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REVIEW ARTICLE

Negative emissions and international climate goals—learning from and about mitigation scenarios

Jérôme Hilaire[1,2] · Jan C. Minx[1,3] · Max W. Callaghan[1] · Jae Edmonds[4] · Gunnar Luderer[2] · Gregory F. Nemet[5] · Joeri Rogelj[6,7,8] · Maria del Mar Zamora[1]

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Abstract
For aiming to keep global warming well-below 2 °C and pursue efforts to limit it to 1.5 °C, as set out in the Paris Agreement, a full-fledged assessment of negative emission technologies (NETs) that remove carbon dioxide from the atmosphere is crucial to inform science-based policy making. With the Paris Agreement in mind, we re-analyse available scenario evidence to understand the roles of NETs in 1.5 °C and 2 °C scenarios and, for the first time, link this to a systematic review of findings in the underlying literature. In line with previous research, we find that keeping warming below 1.5 °C requires a rapid large-scale deployment of NETs, while for 2 °C, we can still limit NET deployment substantially by ratcheting up near-term mitigation ambition. Most recent evidence stresses the importance of future socio-economic conditions in determining the flexibility of NET deployment and suggests opportunities for hedging technology risks by adopting portfolios of NETs. Importantly, our thematic review highlights that there is a much richer set of findings on NETs than commonly reflected upon both in scientific assessments and available reviews. In particular, beyond the common findings on NETs underpinned by dozens of studies around early scale-up, the changing shape of net emission pathways or greater flexibility in the timing of climate policies, there is a suite of "niche and emerging findings", e.g. around innovation needs and rapid technological change, termination of NETs at the end of the twenty-first century or the impacts of climate change on the effectiveness of NETs that have not been widely appreciated. Future research needs to explore the role of climate damages on NET uptake, better understand the geophysical constraints of NET deployment (e.g. water, geological storage, climate feedbacks), and provide a more systematic assessment of NET portfolios in the context of sustainable development goals.

Keywords Negative emission · Carbon dioxide removal · Systematic evidence synthesis · Integrated assessment model · 1.5 °C · 2 °C

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✉ Jérôme Hilaire
hilaire@pik-potsdam.de

Extended author information available on the last page of the article

1 Introduction

Fast dwindling carbon budgets are stimulating a lively debate on the role of negative emission technologies (NETs[1]) for keeping warming below 1.5 °C and 2 °C, as illustrated by a growing number of scientific and policy discussions on the subject (Fuss et al. 2014; Geden 2015; Lomax et al. 2015; Gasser et al. 2015; Anderson 2015; Lewis 2015; Williamson 2016; Anderson and Peters 2016; Lackner 2016; Field and Mach 2017; Parson 2017; Peters and Geden 2017; Geden and Löschel 2017; van Vuuren et al. 2017; Obersteiner et al. 2018; Scott and Geden 2018). At the heart of these discussions lays new evidence from long-term climate change mitigation scenarios generated with integrated assessment models (IAMs) as summarized in recent assessments by the Intergovernmental Panel on Climate Change (Bruckner et al. 2014; Clarke et al. 2014; IPCC 2014; Kunreuther et al. 2014; Smith et al. 2014; Stavins et al. 2014).

The Fifth Assessment Report (AR5) by IPCC Working Group 3 (WG3) provided a good overview of the role of NETs for stringent climate stabilization targets. It highlighted that many 2 °C scenarios entail large-scale deployment of NETs after 2050 to compensate for residual CO_2 emissions from sectors that are difficult to decarbonize, such as industry and aviation. It warned that these scenarios are mostly associated with a temporary overshoot of the climate goal and that delays in climate action and limitations in the availability of NETs can render the 2 °C goal infeasible. It also emphasized the challenges (e.g. societal concerns), risks (e.g. technological availability, biodiversity, water, food prices, inter-generational impacts) and uncertainties (e.g. geological storage, large bioenergy production) surrounding these technologies (see also Electronic Supplementary Material (ESM) for a complete review of NET statements in AR5).

Yet, the analysis of NETs in WG3 AR5 remained inaccessible because findings were scattered in various sections and sub-sections of the report (i.e. in Chaps. 2, 6, 7, 11, 13).

