impact of mineral dissolution rates on the carbon cycle due to changes in dissolved inorganic carbon and total alkalinity. Hartmann *et al* (2013) and Taylor *et al* (2016) emphasize the additional potential for improved CO_2 drawn-down by marine diatoms due to the increased land-to-ocean silica fluxes and enhanced alkalinity fluxes, increasing the oceans aragonite saturation state[32]. Taylor *et al* (Taylor *et al* 2016) point out the potential increase in atmospheric CO_2 drawdown by coupling EW with AR.

EW application in the open ocean is less researched, and Hauck *et al* (2016) and Köhler *et al* (2013) found that the efficiency of the method is closely related to the rock powder particle size. Köhler *et al* (2013) recommend a maximum particle size of 1 μm to prevent early sedimentation, but this would demand high energy costs for grinding rock products (Strefler *et al* 2018a). The change in regional export production of organic matter is supposed to be less than 10%. Release of heavy metals from ultramafic rock products like Ni and Cr

[30] A rock that has high magnesium and iron silicate minerals concentration.

[31] A rock which is rich in magnesium and iron silicate minerals but with very low silica content. The low silica content influences weathering rates in a positive way.

[32] The aragonite saturation state (ASS) is obtained by the product of dissolved calcium and carbonate ions in seawater divided by the aragonite solubility in seawater. If ASS is higher or lower than one sea water is respectively over- or undersaturated with respect to aragonite. If ASS is equal to one, the sea water solution is saturated.

is a potential negative side effect and a detailed study on the marine biology related impacts and risks to its ecosystems is missing (Köhler *et al* 2013). Montserrat *et al* (2017) simulated, based on laboratory experiments, coastal zone conditions for EW using olivine dominated rock powder. They confirmed an increase in Mg^{2+}, Si, total alkalinity, and dissolved inorganic carbon, Fe^{2+}, and Ni^{2+} in the aqueous solution concentrations. A better comprehension of heavy metal ecotoxicological effects on coastal environments for large-scale application of olivine is missing.

Permanence and saturation. The sequestered CO_2 by EW on land can be stored in several pools. In the soil pore solution and groundwater, it remains first as dissolved inorganic carbon (or alkalinity). If the solution gets supersaturated, carbonate minerals can precipitate in the soil (Manning and Renforth 2013) and mean residence times can be in the order of 10^6 years or more (Wilson *et al* 2009). If carbonate precipitation does not occur in the land system, and the solution is transported to the ocean by rivers, the dissolved weathering products would be stored as ocean alkalinity (Taylor *et al* 2016, Köhler *et al* 2010, Hartmann *et al* 2013, Manning and Renforth 2013).

The fertilization effect of released nutrients can cause additional biomass production, and the fate of this additional carbon pool would be comparable to that reported in the section for afforestation, soil carbon and bioenergy. Hence these methods are connected and other land-based NETs could rely on EW to create the optimal soil and nutrient supply conditions. However, this connection is not to be found in the literature (at a global scale) at the time of publication.

Authors' assessment. So far, publications on terrestrial EW are mainly comprised of model studies or theoretical discussions. The aforementioned research gaps leave large uncertainties in the potential to sequester CO_2, which can only be overcome by field studies because of the manifold influencing parameters and their interdependencies, which can, so far, only be roughly considered in models. Current published estimates of CO_2 removal potentials and costs should be seen as boundary values, while more progress is evident considering the cost estimation (Strefler *et al* 2018a).

The largest CO_2 penalty as well as costs are created from the energy demand of rock grinding (Strefler *et al* 2018a). The penalty will decrease significantly in the future due to the expected transition to renewable energies and technological advances (Napier-Munn 2015). If prices for fertilizers rise, and resources are expected to decrease (Manning 2015), the EW side effect of geogenic nutrient release and soil amelioration potential may become one of the strong suits of this technology, potentially making it a valuable asset in global agriculture (van Straaten 2006), irrespective of its potential to sequester CO_2 into alkalinity. Including these aspects in detailed techno-enonomic assessments may render EW more attractive (Strefler *et al* 2018a). Accordingly, the cost range of our assessment is US\$50–200/tCO_2 for a potential of 2–4 GtCO_2 yr^{-1} from 2050, excluding biological storage. The cost range is high due to economies of scale and highly variable cost-incurring parameters like source rock properties, transport distances and field application technology.

Ocean alkalinization has been discussed only in very few global modelling studies. Given results are abstract and provide upper limits. The costs can only be estimated after clarification of how alkalinity is produced and distributed at the global scale.

3.5. Ocean fertilization

Ocean fertilization (OF) is based on the effect of biological production increase, which is macro- (Harrison 2017, Matear 2004) or micronutrient (Gnanadesikan *et al* 2003, Raven and Falkowski 1999) limited, by deliberately adding nutrients to the upper ocean waters. Efficiency of the method is determined by the chemical form of the added nutrient (Harrison 2017, Matear 2004). Often, iron is the limiting nutrient in the ocean, so that deliberate iron fertilisation is well discussed (Strong *et al* 2009b, Markels and Barber 2001). The algal bloom resulting from artificial OF leads to carbon fixation and subsequent sediment sequestration, or sequestration on shorter time scales in the water column. Due to the low iron requirement of phytoplankton, the ratio of CO_2 uptake per iron application is high (2600–26600 C per added amount of Fe, de Baar *et al* 2008). The increase in the biological production (phytoplankton) would reach a maximum until further nutrients become limited (Markels and Barber 2001).

Köhler *et al* (2013) and Hauck *et al* (2016) proposed a coupling OF with EW, because the studied mineral olivine releases iron and silicic acid during dissolution. However, slow dissolution reactions and the sinking of the particles remain a limiting factor (Hauck *et al* 2016). OF can also be achieved by artificial upwelling of nutrient-rich deep ocean water (Oschlies *et al* 2010). Some early work authors doubt that OF is feasible due to the large area needed to sequester substantial amounts of CO_2 (Zeebe 2005).

Sequestration potentials and costs. Different factors control the atmospheric CO_2 uptake and storage by OF, like duration of the experiment (Jin *et al* 2008), carbon export (Bakker *et al* 2005), changes in mixing layer depth (Bozec *et al* 2005), mixing, lateral and vertical transport (Jin *et al* 2008, Joos *et al* 1991), and wind speed (Bakker *et al* 2001). The global atmospheric CO_2 drawn down potentials were obtained from model simulations based on experimental data. The obtained values can be divided in three main approaches: modelled CO_2 sequestration, process-based/experimental results and literature estimates. The overall reported minimum sequestration value for OF is 1.52×10^5 tCO_2 yr^{-1} (Bakker *et al* 2001) for a spatially constraint field experiment while the maximum reported value is 9.8×10^{10} tCO_2 yr^{-1}

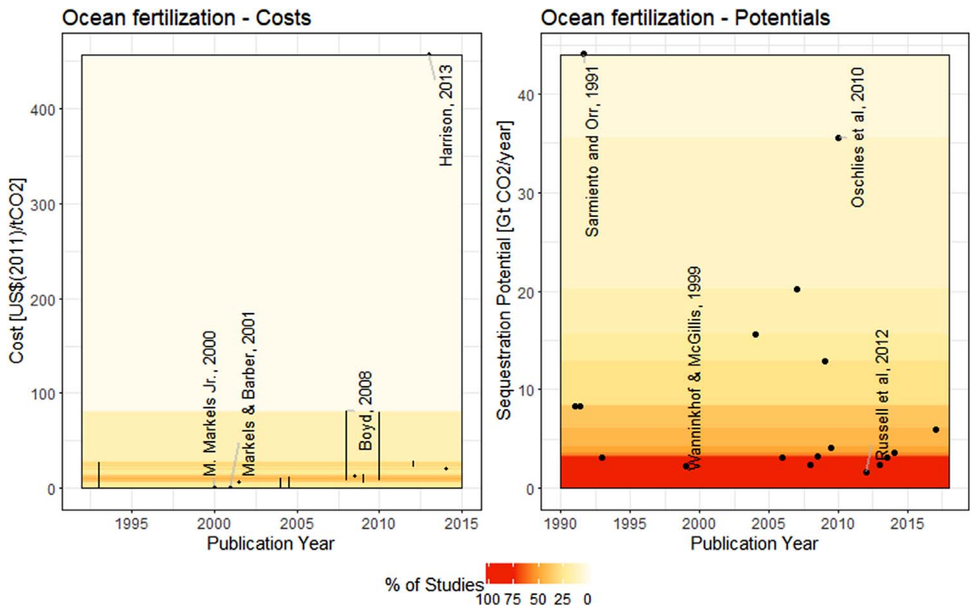

Figure 11. Costs and potentials for ocean fertilization. The heat bar distribution of literature estimates in each panel is calculated as in figure 6, with individual publication cost ranges represented by lines (costs panel); and maximum estimates of negative emissions potential plotted by publication year (potentials panel). Estimates and ranges at the top and bottom end of the distribution are labelled; the data can be further explored in our online supporting material available at https://mcc-apsis.github.io/NETs-review/.