The recent IPCC Special Report on Global Warming of 1.5 °C (SR1.5) (IPCC 2018) filled this gap by drawing upon a set of recent reviews (Minx et al. 2018; Fuss et al. 2018; Nemet et al., 2018) that used formal methods of evidence synthesis. It further added a comprehensive analysis on the role of NETs in 1.5 °C scenarios based on newly emerging evidence. The report highlighted that all 1.5 °C scenarios with limited or no overshoot require NETs on the order of 100–1000 $GtCO_2$ over the twenty-first century but that significant near-term emissions reductions (e.g. low energy demand, low material consumption, low GHG-intensive food consumption) can limit NET deployment to a few hundred $GtCO_2$ without reliance on Bioenergy with Carbon Capture and Storage (BECCS). It also called attention to the lack of published pathways featuring NETs other than afforestation and reforestation (AR) and BECCS (see also Electronic Supplementary Material (ESM) for a complete review of NET statements in Fuss et al. 2018, IPCC 2018 and Rogelj et al. 2018b).

Despite all this progress in the understanding of NETs, the assessment practice on scenario evidence remains unsatisfactory. In particular, the imbalance in systematicity between the treatment of quantitative and qualitative findings is concerning. On the one hand, pathways are extracted from various studies, pulled together in a large database and analysed in a complete

[1] In this review, we consider NET as any human action that removes CO_2 from the atmosphere. This definition includes: afforestation and reforestation (AR), bioenergy with carbon capture and storage (BECCS), biochar, direct air capture and carbon storage (DACCS), enhanced weathering (EW), ocean alkalinisation (OA), ocean fertilisation (OF), soil carbon sequestration. See ESM for more details.

systematic fashion. On the other hand, the inclusion or exclusion of qualitative findings is left to the discretion of the expert review team. While analyses based on larger scenario ensembles are more robust and generate new synthetic insights, the lack of a systematic approach for qualitative evidence is problematic for at least three reasons. First, the absence of systematic methods overall in many circumstances leads to bias (Haddaway and Macura, 2018). Second, findings in reviews and scientific assessments cannot be traced back to all relevant studies. For instance, the sentence "CDR requirements are reduced under 'sustainability' related assumptions." (Rogelj et al. 2018b, p. 149) only cites Strefler et al. (2018) while studies by Bertram et al. (2018) and van Vuuren et al. (2018) are equally relevant. In a similar vain, evidence resulting from the analysis of large databases—those created specifically for reviews and assessments—can be disconnected from original findings. These problems reduce the transparency of synthetic works, a crucial element of any systematic approach. Finally, we argue and will show in this article that the lack of systematicity also runs the risk of omitting important niche and newly emerging results.

To address these shortcomings with a view on the upcoming Sixth Assessment Report (AR6), we present here the first thematic review (Boyatzis 1998; Guest et al. 2012) of the available scenario literature on NETs; provide a comprehensive, traceable and easily updatable synthetic table of all statements on NETs; and re-analyse the most important ones quantitatively. The main novelty of our approach is that it links a systematic assessment of individual findings to the literature base and evidence from scenario data. As in any systematic approach, we describe the procedures to search and select the literature, to extract evidence and to evaluate the quality of included studies in a comprehensive and transparent manner (Petticrew and McCartney 2011; Minx et al. 2017a). Such a method provides a crucial synthetic account to inform upcoming climate change assessments. In particular, we contribute to the systematic assessment literature by developing and employing a computer-assisted method to review 138 studies on the subject in a comprehensive and transparent manner, allowing us to synthesize many qualitative findings. We complement this analysis by connecting it to a summary of the available quantitative evidence. Our review includes the rapidly emerging literature on the 1.5 °C limit (Luderer et al. 2013, 2018; Rogelj et al. 2015, 2018a, b; Manoussi et al. 2017; Marcucci et al. 2017; Mintenig et al. 2017; Bauer et al. 2018; Bertram et al. 2018; Holz et al. 2018; Kriegler et al. 2018a; Rickels et al. 2018; Strefler et al. 2018; Séférian et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018) that include scenarios that emphasise the role of NETs even more than the 2 °C scenarios in AR5.