(Oschlies 2009) using a modelling approach (see also figure 11). The latter consider upscaling local experimental process to global boundaries in order to predict the potential CO_2 sequestration. Different authors point out the low efficiency of OF in general (Rembauville *et al* 2018, Aumont and Bopp 2006, Jin *et al* 2008, Zahariev *et al* 2008, Zeebe 2005) or that OF efficiency has a high degree of uncertainty (Aumont and Bopp 2006).

Ocean fertilization costs depend on nutrient production and its delivery to the application area (Jones 2014). The costs range from US\$2/ tCO_2 (Boyd and Denman 2008) to US\$457/tCO_2 (Harrison 2013). A detailed economic analyses for macronutrient application reports US\$20/tCO_2 (Jones 2014), whereas Harrison (2013) details that costs are much higher due to the overestimation of sequestration capacity and underestimation of logistic costs.

Side effects. OF is expected to alter local to regional food cycles by stimulating phytoplankton production, which is the food cycle's basis. Long-term reductions in ocean productivity could also occur (Matear 2004, Denman 2008) and a more rapid increase in ocean acidity (Cao and Caldeira 2010) due to fast CO_2 dissolution and dissociation into bicarbonate and carbonate ions (Denman 2008). Impacts on the food cycle would be unpredictable (Strong *et al* 2009a). Extensive blooms may cause anoxia (Matear 2004, Russell *et al* 2012, Sarmiento and Orr 1991) in the surface ocean due to the remineralization of sinking organic matter and probable toxic algal blooms (Bertram 2010, Trick *et al* 2010). Deep water oxygen decline, as a potential side effect, has been observed in the Baltic sea due to anthropogenic nitrate inputs (Matear 2004). Nutrient (iron, silica or phosphate) inputs potentially cause a shift in ecosystem production from an iron-limited system to a phosphate-limited, nitrogen-limited or a silicate-limited system, depending on the location (Bertram 2010, Matear 2004). An increase in the production of further greenhouse gases may occur, including N_2O (Bertram 2010, Matear 2004, Cullen and Boyd 2008, Denman 2008) or CH_4 (Bertram 2010, Matear 2004, Sarmiento and Orr 1991, Cullen and Boyd 2008).

Permanence and saturation. Ocean CO_2 permanence is rather controversial and depends on whether the carbon remains dissolved in the different ocean layers (short-term pool) or if it sediments as organic carbon to the ocean abyssal plains, or to other ocean compartments as long-term pool. Authors like Williams and Druffel (1987) in Markels and Barber (2001) suggest residence times of sinking carbon to the deep waters being around 1600 years, or millennia in the deep ocean (Jones 2014), while Aumont and Bopp (2006) state that the sequestered carbon is rapidly re-exposed to the atmosphere after cessation of OF, due to the low final sedimentation rate (only 10%–25%) (Zeebe 2005).

Authors' assessment. The high recycling rate of organic carbon that stores the CO_2 leads to very low overall potentials to sequester CO_2 on a longer time scale. This meager efficiency as a NET, combined with wide impacts on ecosystems, e.g. food web disturbances, suggests that OF is not a viable negative emissions strategy when performed with sustainability issues under consideration (Strong *et al* 2009a), particularly when compared to alternative portfolio options.

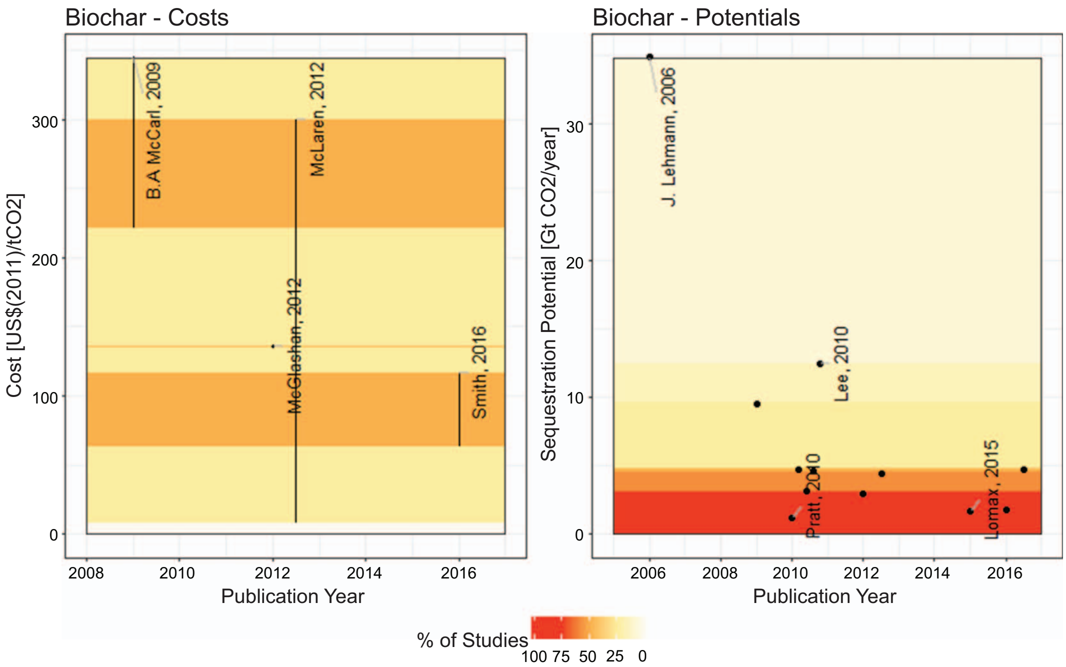

Figure 12. Costs and potentials for biochar. The heat bar distribution of literature estimates in each panel are calculated as in figure 6, with individual publication cost ranges represented by lines (costs panel); and maximum estimates of negative emissions potential plotted by publication year (potentials panel). All estimates are global. Estimates and ranges at the top and bottom end of the distribution are labelled; the data can be further explored in our online supporting material available at https://mcc-apsis.github.io/NETs-review/.

3.6. Biochar

Biochar is obtained from pyrolysis, i.e. the thermal degradation of organic material in the absence of oxygen. Added to soils, biochar is a means to increase soil carbon stocks as well as improve soil fertility and other ecosystem properties.

Potentials and costs. Recent assessments estimate that the use of biochar could sequester between 0.6 $GtCO_2\ yr^{-1}$ and 11.9 $GtCO_2\ yr^{-1}$, largely depending on the availability of biomass for biochar production (see figure 12). Lenton (2010) calculated CO_2 removal rates of 2.8–3.3 $GtCO_2\ yr^{-1}$ if all felling losses from forestry, 50% of currently unused crop residues, and burned biomass from shifting cultivation fires were used to produce biochar. Lee *et al* (2010) finds an even higher potential of 11.9 $GtCO_2\ yr^{-1}$ by assuming that more than 80% of all currently harvested biomass is converted into biochar. The author revised this estimate to 6.1 $GtCO_2\ yr^{-1}$ in a later publication (Lee and Day 2013) based on the assumption that the worlds annual unused waste biomass contains only about 12.1 $GtCO_2\ yr^{-1}$. Accounting only for the use of late stover as a feedstock for biochar, Roberts *et al* (2010) estimate achievable annual carbon sequestration around 0.7 $GtCO_2\ yr^{-1}$.

Higher GHG mitigation potentials are generally found in studies of future biochar applications rising from 1–1.8 $GtCO_2\ yr^{-1}$ in 2030 (Lomax *et al* 2015, Paustian *et al* 2016, Pratt and Moran 2010, Griscom *et al* 2017), 1.8–4.8 $GtCO_2\ yr^{-1}$ in 2050 (Powell and Lenton 2012, Smith 2016, Moore *et al* 2010), and 2.6–4.8 $GtCO_2\ yr^{-1}$ in 2100 (Woolf *et al* 2010). Abatement cost estimates vary significantly. While some studies suggest that CO_2 prices between less than US$30 and 50/$tCO_2$ are sufficient for economically viable biochar application (Lomax *et al* 2015, Roberts *et al* 2010), other estimates reach US$ 60–120/tCO_2 (Shackley *et al* 2011, McGlashan *et al* 2012, Smith 2016), especially for dedicated feedstocks, highlighting the potential importance of waste feedstock for commercially viable biochar projects. Currently, high biochar prices prevents its large-scale application (Vochozka *et al* 2016, Dickinson *et al* 2015).

Side effects. A meta-analysis by Jeffery *et al* (2011) indicates that crop productivity increases by 10% on average following biochar soil amendment, but yield effects ranged between positive and negative with different soil types, environmental, and management conditions. Further effects of biochar amendments include lower emissions of N_2O and CH_4, where lower CH_4 emissions were measured especially on flooded soils (Kammann *et al* 2017). Biochar can also have a positive effect on the soil's water balance. On temperate soils, a 16% reduction in water losses was measured, which at the same time reduced the negative effects of soil dryness on microbial abundances by up to 80% (Bamminger *et al* 2016). However, the effects of high biochar application rates which change the microbial composition of the soil are still unknown (Jiang *et al* 2016). Furthermore, increased plant growth due to biochar may lead to a lower defense effectiveness of the genes related to the defense of the plants, thus increasing the vulnerability against insects, pathogens and drought (Viger *et al* 2015). Large-scale biochar application can also darken the soil surface, decrease surface albedo and hence change the land surface radiation balance, although application rates would need to be extreme for such an effect to occur. A recent study in Mediterranean agricultural landscapes found that the albedo effect can reduce biochar's mitigation potential by up to ∼30% during periods of high solar irradiance (Bozzi *et al* 2015). Fine biochar particles may also be released into the atmosphere during production, transportation and distribution by wind. These black carbon aerosols can reduce air quality and cause a positive direct and indirect radiative forcing which would further reduces the net mitigation effect of biochar application (Ravi *et al* 2016, Genesio *et al* 2016).

Permanence and saturation. The most important property of biochar with regard to climate protection is its stability in the soil. In order to achieve effective and long-term carbon storage, biochar should remain in the soil for as long as possible. Laboratory tests and other observations indicate centennial scale turnover of biochar (Wang *et al* 2016). However, depending on soil type and biochar production temperature, results may vary between a few decades and several centuries (Fang *et al* 2014). Lower residence times occur under higher temperature typical for tropical and sub-tropical regions (Zimmermann *et al* 2012) and acidic soils (Sheng *et al* 2016).

Authors' assessment. Large-scale trials of biochar addition to agricultural soils under field conditions are still missing. Feasibility, long-term mitigation potentials, side-effects, and trade-offs therefore remain largely unknown. Furthermore, available global estimates of biochar CO_2 sequestration potentials do not yet account for the complex, site-dependent effects of biochar applications that differ on with biochar types, soil types, environmental, and management conditions highlighted by recent laboratory analysis. In our opinion, a lower range of 0.3–2 $GtCO_2\ yr^{-1}$ by 2050 seems plausible given the limited availability of biomass realistically available for the production of biochar. For comparison, the World's total biomass harvest on cropland and in forests in 2000 amounted to 0.4 $GtCO_2\ yr^{-1}$ (Haberl *et al* 2007). The wide range of cost estimates reflects the underlying uncertainties regarding feedstock availability as well as biochar production technologies and application strategies. Economic benefits from higher yields may offset some costs of biochar application. Because there is no experience with large-scale production and use of biochar, cost estimates remain inherently uncertain. Against this background, mean ranges of biochar costs between US\$ 90/tCO_2 and US\$ 120/tCO_2 based on literature reviews (see for example (Smith 2016)) should be regarded as first rough estimates. Introducing biochar carbon offset methods to carbon trading markets to further offset costs may also be complicated because soil carbon is difficult to measure, especially over large areas.

3.7. Soil carbon sequestration

Soil carbon sequestration (SCS) occurs when land management change increases the soil organic carbon content, resulting in a net removal of CO_2 from the atmosphere. Since the level of carbon in the soil is a balance of carbon inputs (e.g. from litter, residues, roots, manure) and carbon losses (mostly through respiration, increased by soil disturbance), practices that either increase inputs, or reduce losses can promote SCS.

Potentials and costs. Of the 22 articles (Batjes 1998, Benbi 2013, Conant 2011, Henderson *et al* 2015, Lal 2003b, 2003a, 2004a, 2004c, 2004b, 2010, 2011, 2013, Lassaletta and Aguilera 2015, Lorenz and Lal 2014, Powlson *et al* 2014, Salati *et al* 2010, Smith 2012, 2016, Sommer and Bossio 2014, Minasny *et al* 2017, Metting *et al* 2001, Smith *et al* 2008) that included global technical potentials for SCS, 16 provided minimum-maximum ranges, and six provided best estimates without a range. All estimates are 'bottom-up' and are calculated by multiplying a per-area sequestration potential for each practice with an area over which the practice could be applied.

Most of the variation contributing to the large variation in estimates arises from the area assumed to be available, with the estimates at the high end of the ranges assuming that e.g. all cropland and grassland area are amenable to SCS. Lower estimates assume constraints (e.g. not all grassland is managed, degraded land excluded etc (Smith *et al* 2008)).

Among the high estimates of maximum potential (six articles, with around or above 7 $GtCO_2\ yr^{-1}$), five are the top end of wide ranges (Lal 2003b, 2010, 2013, 2011, Minasny *et al* 2017), though the mean of the ranges are also above 7 $GtCO_2\ yr^{-1}$. The other high estimate (Batjes 1998) was not estimated in the paper, but was aggregating estimates from other papers (figure 13).

Ten of the global estimates of potential are at the low end of the range as they consider individual practices. For individual practices applied globally, the technical potentials are 1.47–2.93 $GtCO_2\ yr^{-1}$ for croplands, 0.73–1.47 $GtCO_2\ yr^{-1}$ for desertification control (Lal 2004b), 3.6 $GtCO_2\ yr^{-1}$ in dryland ecosystems (Lal 2004a), 1.47–3.67 $GtCO_2\ yr^{-1}$ for reclamation of agricultural soils (Benbi 2013), 0.4–0.6 $GtCO_2\ yr^{-1}$ for no tillage in croplands (Powlson *et al* 2014), 0.51–1.25 $GtCO_2\ yr^{-1}$ for degraded land restoration (Salati *et al* 2010), 4–8 $GtCO_2\ yr^{-1}$ for agro-forestry (Lorenz and Lal 2014), 1.1–2.5 $GtCO_2\ yr^{-1}$ through forestry and agriculture (Conant 2011), 3.3–6.7 $GtCO_2\ yr^{-1}$ in croplands (Zomer *et al* 2017), 1.36–2.71 $GtCO_2\ yr^{-1}$ for croplands and pastures (Sommer and Bossio 2014) and 0.15 and 0.20 $GtCO_2\ yr^{-1}$ for grazing optimization and planting of legumes in grazing land, respectively (Henderson *et al* 2015).

The remainder of the estimates of maximum potential (seven articles: (Lal 2003a, 2004c, Lassaletta and Aguilera 2015, Metting *et al* 2001, Smith 2012,