Importantly, our approach provides:

- a ready-to-use method for systematically reviewing the scenario literature;
- a comprehensive, traceable and easily updatable synthetic table that maps 1360 paragraphs from 138 studies related to NETs into 66 summary statements (see Excel spreadsheet in ESM);
- a focused assessment of key evidence on the distinct role of NETs for limiting climate change to 1.5 °C and 2 °C, respectively (i.e. upscaling, maximum deployment, near-term mitigation trade-offs, role of socio-economic drivers, regional NET deployment);
- an improved understanding of how deployment dynamics change as multiple NETs get deployed in small portfolios.

In the next section, we review some key findings on NETs that are important to understand scenario results and are particularly useful for the discussions of the 1.5 °C and 2 °C limits. We support this review with quantitative evidence on the dynamics of emission pathways, climate change mitigation costs, and regional CO_2 sequestration whilst giving some special attention to small NET portfolios. Throughout the analysis, we discuss relevant key assumptions as appropriate. We close by providing a more comprehensive overview of the landscape of findings and discuss major open avenues for research.

2 Main findings from the scenario literature

The statements on NETs that we synthesized from the available literature and that are relevant to the focus of this review are organized in Table 1. We refer to them in the remainder of this article by using their unique identifier (e.g. O1, see column ID in Table 1). The methodology employed to find each statement is detailed in the ESM. It should be noted that in most mitigation scenarios, BECCS is the only explicit NET available.[2] Unless a statement is specific to a particular NET, we therefore consider BECCS as a proxy for NETs in the following discussion and as a result interpret its deployment as total NET deployment. Towards the end of this section, we explicitly consider portfolios with multiple NETs.

The literature highlights the importance of NETs for meeting stringent climate policy targets O1. This importance is illustrated by the large amounts of carbon withdrawn from the atmosphere in most 1.5 °C and 2 °C scenarios. In 85% of 2 °C scenarios (above 15th percentile), more than 300 Gt CO_2 are removed over the twenty-first century as long as no drastic GHG emission abatement, radical changes towards sustainable lifestyles, nor constraints on technological availability and climate policy timing are imposed (see Fig. 1a1 vs Fig. 1a2–a4). This estimate increases to nearly 500 in 1.5 °C scenarios with similar assumptions (Fig. 1a5).

Differences in cumulative carbon removal reflect qualitative differences in 1.5 °C and 2 °C scenarios. Global warming cannot be limited to 1.5 °C without NETs because the overshoot of the small carbon budget associated with this goal[3]—resulting from socio-economic inertias—must be offset by negative emissions (Fig. 1a) (Luderer et al. 2013; Rogelj et al. 2015; Strefler et al. 2018; Rogelj et al. 2018a; Kriegler et al. 2018b). In other words, in the absence of large-scale negative emissions, scenarios without draconian near-term CO_2 emission reductions are infeasible O11 (Fig. 1a6, see Table 2 for illustration). Even in recent 1.5 °C scenarios that explore goal achievement with minimum NETs, net negative emissions during the second half of the twenty-first century are required (Bertram et al. 2018; Holz et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018) (Fig. 1a6). In contrast, a variety of 2 °C scenarios exist without any explicit NET deployment, although the near-term CO_2 emission reductions envisaged in these scenarios are more severe than when NETs are deployed (Fig. 1a2) (Krey et al. 2014; Kriegler et al. 2014; Iyer et al. 2015; Eom et al. 2015). Moreover, the global economy is fully decarbonised by the second half of the twenty-first century in 1.5 °C scenarios D2 with a sustained period of net negative emissions thereafter. The scale-up of NETs between 2030 and

[2] This is mostly the case for scenarios prior to AR5. New scenarios increasingly feature 2 or more NETs. In addition, the new scenario data reporting template from the Integrated Assessment Modelling Consortium now separates individual NET contributions (e.g. Carbon Sequestration|CCS|Biomass, Carbon Sequestration|Land Use|Afforestation, Carbon Sequestration|Land Use|Biochar, Carbon Sequestration|Direct Air Capture, Carbon Sequestration|Enhanced Weathering…).