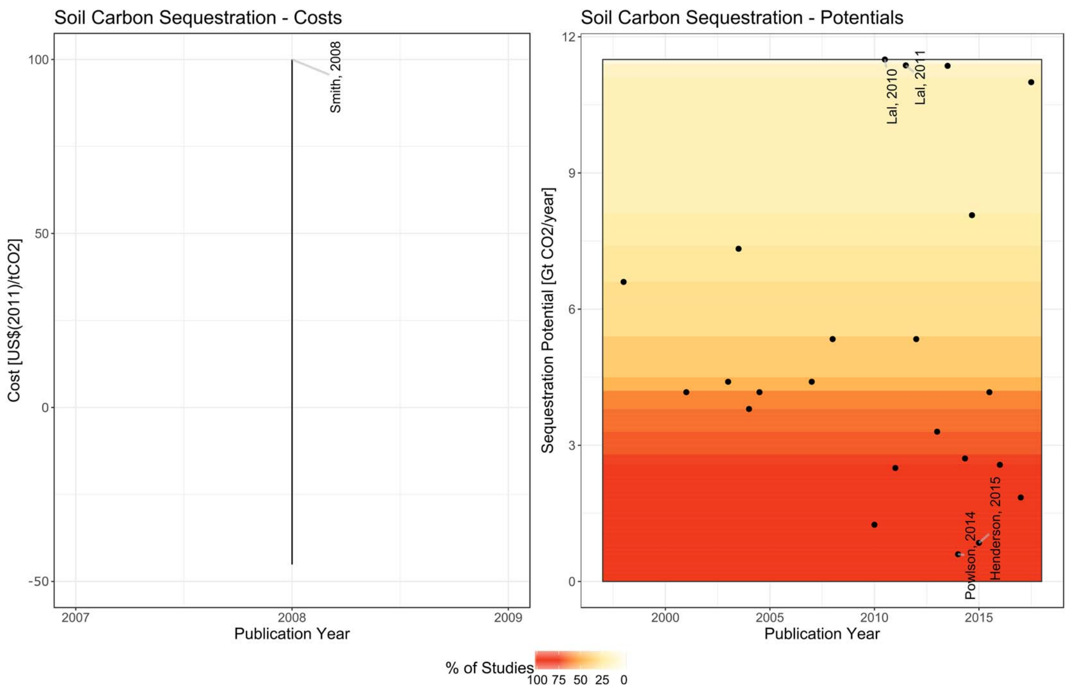

Figure 13. Costs and potentials for soil carbon sequestration. The heat bar distribution of literature estimates in each panel are calculated as in figure 6, with individual publication cost ranges represented by lines (costs panel); and maximum estimates of negative emissions potential plotted by publication year (potentials panel). Estimates and ranges at the top and bottom end of the distribution are labelled; the data can be further explored in our online supporting material available at https://mcc-apsis.github.io/NETs-review/.

Smith *et al* 2016b, 2008)) are in the range of around 3–5 $GtCO_2\ yr^{-1}$, consistent with mean or median of all estimates. Using the mid-point of the range for the seventeen studies quoting ranges, and the best estimate for the six articles not giving ranges, the mean and median global technical potential for SCS were 4.28 and 3.677 $GtCO_2\ yr^{-1}$, respectively ($n = 23$), with a range of 1.1–1.37 $GtCO_2\ yr^{-1}$ using absolute minimum and maximum range values, or 2.91–5.65 or 2.28–5.34 $GtCO_2\ yr^{-1}$ using the mean and median of the minimum range values, respectively ($n = 17$), with this range considered feasible as a technical potential.

There are few papers providing estimates of cost per tonne of CO_2 equivalent (tCO_2eq) removed by SCS since this is very practice- and context-specific, and depends greatly on, for example, labor costs and degree of mechanization (Smith 2016). Only three papers (Smith 2012, 2016, Smith *et al* 2008) provided estimates of economic potential for SCS, at US$20, US$50 and 100/tCO_2e, all of which are derived from the same analysis. The SCS potential at US$20/$tCO_2e$ was 1.38 (1.34–1.42) $GtCO_2\ yr^{-1}$, at US$50/$tCO_2e$ was 2.32 (2.23–2.44) $GtCO_2\ yr^{-1}$ and at US$100/$tCO_2e$ was 3.7 (3.56–3.83) $GtCO_2\ yr^{-1}$, though (Smith 2016) provides a lower estimate for global SCS at US$100/$tCO_2e$ of 1.47–2.57 $GtCO_2\ yr^{-1}$ since it excludes some practices. The higher estimates of potential are associated with higher carbon prices, as expected, since carbon price is an indicator of level of climate change mitigation ambition. Using practices and costs listed in (Smith *et al* 2008), (Smith 2016) note that about 20% of the mitigation from SCS is realized at negative cost (−45–0 US$/$tCO_2eq$.) and about 80% realized is between US$0 and US$10/tCO_2eq. giving estimates of global costs for implementation of SCS globally as −7.7 B$ (comprising 16.9 B$ of savings, and 9.2 B$ of positive costs).

Side effects. Side effects are noted in a number of articles, featuring for example, improved soil quality and health (Lal 2004b), improved and more stable crop yield (Pan *et al* 2009), increased methane emissions when SCS is encouraged in rice paddies through addition of farmyard manure (Nayak *et al* 2015), or increased emissions of nitrous oxide if SCS is encouraged by increasing plant productivity with nitrogen fertilizer (Liao *et al* 2015). Nonetheless, many practices can be used with no adverse side effects. Side effects were assessed and summarized in Smith (2016). Though SCS is applied on large land areas, it can be done without changing land use, so the land footprint is zero. The water footprint is also negligible, as is energy use and impact on albedo (Smith 2016). Increased SCS results in more organic nitrogen in the soil, which could be mineralized to become a substrate for nitrous oxide (N_2O) production, although the effect is difficult to quantify (Smith 2016). The stoichiometry of the organic matter means that for every t C/ha of soil organic matter added, nutrients, that is nitrogen, phosphorous and potassium, would increase by 80 kg ha^{-1}, 20 kg ha^{-1} and 15 kg ha^{-1}, respectively (Lal 2004b, Smith 2016). This could be derived from the organic matter added, though if it requires external nutrient addition, the increased nutrient level could have knock-on effects on pollution if those nutrients were lost to water courses.

Permanence and saturation. A drawback of SCS is sink saturation. Though SCS negative emission potentials are often expressed as per-year values, the potential is time limited. SCS potential is large at the outset, but decreases as soils approach a new, higher equilibrium value (Smith 2012), such that the potential decreases to zero when the new equilibrium is reached. This sink saturation occurs after 10–100 years, depending on the SCS option, soil type and climate zone (slower in colder regions), with IPCC using a default saturation time of 20 years (Smith 2016). As sinks derived from SCS are also reversible (Smith 2012), practices need to be maintained, even when the sink is saturated so any yearly costs will persist even after the emission potential has reduced to zero at sink saturation. Sink saturation also means that SCS implemented in 2020 will no longer be effective as a NET after 2040 (assuming 20 years for sink saturation; Smith 2016).

Authors' assessment. The mean and median global technical potentials for SCS of 4.28 and 3.677 $GtCO_2\ yr^{-1}$ ($n = 23$) represent good global estimates of the technical global potential for SCS, with ranges of 2.91–5.65 (using mean values of range minimums/maximums) or 2.28–5.34 (using median values of range minimums/maximums) $GtCO_2\ yr^{-1}$ ($n = 17$), providing a good estimate of the spread of literature ranges. Values below these ranges mostly consider only single practices (e.g. no tillage, agro-forestry, restoration of degraded land, grazing management), so do not provide estimates for full global potential for SCS, while values above these ranges (>7 $GtCO_2\ yr^{-1}$) are characterized by unconstrained estimates (e.g. by assuming that high per-area estimates could be applied to all cropland/ grassland areas globally with the same effectiveness), so provide the very maximum, unconstrained theoretical potential that would never be achievable in reality. Based on this analysis, the best estimate (with range) of realistic technical potential is considered to be close to the median of the minimums of the ranges provided, which for SCS is 3.8 (2.3–5.3) $GtCO_2\ yr^{-1}$. Costs are low, estimated here in the range of US\$0–100/tCO_2, and the side effects are likely to be less of an issue than for many other NETS, though sink saturation and reversibility (non-permanence) are significant drawbacks for SCS. As with the other technology estimates, these ranges are for 2050, but once achieved, cannot be maintained indefinitely due to sink saturation. Since soils have been managed for millennia, there is a high level of knowledge of practices and readiness for adoption. Soil carbon sequestration is immediately deployable since the agricultural and land management practices required (e.g. improved rotations with reduced fallow that increase carbon inputs to the soil and addition of organic materials, such as manure or compost, and other aspects of improved cropland and grazing land management), are generally well known by farmers and land managers (UNEP 2017).

3.8. Other and emerging NETs

There is a plethora of new ideas on how to extract carbon from the atmosphere, some of which are yet to be exposed in the literature. We discuss here some of the newer literature based on a broad search of the Web of Science and Scopus, and expert advice, focusing on three avenues that have gained traction in the debate around negative emissions.

Firstly, a recent strand of literature examines the removal of non-CO_2 GHGs (GGR) such as methane from the atmosphere. Such a process would be valuable—per unit mass, methane is a more potent GHG than CO_2 (Montzka *et al* 2011)—and could compensate for emissions in the food sector and outgassing from lakes, wetlands, and oceans (Stolaroff *et al* 2012). (Boucher and Folberth 2010) review several existing technologies for methane removal (cryogenic separation, molecular sieves or gates, and adsorption filters based on zeolite minerals) and find low confidence that any of these are currently economically or energetically suitable for large-scale air capture, however. More recent research (e.g. by de Richter *et al* 2017) examines other technologies that also consider non-CO_2 GHGs like N_2O.

Secondly, there is a growing branch of literature on Blue Carbon, i.e. the management of sea grasses, mangroves, and salt marshes along coasts in order to expand their carbon sinks. (Macreadie *et al* 2017) assess the literature for three different routes of Blue Carbon. They find that reducing nutrient inputs, avoiding unnaturally high levels of bioturbation (i.e. the turning of soils and sediments by animals or plants), and restoring natural hydrology will maximize carbon sequestration and minimize carbon losses. However, there are to date no robust quantifications of a global negative emissions potential from Blue Carbon. Still, most of the options to enhance Blue Carbon also reduce human and environmental impacts on coastal ecosystems—an important co-benefit. (Johannessen and Macdonald 2016) report the Blue Carbon sink at 0.4%–0.8% of global human-made emissions.

Thirdly, CO_2 could be used as synthetic feedstock for chemical materials because of its apparent abundance, non-toxicity, and low cost. Potential products include Poly Propylene Carbonate (Qin *et al* 2015), carbon mineralization, Enhanced Oil Recovery (EOR), biodiesel and synfuel production (Abanades *et al* 2017) and other chemical applications providing economic incentives and opportunities for technological learning for carbon capture. Note however that current Life Cycle Analyses suffer from at least one of the three following pitfalls that raise doubts as to whether carbon capture and utilisation can really contribute much to achieving large-scale negative emissions: (i) utilized CO_2 might intuitively be considered as carbon-negative without actually being so; (ii) accounting problems exist with respect to the allocation of emissions to individual products; and (iii) there may be negligence of CO_2 storage duration (von der Assen *et al* 2013). Furthermore, MacDowell *et al* (2017) voice serious concern about scale issues, concluding that it is highly improbable that the chemical conversion of CO_2 will contribute more than 1% to the mitigation needed to achieve the Paris Agreement's long-term temperature goal.

4. Synthesis

In this section, we synthesize the findings from the different NETs assessments in section 3 and situate them in the scenario evidence from section 2. Figure 14 and table 2 show the ranges for the global potentials and costs in 2050 and distill the main side effects, subcategorized as either positive, or at risk of being negative. We condition the cost and potential ranges with the authors' assessments (summarized in the central plot in figure 14). These assessments should be interpreted as deployment ranges that are feasible in the context of generally favorable conditions, i.e. long-term policy support, with key decisions made in the technology cycle and deployment phase to generate demand pull, and few social, economic or environmental shocks in the relevant agricultural and land use sectors[33]. One aim of this review is to comprehensively cover the relevant literature based on a transparent literature search and selection process (see SI). We therefore also compare our results with those from existing, previous assessments.

4.1. Potentials

The deployment potentials in previous NETs assessments vary considerably across studies. This study spans the entire ranges of estimates for all individual NETs reported in these previous assessments (Royal Society 2009, McLaren 2012, Friends of the Earth 2011, Vaughan and Lenton 2011, McGlashan *et al* 2012, National Academy of Sciences 2015, Caldecott *et al* 2015, Fuss *et al* 2016, Smith *et al* 2016a, Rubin *et al* 2015, Ciais *et al* 2013, Lenton 2010). This overlap, in principle, confirms the ambition of this review to provide comprehensiveness, yet it does not ensure that estimates are weighted according to the distribution of evidence. In the absence of comparable efforts, this can only be judged in terms of the review procedure: our general approach is summarized in Minx *et al* (2017) and outlined in detail in the SI of this review.

Land-based mitigation options including biochar, AR, EW as well as SCS each have a potential in the range of 1–4 $GtCO_2\ yr^{-1}$ in 2050—noting that achieving the higher end of the ranges gets increasingly demanding and will require higher carbon prices. There is considerable disagreement about reasonable deployment potentials for BECCS and skepticism that deployment ranges as seen in many scenarios can be reached. To our judgment, due to constraints on the availability of sustainable biomass, it will be extremely difficult to achieve annual carbon removal rates of 5 $GtCO_2$ with this technology by mid-century; however, end-of the-century potentials might be considerably higher, assuming that population peaks and reduces pressure on land, alongside further yield improvements. DACCS deployment will heavily depend on suitable energy sources and cost developments. Given its nascent stage of development, it will be an option with limited potential in 2050. Yet, if DACCS becomes competitive, potential deployment will be driven by cost support and rates of upscaling, with no obvious upper biophysical limit, barring storage, material and thermodynamic constraints.

Whether these deployment potentials are well-aligned with requirements identified in long-term mitigation scenarios consistent with the 1.5 °C and 2 °C scenarios, respectively, is questionable. This review shares the wide-spread concern that reaching annual deployment scales of 10–20 $GtCO_2\ yr^{-1}$ via BECCS at the end of the 21st century, as is the case in many scenarios, is not possible without severe adverse side effects. Deployment scales reached in 2 °C scenarios with limited BECCS deployment (corresponding to about 100EJ of bioenergy) appear to be more realistic. Opportunities for reaching larger deployment scales emerge when NET portfolios composed of the various technologies—rather than a single technology—are developed and scaled-up over time. A discussion and synthesis of development and upscaling bottlenecks are provided in Nemet *et al* (2018) and Minx *et al* (2017), respectively. Such a discussion of NET portfolios with a variety of technologies contributing potentially at more modest scales is important, but almost completely absent from the discussion and the reviewed body of literature. Exceptions such as in (Strefler *et al* 2018a) confirm that adding other NETs (in this case terrestrial enhanced weathering) to BECCS can substantially reduce side effects (in this case reduce the land footprint, while still reaching considerable negative emissions potentials).

However, the deployment scales of individual technologies cannot be simply added up: first, some technologies or practices compete with one another for resources, e.g. land in the case of afforestation, reforestation and BECCS; and competition for biomass in the case of soil carbon sequestration, biochar and BECCS (high biomass extraction rates for BECCS will undermine the build-up and retention of soil carbon via sustainable management practices, or via biochar production). Second, scenarios that deploy small portfolios of two or three NETs show that adding another technology raises deployment, but at a decreasing rate, i.e. NETs deployment is lower for each technology when two or more rather than a

[33] They do not represent technical potentials, however, and do take constraints into account, while the larger ranges we find in the literature are partially due to the fact that different potentials are considered, e.g. economic potentials and technical potentials.