[3] To date, no publicly available scenario considers the much larger carbon budget estimate from Millar et al. (2017).

Table 1 Thirty-one of 66 qualitative findings retrieved from 138 selected studies and supporting the focus of this review, i.e. the role of NETs for international climate goals. Findings are clustered in 5 broad categories. Studies supporting each finding are provided and tagged in blue when they contain at least one 1.5 °C scenario and in red when they do not contain any 1.5 °C scenario but at least one 2 °C scenario. The 66 qualitative findings are available in the Electronic Supplementary Material (Table S3)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Mitigation pathway dynamics	D1	Upscaling	Even though net negative emissions occur later in the twenty-first century, NETs require rapid and wide-spread upscaling in the near-term (2030–2050) and must be maintained at least until 2100.	Figure 1 b2 and b3	69	Azar et al. (2001), Obersteiner et al. (2002), Azar et al. (2006), Manne and Richels (2006), Rao and Riahi (2006), Sohngen and Sedjo (2006), van Vuuren et al. (2006), Riahi et al. (2007), Strengers et al. (2008), Krey and Riahi (2009), van Vliet et al. (2009), Azar et al. (2010), Luckow et al. (2010), Klein et al. (2011), Lemoine et al. (2012), Ricci (2012), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Tavoni and Socolow (2013), van Vuuren et al. (2013), Aboumahboub et al. (2014), Bibas and Méjean (2014), Blanford et al. (2014b), Calvin et al. (2014), Humpenöder et al. (2014), Klein et al. (2014), Kober et al. (2014), Kriegler et al. (2014), Rose et al. (2014a), Selosse and Ricci (2014), van der Zwaan et al. (2013), Yamamoto et al. (2014), Daioglou et al. (2015), Eom et al. (2015), Kriegler et al. (2015a), Riahi et al. (2015), Bauer et al. (2016), Fujimori et al. (2016), Kriegler et al. (2016), Leibowicz et al. (2016), Luderer et al. (2016a), Luderer et al. (2016b), Vaughan and Gough (2016), Favero et al. (2017), Fricko et al. (2017), Gambhir et al. (2017), Manoussi et al. (2017), Marcucci et al. (2017), Mintenig et al. (2017), Popp et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Akimoto et al. (2018), Bertram et al. (2018), Holz et al. (2018), Kober et al. (2018), Luderer et al. (2018), Mousavi et al. (2018), Obersteiner et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Sanchez et al. (2018), Séférian et al. (2018), Strefler et al. (2018), Tanaka and O'Neill (2018), van Vuuren et al. (2018), Vaughan et al. (2018), Winning et al. (2018)
Mitigation pathway dynamics	D2		The availability and use of NETs in models strongly affect net CO2 emission pathways. In a typical	Figure 1a	63	Obersteiner et al. (2002), Azar et al. (2006), Rao and Riahi (2006), Sohngen and Sedjo (2006), van