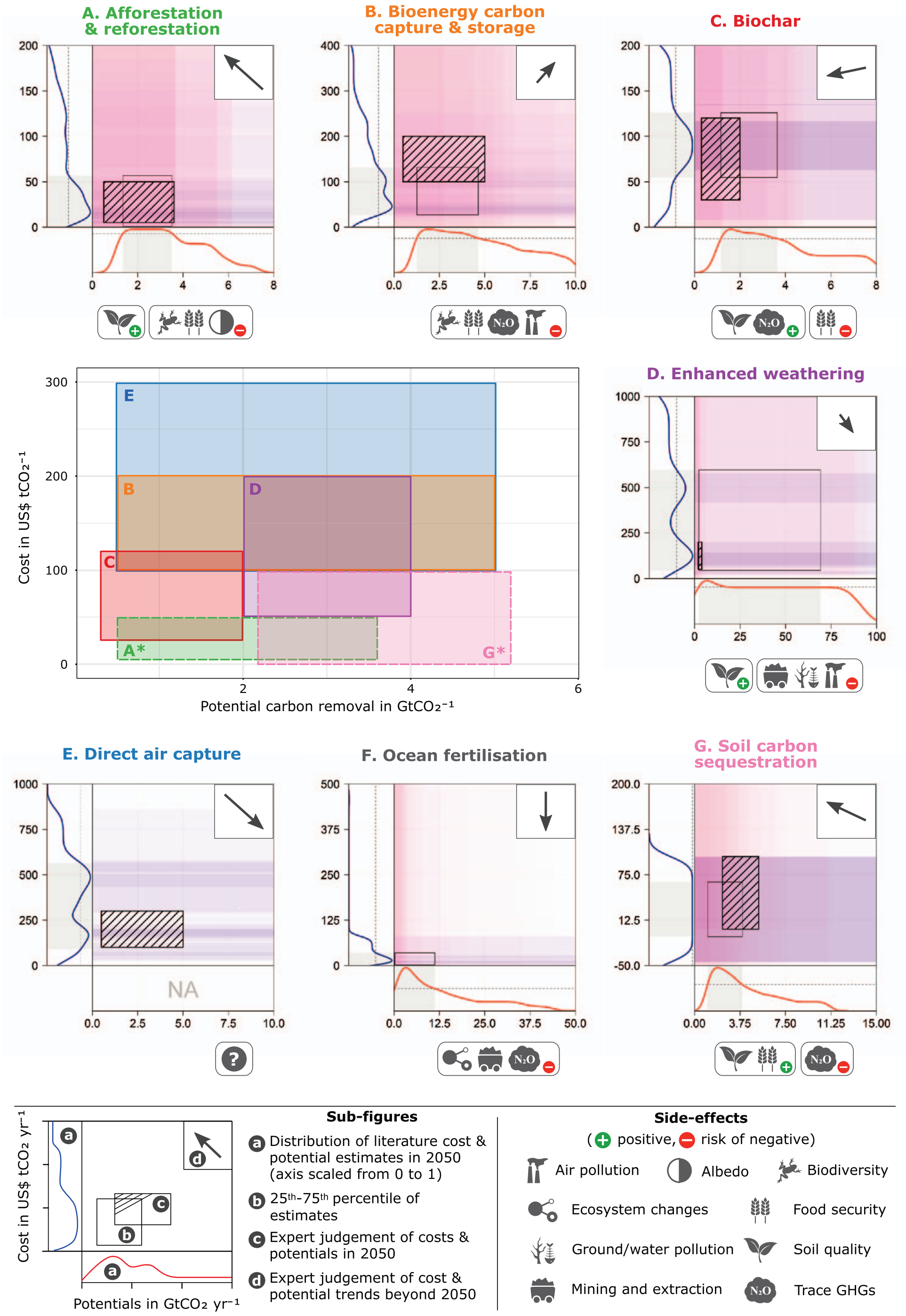

Figure 14. Evidence and authors' assessments on negative emissions costs, deployment potentials, key side-effects, and cost/potential trends beyond 2050. Note that risks of negative side effects are often contingent on implementation, e.g. large-scale afforestation with mono-cultures versus agroforestry projects, or biochar from dedicated crops versus residues. Panels A-G contrast authors' assessments (hatched box, also reproduced in the central overview figure) with literature estimates (represented by a distribution function and density plot). Density functions are computed using a Gaussian smoothing kernel density estimator; grey areas are defined by taking the range of costs (potentials) that include the maximum density and that yield a bounded integral value of 0.5. Reference year for all estimates provided is 2050. As annual deployments of soil carbon sequestration and afforestation cannot be sustained as long as other technologies (due to sink saturation) we represent these technologies as dashed boxes in the central figure with an asterisk (*).

Table 2. Summary of assessment results (potentials and cost authors' assessment with the full range across the literature in square brackets, rounded numbers).

NET	Potentials	Cost	Positive impacts			Negative impacts			Permanence/ Saturation
	$GtCO_2\ yr^{-1}$	US$/$tCO_2$	*Socio-economic*	*Environmental*	*Biophysical*	*Socio-economic*	*Environ-mental*	*Biogeo-physical*	
BECCS	0.5–5 [1–85]	100–200 [15–400]	Market opportunities, economic diversification, energy independence, technology development and transfer	GHG emissions substitution		Food security, health impacts	Biodiversity losses, deforestation and forest degradation, through air pollution CO_2 leakage, impacts of fertilizer use on soil and water	Albedo change, direct and indirect LUC GHG emissions (N_2O, CO_2 under leakage)	High permanency for adequate geological storage, long-term governance of storage, limits on rates of bioenergy production and carbon sequestration
DACCS	0.5–5 [limited by upscaling and costs]	100–300 [25–1000]	Business opportunities, subject to a predictable CO_2 price	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.	Material/waste implications not known but cannot be excluded	Some spatial requirements	High permanency for adequate geological storage
Afforestation and re-forestation	0.5–3.6 [0.5–7]	5–50 [0–240]	Employment (caveat: low-paid seasonal jobs), local livelihoods	Biodiversity if native and diverse species are used (in spite of lower CO_2 storage)	Improved soil carbon, nutrient and water cycling impacts	Less agricultural exports, higher food prices	Biodiversity losses for high-carbon monocultures and under displacement	Direct and indirect LUC, albedo change (boreal: offsetting impact; temperate: neutralized)	Saturation of forests; vulnerable to disturbance; post-AR forest management essential

Table 2. *Continued.*

NET	Potentials	Cost	Positive impacts			Negative impacts			Permanence/ Saturation
	$GtCO_2\ yr^{-1}$	US$/$tCO_2$	*Socio-economic*	*Environmental*	*Biophysical*	*Socio-economic*	*Environ-mental*	*Biogeo-physical*	
Enhanced weathering	2–4 [0–100]	50–200 [15–3460]	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 impacts associated to fine grained material	Ecological impacts of mineral extraction and transport on a massive scale	Direct and indirect land use change if biomass sourced from dedicated crops, potentially heavy metal release depending on the soil characteristics, risks of fine grained material, changes in soil hydraulic properties	Saturation of soil; Residence time from months to geological time scale
Ocean fertilization	extremely limited [0.5–44]	No authors' assessment due to limited potential [0–460]	Potential increase in fish catches	Enhanced biological production		None	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
Biochar	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	Down-regulation of plant defence genes may increase plant vulnerability against insects, pathogens, and drought	Albedo change partly offsetting mitigation effect, even though likelihood low, as biochar would be buried.	Residence times of biochars between decades to centuries depending on soil type, management & environmental conditions
Soil carbon sequestration	2–5 [0.5–11]	0–100 [−45–100]	Improved soil resilience and improved agricultural production, Negative cost options	Mostly reduced pollution and improved soil quality	Mostly positive impacts on soil, water and air quality	None	Possible increase in N_2O emissions and N and P losses to water due to more N and P substrate for mineralisation	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

single technology is deployed (even if technologies are of very different types such as BECCS and DACCS (or EW)) (Marcucci *et al* 2017, Humpenöder *et al* 2014, Chen and Tavoni 2013).

Beyond 2050, long term cumulative potentials are a function of scalability and sink saturation. We summarise these in figure 14 by indicating the expected post-2050 trend in costs and potentials for each technology (qualitative arrows in the top-right of each sub-figure). In the case of land-based options, these constraints are severe. For instance, although SCS has a very high mid-century potential (4–7 $GtCO_2\ yr^{-1}$)—and can be quickly realised through changes in farming and land management practices—after consistent application the sink will saturate within ∼20 years and will require on-going maintenance. Biochar is similarly constrained in terms of saturation, although few studies yet point to the total feasible sink potential. Cumulative afforestation potential is constrained by available land, with newly afforested sites saturating within ∼100 years. We might then consider these three options '21st century NETs': promising stop-gaps, but limited in long-term potential.

While our review highlights the limitations of BECCS, unlike other land-based options it does not saturate as quickly over time. The cycle of biomass production and sequestration could conceivably continue up to the point that geological storage potential is maximised, thereby sequestering a large cumulative amount of CO_2. However, BECCS is constrained to maximum yearly potentials, as determined by a sustainable scale of biomass production on land (though as mentioned previously, technological progress and a population peak could ease this pressure, allowing for more annual CO_2 uptake). Lastly, DACCS emerges as a relatively promising long-term option beyond 2050, being limited in potential only by the economic (and energetic) feasibility of scale-up.

4.2. Costs

Costs impose further economic limits to NETs deployment (see Smith *et al* 2016a). Across technologies, costs vary significantly (figure 14). Particularly, land management options like soil carbon sequestration, biochar, afforestation and reforestation have a small-scale availability at low, zero, or even negative costs in places. Yet, despite technology cost reductions from learning, the marginal costs of abatement tend to increase with deployment, particularly for land management options such as afforestation and reforestation (due to opportunity costs for land) and soil carbon management (due to the exhaustion of cost-efficient 'low-hanging' management options). Hence we see these options increasing in costs beyond 2050 (figure 14). On the other hand, biochar may offer some prospects for modest cost decreases as pyrolysis techniques are still in their infancy and may yet benefit from scale and learning dynamics.

Enhanced weathering is a relatively expensive option due to the high energy requirements for grinding the minerals to sufficiently small size. Hence, carbon prices of US\$50 and more are required if larger deployments are to be reached, with prices progressively increasing as proximate mining and deployment locations are exhausted. On the other hand, less developed technologies like BECCS and DACCS (Nemet *et al* 2018) are comparatively costly (US\$100–200 and US\$100–300/tCO_2, respectively), but once available can be more easily scaled up—particularly in the case of DACCS. The long-term cost trends of BECCS are a matter of significant uncertainty—in the literature and within the authors' assessment—as they are shaped by multiple dynamics. Principally these include the opportunity costs for land and biomass, prospects for biomass yield increases and alternative sources (e.g. algae), and the prospects for bringing down plant costs via scaling and technological learning. However, beyond a deployment level of 5$GtCO_2\ yr^{-1}$, we judge costs to increase as pressures on land and biomass progressively grow, albeit with a heavy caveat of uncertainty. With DACCS, however, the literature is strongly suggestive of long-term cost decreases, albeit starting from a high level.

Overall, cost and potential considerations could suggest a natural order for phasing in different NETs—a discussion we will further elaborate in Minx *et al* (2017) by infusing development and upscaling considerations from Nemet *et al* (2018). Interestingly, these clusters of technologies also differ in terms of how securely they store carbon. While DACCS and BECCS store the carbon relatively safely mainly in geological reservoirs (Bui *et al* 2018, de Coninck and Benson 2014), soil and biomass-sequestered carbon are permanently at risk of rapid release, should a reversal in management decisions take place.

4.3. Side-effects

An often neglected aspect of NETs is constituted by the co-benefits they may yield. The literature shows evidence that afforestation, soil carbon management, enhanced weathering (on land), and biochar may all contribute to soil quality, nutrient retention and water cycling under appropriate management regimes. Where these changes result in enhanced crop yields, the socio-economic benefits to local and regional livelihoods may be considerable. These benefits partially explain the negative costs associated with soil carbon management, as well as its maturity and existing implementation, alongside that of afforestation. Nonetheless, there is a clear literature bias towards developed countries concerning the land-based NETs, raising an obvious need for research into the generally poorer initial site conditions and more fragile social institutions that are prevalent in developing nations. Another non-trivial consideration is whether trace-GHGs will be mitigated (potentially biochar) or intensified (BECCS) by changes to land management practices—an issue that will require concerted long-term studies to track fertilizer inputs, management practices, and resulting land-use emissions.

For most NETs, whether co-benefits or negative impacts are realized depends on implementation strategy and scale, at least in principle. For instance, monocrop plantations of eucalyptus may be an efficient means to draw down carbon, but are inferior to agroforestry initiatives when considering a broader set of social and environmental goals. More problematically, large-scale BECCS and afforestation programs will drive up demand for land, posing risks for food production, biodiversity, and land set aside for other purposes (living space, nature reserves, and other cultural, aesthetic or productive uses) (Newbold *et al* 2015, Creutzig 2017). As these effects play out in global markets, the broader success of large-scale land-based NETs will hence crucially depend on global governance of land (Creutzig 2017). Cultivating marginal land offsets this risk, as would exploiting waste biomass feedstocks as inputs for biochar and BECCS. However, with increasing scale, the opportunities for careful implementation decline, forcing trade-offs among valued land uses, and indeed between land use NETs themselves. Another important consideration here is the direct warming effect from a changing surface albedo in Northern latitudes. This issue is principally relevant for afforestation (planting trees in in high latitudes is effectively counterproductive)—but also for biochar and BECCS, both of which will change prevailing soil and crop appearances. In addition, it is not always clear what marginal and degraded land really is and where it is, as definitions and mappings diverge widely, so the potential of biomass from marginal and degraded land is unclear[34].

Given the nascent stage of direct air capture, enhanced weathering and ocean fertilization options, some side-effects are probably not yet anticipated—or have already been anticipated, but not subjected to sufficient research. Research on the side effects of direct air capture is basically non-existent. Conceivably, a large scale DACCS program will require extensive amounts of materials, and therefore mineral extraction, refining, transportation and waste disposal infrastructures. The ecological impacts of these infrastructures could be even more problematic for enhanced weathering and ocean fertilization, which would require an extensive mobilization of materials at a regional or global scale. Further issues have been anticipated for enhanced weathering (local air pollution, heavy metal pollution in soils) and for ocean fertilization (surface ocean anoxia, nutrient balance shifts, potential large-scale ecosystem changes), but remain under-examined in practice.

[34] Scientists do not agree how much land is actually unused and at the same time available for cultivation (Coelho *et al* 2012, Erb *et al* 2007, Haberl *et al* 2010, Fritz and See 2008), and the datasets and definitions used for degraded and marginal land are ambiguous (Sonneveld and Dent 2009). Even the terminology of marginal or degraded lands is usually not clear.

4.4. Knowledge gaps

The systematic review of the NETs literature conducted here does not only provide us with a comprehensive assessment of their potentials, costs and side effects, but has also unveiled areas of uncertainty.

For the study of the individual options to remove carbon, all of them still need further work on estimating the economic costs (and benefits) of real world deployment and a quantification of environmental, economic and social externalities associated with deployment. This will then also enable more comprehensive modelling. In addition, there is a need to better understand the barriers to implementation of NETs and how these can be overcome. This includes research on policies, incentive schemes and finance, public acceptance, governance and actual demonstration projects. For enhanced weathering and ocean fertilisation, for instance, the largest research gap identified in this assessment is the missing existence of real field experiments. Also, potentials need to be adjusted for new insights with respect to biophysical impacts of NETs deployment (e.g. on albedo), changes in the carbon cycle caused by large-scale negative emissions (Jones *et al* 2016, Tokarska and Zickfeld 2015) and changes in land cover due to climate change. Finally, moving from research needs to gaps in practical knowledge, more actual pilot projects are necessary.

Other research gaps are specific to certain NETs. For example, in the case of NETs with high land requirements such as BECCS, it will be important to improve the mapping of available land, especially marginal and degraded land. To this end, harmonized definitions need to be developed and operationalized. Based on this, geographically explicit regional studies on potentials are needed. These bottom-up potentials furthermore have to be matched to the global, top-down ones. For afforestation and reforestation, for example, there are too few studies explicitly covering the tropics, yet this is the biome that global models associate with the largest carbon removal potentials. Similarly, only few studies examine the practical issues of implementing soil carbon sequestration in the developing countries, where biophysical as well as socio-economic challenges may diverge substantially from the existing knowledge base. Also in the case of enhanced weathering, proper management at the global scale would demand databases of possible application scenarios combining rock products, soil conditions, local climates and targeted plant systems.

Furthermore, there are many emerging ideas for removing greenhouse gases, some of which have been discussed in this review (e.g. methane removal), but not assessed due to smaller or more fragmented bodies of literature. As the corresponding knowledge matures and more studies on their global potentials and costs becomes available, they need to be systematically assessed as well.

Finally, for the IAMs, the following research gaps can be identified: (i) the need for integrated portfolios of NETs in IAMs, which should include an evaluation of interactions with other mitigation options and effects of NETs on non-climate sustainable development goals; (ii) a better understanding of geo-physical constraints of negative emissions and implementation in IAMs; (iii) an analysis of NETs deployment dynamics in a risk management framework, acknowledging that many decisions in climate change mitigation will have to be made in the short term and therefore under uncertainty.

5. Outlook

The assessment conducted in this paper has shown that the state of the literature is at very different stages for each of the various NETs considered: there is a rapidly growing literature on BECCS, which is closely interlinked with the scenario literature on low-stabilization pathways. On the other hand, some NETs look back at a much longer history in terms of literature—even if carbon removal from the atmosphere has not historically been the main motivation. Examples of these are afforestation and reforestation, biochar and soil carbon storage. DACCS, ocean fertilization and terrestrial and marine enhanced weathering still have to find their way into the scenario literature, though this is starting to happen for some of the options. Beyond that, more ideas are emerging to withdraw CO_2 and also other GHGs from the atmosphere, as has been briefly discussed.

Our review highlights some more general confusion around the role of negative emissions in climate change mitigation: while 1.5 °C scenarios stronlgy depend on NETs, 2 °C scenarios may rely on only limited or zero deployment of NETs. This result is in contrast to some of the claims that have been made in the literature (Williamson 2016, Gasser *et al* 2015, Parson 2017). Yet, right-sizing negative emissions towards what seems possible today (Field and Mach 2017) would require rapid and sustained emission reductions in the short-term. The window of opportunity for limiting NETs dependence is closing rapidly due the cumulative warming effect of CO_2 in the atmosphere and the lock-in of large-scale carbon-intensive infrastructure. An emission trajectory as suggested by the current nationally determined contributions (NDCs) would already lock remaining 2 °C pathways deeply into NETs dependence—similar to the NETs dependence for 1.5 °C pathways today (Riahi *et al* 2015).