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
		Shape_CO2_pathway	2 °C scenario in AR5, including NETs increase near-term net CO2 emissions (e.g. 2020–2050) and the speed of decarbonisation in the long-term (e.g. 2050–2100). Net CO2 emissions become eventually negative in the second half of the century.			Vuuren et al. (2006), Clarke et al. (2009), Krey and Riahi (2009), Azar et al. (2010), Leimbach et al. (2010), Luckow et al. (2010), Magné et al. (2010), Lemoine et al. (2012), Azar et al. (2013), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Tavoni and Socolow (2013), van Vuuren et al. (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Blanford et al. (2014b), Bowen et al. (2014), Humpenöder et al. (2014), Klein et al. (2014), Kober et al. (2014), Krey et al. (2014), Kriegler et al. (2014), Rose et al. (2014b), Selosse and Ricci (2014), Tavoni et al. (2013), van der Zwaan et al. (2013), van Vliet et al. (2014), Eom et al. (2015), Iyer et al. (2015), Riahi et al. (2015), Schaeffer et al. (2015), Fujimori et al. (2016), Kriegler et al. (2016), Leibowicz et al. (2016), Luderer et al. (2016a), Muratori et al. (2016), Vaughan and Gough (2016), Bauer et al. (2017), Calvin et al. (2017), Fujimori et al. (2017), Gambhir et al. (2017), Kriegler et al. (2017), Marcucci et al. (2017), Mintenig et al. (2017), van Vuuren et al. (2017), Akimoto et al. (2018), Bertram et al. (2018), Holz et al. (2018), Lehtilä and Koljonen (2018), Méjean et al. (2018), Mousavi et al. (2018), Obersteiner et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Tanaka and O'Neill (2018), van Vuuren et al. (2018), Vaughan et al. (2018), Winning et al. (2018)
Mitigation pathway dynamics	D4	Compensate	NETs can compensate for past and current GHG emissions. From a sectoral viewpoint it can offset emissions that arise from sectors and activities that are difficult to decarbonize, e.g. aviation. From a regional perspective, one or several regions can offset emissions from other regions. From a GHG emission point of view, it can offset non-CO2 emissions (e.g. CH4 from agriculture).		38	Azar et al. (2006), Luckow et al. (2010), Lemoine et al. (2012), Chen and Tavoni et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Blanford et al. (2014b), Humpenöder et al. (2014), Klein et al. (2014), Kober et al. (2014), Koelbl et al. (2014), Kriegler et al. (2014), Selosse and Ricci (2014), van der Zwaan et al. (2013), Bosetti et al. (2015), Eom et al. (2015), Sanchez et al. (2015), Luderer et al. (2016a), Luderer et al. (2016b), Kriegler et al. (2017), Manoussi et al. (2017), Marcucci et al.

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
						(2017), Mintenig et al. (2017), van Vuuren et al. (2017), Akimoto et al. (2018), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Kober et al. (2018), Luderer et al. (2018), Méjean et al. (2018), Mousavi et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Séférian et al. (2018), Su et al. (2018), van Vuuren et al. (2018), Vaughan et al. (2018)
Mitigation pathway dynamics	D5	Prolong_fossil_fuels_use	By redirecting investments from low-carbon technologies to fossil fuel technologies, the availability and use of NETs allow the prolonged use of fossil fuels. Conversely, reducing the availability and use of NETs increase the number of stranded assets in the fossil fuel sector and requires a greater deployment of low-carbon technologies.		30	Azar et al. (2006), Sohngen and Sedjo (2006), Krey and Riahi (2009), van Vliet et al. (2009), Luckow et al. (2010), Lemoine et al. (2012), Ricci (2012), Chen and Tavoni et al. (2013), Fuss et al. (2013), Kriegler et al. (2013a), Bibas and Méjean (2014), Blanford et al. (2014a), Blanford et al. (2014b), Kanudia et al. (2014), Klein et al. (2014), Krey et al. (2014), Kriegler et al. (2014), Rose et al. (2014a), Riahi et al. (2015), Sanchez et al. (2015), Bauer et al. (2016), Muratori et al. (2016), Calvin et al. (2017), Kriegler et al. (2017), Marcucci et al. (2017), Mintenig et al. (2017), van Vuuren et al. (2017), Luderer et al. (2018), Séférian et al. (2018), Winning et al. (2018)
Mitigation pathway dynamics	D6	Flexibility	NETs allow for a greater flexibility in the timing of mitigation policies.	Figure 1a2	25	Obersteiner et al. (2002), Azar et al. (2006), Sohngen and Sedjo (2006), Krey and Riahi (2009), van Vliet et al. (2009), Azar et al. (2010), Lemoine et al. (2012), Blanford et al. (2014a), Blanford et al. (2014b), Klein et al. (2014), Krey et al. (2014), Kriegler et al. (2014), McCollum et al. (2014), Rose et al. (2014a), Selosse and Ricci (2014), Tavoni et al. (2013), Bertram et al. (2015), Bosetti et al. (2015), Eom et al. (2015), Riahi et al. (2015), Marcucci et al. (2017), Mintenig et al. (2017), van Vuuren et al. (2017), Bertram et al. (2018), Vaughan et al. (2018)
Mitigation pathway dynamics	D7	Regional_distribution	The regional distribution of NET deployment vary greatly across models, depending on modelling assumptions (e.g. regional baselines, regional abatement potentials, available technology options, techno-economic parameters) and model	Figure 3	25	Sohngen and Sedjo (2006), van Vuuren et al. (2006), Tavoni et al. (2007), Strengers et al. (2008), Calvin et al. (2009), Krey and Riahi (2009), Leimbach et al. (2010), Chen and Tavoni et al. (2013), Tavoni and Socolow (2013), Calvin et al.