From a risk management perspective, the uncertainties and risks around large-scale NETs deployment suggest a need for swiftly ratcheting up emissions reductions over the next decade in order to limit our dependence on NETs for keeping temperature rise below 2 °C. Based on our assessment, large-scale deployment of NETs, as implied by some of the current literature on 1.5 °C scenarios, appears unrealistic given the biophysical and economic limits that are suggested by the available, yet still patchy, science today. The same concerns of realism apply equally to 2 °C scenarios that delay action until 2030. The direct policy implications of this NETs review are thus that, given the assessed uncertainties, strategies should aim at limiting warming to below 2 °C with the least possible assumed dependence on NETs. Simultaneously, NETs should be further researched, but until they are demonstrably available at the global scale there should be no delay in a global peak and decline of CO_2 emissions. Whether global temperature can be limited to 1.5 °C as part of the Paris Agreements long-term temperature goal will depend on the pace of technological learning and would require positive surprises compared to the current state of knowledge. If NETs become available at scale over the course of the next 50 years, they will still play a fundamental role in the context of 1.5 °C by enabling to revert global mean temperature rise from possibly higher peak levels.

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Glossary

Term	Acronym	Definition
Afforestation and reforestation	AR	Afforestation refers to planting of new forests on lands that historically have not contained forests, while reforestation refers to planting of forests on lands which have, historically, previously contained forests but which have been converted to some other use. (IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC 2000))
Albedo		The fraction of solar radiation reflected by a surface or object, often expressed as a percentage (IPCC 2014a, AR5 WGIII Glossary).
Alkalinity		A measure of the capacity of an aqueous solution to neutralize acids. (AR5 WGI Glossary): $HCO_3^- + 2 * CO_3^{2-} + OH^- – H^+$ + minor chemical species
Aragonite saturation state	ASS	Is obtained by the product of dissolved calcium and carbonate ions in seawater divided by the aragonite solubility in seawater. If ASS is higher or lower than one sea water is respectively over- or undersaturated with respect to aragonite. If ASS is equal one, the sea water solution is saturated.
Bicarbonate		A chemical compound: HCO_3^-
Biochar		Biochar is charcoal used as a soil amendment produced through pyrosysis or gasification.
Biochar turnover time		Average lifetime biochar in a soil after application.
Bioenergy carbon capture and storage	BECCS	The application of carbon dioxide capture and storage (CCS) technology to bioenergy conversion processes. Depending on the total lifecycle emissions, including total marginal consequential effects (from indirect land-use change (iLUC) and other processes), BECCS has the potential for net carbon dioxide (CO_2) removal from the atmosphere.
Biological synthetic natural gas	Bio-SNG	Bio-gas made by chemical synthesis
Biomass gasification		Gasification combines pyrolysis with further processing of generated gases to produce syngas with energetic properties
Black liquor		A liquid residue containing lignin compounds and inorganic chemicals, formed when pulpwood is heated in alkaline solution in the kraft papermaking process (Oxford Dictionaries).
Carbon budget		The cumulative amount of net carbon dioxide emissions that can be released while still limiting warming with a specific minimum probability to below a given temperature threshold.
Carbon capture and storage	CCS	A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for longterm isolation from the atmosphere.
Carbon dioxide emission		The release of carbon dioxide to the atmosphere from various anthropogenic activities (e.g. fossil fuel combustion, cement production, land-use changes). (AR5 WGIII Glossary). In this review, we distinguish: gross positive CO_2 emissions (the amount of CO_2 that is released into the atmosphere via anthropogenic activities), gross negative CO_2 emissions (the amount of CO_2 that is removed from the atmosphere via negative emission technologies), net positive CO_2 emissions (net CO_2 emissions that are positive), and net negative emissions (net CO_2 emissions that are negative). Note that the adjectives 'positive' and 'negative' refer only to the sign of CO_2 emissions. See also definition of net emissions.
Carbon dioxide removal	CDR	See NETs definition.
Cogeneration		Cogeneration (also referred to as combined heat and power, or CHP) is the simultaneous generation and useful application of electricity and useful heat. (IPCC 2014a, AR5 WGIII Glossary)
Computable general equilibrium model	CGE	A class of economic models that use actual economic data (i.e. input/output data), simplify the characterization of economic behaviour, and solve the whole system numerically. CGE models specify all economic relationships in mathematical terms and predict the changes in variables such as prices, output and economic welfare resulting from a change in economic policies, given information about technologies and consumer preferences. (Hertel 1997) (IPCC 2014a, AR5 WGIII Glossary)
Cost effectiveness		A policy is more cost-effective if it achieves a goal, such as a given pollution abatement level, at lower cost. (IPCC 2014a, AR5 WGIII Glossary)
Cost-benefit analysis	CBA	Monetary measurement of all negative and positive impacts associated with a given action. Costs and benefits are compared in terms of their difference and/or ratio as an indicator of how a given investment or other policy effort pays off seen from the society's point of view. (IPCC 2014a, AR5 WGIII Glossary)
Direct air carbon capture and storage	DACCS	Chemical process by which dilute CO_2 is removed from the surrounding atmosphere.

Discounting		A mathematical operation making monetary (or other) amounts received or expended at different times (years) comparable across time. The discounter uses a fixed or possibly time-varying discount rate (>0) from year to year that makes future value worth less today. (IPCC 2014a, AR5 WGIII Glossary)
Enhanced oil recovery	EOR	Enhanced oil recovery: the recovery of oil additional to that produced naturally by fluid injection or other means. (IPCC 2005, Glossary)
Enhanced weathering	EW	Artificial stimulation of the natural process of rock decomposition while increasing the cation release to produce alkalinity and geogenic nutrients.
Evaporative cooling		The process of water transpiration from vegetation, which results in a local cooling effect.
Fermentation		The biochemical process by which organic substances, particularly carbohydrates, are decomposed by the action of enzymes to provide chemical energy, as in the production of alcohol (Oxford Reference).
Fischer-Tropsch	FT	A process that transforms a gas mixture of CO and H2 into liquid hydrocarbons and water. (IPCC 2005, Glossary)
Integrated assessment	IA	A method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it. (IPCC 2014a, AR5 WGIII Glossary)
Integrated gasification combined cycle	IGCC	Power generation in which hydrocarbons or coal are gasified (q.v.) and the gas is used as a fuel to drive both a gas and a steam turbine.
Integrated model		Integrated models explore the interactions between multiple sectors of the economy or components of particular systems, such as the energy system. They may also include representations of the full economy, land use and land use change (LUC), and the climate system (based on IPCC 2014a, AR5 WGIII glossary).
Macronutrient		nitrogen, phosphorus, potassium, calcium, sulfur, magnesium, carbon, oxygen, and hydrogen are macronutrients for plants.
Mafic		A rock with relative high magnesium, calcium and iron silicate content.
Micronutrient		Iron, boron, manganese, zinc, copper, molybdenum or nickel are micronutrients for plants.
Natural sink		Process or mechanism of the Earth System that removes CO_2 from the atmosphere after an initial perturbation.
Negative emission technology	NET	A technology or management option referring 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 (based on CDR definition in IPCC 2014a: Annex II: Glossary).
Net emissions		The sum of gross positive and gross negative CO_2 emissions. See also definition of carbon dioxide emission.
Ocean CO_2 permanence		Correspond to the time, in which CO_2 would remain within the different ocean layers as dissolved inorganic/organic carbon.
Overshoot pathways/scenarios		Emissions, concentration, or temperature pathways/scenarios in which the metric of interest temporarily exceeds, or 'overshoots', the long-term goal. (IPCC 2014a, AR5 WGIII Glossary)
Oxyfuel combustion		Combustion of a fuel with pure oxygen or a mixture of oxygen, water and carbon dioxide
Pyrolysis		Heating of biomass in the absence of oxygen. In this process, the chemical compounds of biomass decompose into charcoal and combustible gases, and some of them can be condensed into bio-oil.
Representative Concentration Pathway	RCP	RCPs are scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover. The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome (Moss *et al* 2010). (IPCC 2014a, AR5 WGIII Glossary)
Shared socioeconomic pathway	SSP	The SSPs are new emission and socio-economic scenarios (Riahi *et al* 2017) that have been developed to supersede the SRES scenarios (IPCC 2000). An SSP is one of a collection of pathways that describe alternative futures of socio-economic development in the absence of climate policy intervention. The combination of SSP-based socio-economic scenarios and Representative Concentration Pathway (RCP)—based climate projections provide a useful integrative frame for climate impact and policy analysis. (IPCC 2014a, AR5 WGIII Glossary)
Soil amendment		Material worked into the soil or applied on the surface to enhance plant growth.
Structural trap		A geological structure capable of retaining hydrocarbons, sealed structurally by a fault or fold. (IPCC 2005, Glossary)
Ultramafic		A rock with very high magnesium silicate, as well as high calcium and iron silicate content. The high cation content of magnesium and calcium is the cause for high dissolved inorganic carbon binding capacity in the form of alkalinity.

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