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
			structures. Regions well-endowed with biomass and/or geological storage have a competitive advantage over others. Consequently, afforestation/reforestation is mostly carried out in tropical regions (Africa, Latin America). BECCS is mainly deployed in China, Europe, USA. DAC is mostly used in regions with large storage potentials like Middle East, North Africa, Russia. Limits on geological storage strongly affect these results.			(2014), Humpenöder et al. (2014), Kober et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), Tavoni et al. (2013), van Sluisveld et al. (2013), Eom et al. (2015), Leibowicz et al. (2016), Mouratiadou et al. (2016), Calvin et al. (2017), Marcucci et al. (2017), Tavoni et al. (2017), Sanchez et al. (2018), Séférian et al. (2018), Vaughan et al. (2018)
Mitigation pathway dynamics	D8	CO2_emission_reduction	Gross CO2 emission reductions rates have been scarcely reported in the past but remain central to climate action. Mid-term gross CO2 emission reduction rates envisaged in scenarios have no historical precedence. When NETs are unavailable, emission reductions must occur earlier and more rapidly over the century. Conversely, when NETs are available, emission reductions are postponed. Current national climate actions (NDCs) remain insufficient to satisfy the climate targets of the PA without a high dependency on NETs.		22	Luckow et al. (2010), Lemoine et al. (2012), van Vuuren et al. (2013), Kriegler et al. (2014), Eom et al. (2015), Iyer et al. (2015), Kriegler et al. (2015c, 2016), Luderer et al. (2016a), Luderer et al. (2016b), Mintenig et al. (2017), van Vuuren et al. (2017), Bertram et al. (2018), Grubler et al. (2018), Holz et al. (2018), Luderer et al. (2018), Mousavi et al. (2018), Rogelj et al. (2018a, b), Séférian et al. (2018), Strefler et al. (2018), van Vuuren et al. (2018), Winning et al. (2018)
Mitigation pathway dynamics	D9	Postpone_CO2_abatement	The anticipated availability and use of NETs can be used as a reason to postpone near-term climate action.		18	Azar et al. (2006), Krey and Riahi (2009), van Vliet et al. (2009), Lemoine et al. (2012), Azar et al. (2013), Chen and Tavoni et al. (2013), Fuss et al. (2013), Tavoni and Socolow (2013), van Vuuren et al. (2013), Klein et al. (2014), Kriegler et al. (2014), Selosse and Ricci (2014), Luderer et al. (2016a), Marcucci et al. (2017), Mintenig et al. (2017), van Vuuren et al. (2017), Holz et al. (2018), Luderer et al. (2018)
Mitigation pathway dynamics	D10	Bioenergy	Bioenergy is not only used in BECCS. It is a standalone low-carbon energy option that is cost-effective in ambitious climate scenarios. It is particularly attractive in the transportation sector where it provides the only cost-effective alternative to oil. Consequently, without limits on its production and irrespective of the deployment of BECCS, bioenergy is greatly used in 1.5 °C and 2 °C scenarios.		14	Obersteiner et al. (2002), Luckow et al. (2010), Klein et al. (2011), Kriegler et al. (2013a), Bibas and Méjean (2014), Popp et al. (2014), Selosse and Ricci (2014), Daioglou et al. (2015), Bauer et al. (2017), Mintenig et al. (2017), Popp et al. (2017), van Vuuren et al. (2017), Luderer et al. (2018), Séférian et al. (2018)

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Mitigation pathway dynamics	D11	Carbon_budget	The availability and use of NETs effectively increase the available carbon budget. This is because NETs can offset CO2 emissions, thus allowing for a temporary overshoot of the carbon budget in the near-term and removal of excess carbon later. Under a continuation of current socio-economic trends, this offset amounts to hundreds of GtCO2 in 1.5C and 2C scenarios.		13	Azar et al. (2006), Klein et al. (2011), van Vuuren et al. (2013), Koelbl et al. (2014), Luderer et al. (2016b), Manoussi et al. (2017), Mintenig et al. (2017), Tavoni et al. (2017), Holz et al. (2018), Kober et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Rickels et al. (2018)
Mitigation costs	C1	Lower_costs	The availability and use of NET lower carbon prices and so decrease aggregated discounted mitigation costs. Any techno-economic limitations of NETs would result in an increase of mitigation costs (e.g. biomass limitations for BECCS)	Table 2	48	Obersteiner et al. (2002), Azar et al. (2006), Rao and Riahi (2006), Tavoni et al. (2007), van Vuuren et al. (2007), Keller et al. (2008), Clarke et al. (2009), Krey and Riahi (2009), van Vliet et al. (2009), Wise et al. (2009), Azar et al. (2010), Leimbach et al. (2010), Lemoine et al. (2012), Ricci (2012), Azar et al. (2013), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Klein et al. (2014), Koelbl et al. (2014), Krey et al. (2014), Kriegler et al. (2014), Rose et al. (2014a), Selosse and Ricci (2014), van Vliet et al. (2014), Bosetti et al. (2015), Eom et al. (2015), Iyer et al. (2015), Sanchez et al. (2015), Kreidenweis et al. (2016), Muratori et al. (2016), Vaughan and Gough (2016), Deng et al. (2017), Gambhir et al. (2017), Marcucci et al. (2017), Mintenig et al. (2017), Su et al. (2017), Bertram et al. (2018), Luderer et al. (2018), Mori et al. (2018), Séférian et al. (2018), Strefler et al. (2018), van Vuuren et al. (2018), Winning et al. (2018)
Mitigation costs	C2	High_carbon_price	Compared to other mitigation technologies, BECCS is a relatively costly option. Hence it requires a high carbon price (> US$100) for upscaling.		37	Azar et al. (2001), Obersteiner et al. (2002), Azar et al. (2003), Makihira et al. (2003), Azar et al. (2006), Keith et al. (2006), Sohngen and Sedjo (2006), van Vuuren et al. (2007), Canadell and Raupach (2008), Strengers et al. (2008), Calvin et al. (2009, b), Clarke et al. (2009), Krey and Riahi (2009), Luckow et al. (2010), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Tavoni and Socolow (2013), van

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
						Vuuren et al. (2013), Humpenöder et al. (2014), Klein et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), van Vliet et al. (2014), Yamamoto et al. (2014), Daioglou et al. (2015), Kriegler et al. (2015a), Kreidenweis et al. (2016), Muratori et al. (2016), Vaughan and Gough (2016), Favero et al. (2017), Fricko et al. (2017), Gambhir et al. (2017), Marcucci et al. (2017), Luderer et al. (2018), Sanchez et al. (2018), Séférian et al. (2018)
Technology specific	T1	Potential	Scenarios allow to explore the cost-effective potential of NETs. Studies show that AR, BECCS and DACCS can capture hundreds of GtCO2 over the 21st, the annual removal rate of AR is around 0–10 GtCO2/yr. whereas that of BECCS and DACCS is around 0–20 GtCO2/yr. However a number of environmental, governance, legal, political and social challenges could reduce these potentials.	Figure 3	50	Schlamadinger et al. (2001), Azar et al. (2003), Makihira et al. (2003), Manne and Richels (2006), Rao and Riahi (2006), Sohngen and Sedjo (2006), van Vuuren et al. (2006), van Vuuren et al. (2007), Canadell and Raupach (2008), Strengers et al. (2008), Krey and Riahi (2009), Klein et al. (2011), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Tavoni and Socolow (2013), van Vuuren et al. (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Calvin et al. (2014), Humpenöder et al. (2014), Klein et al. (2014), Kriegler et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), van der Zwaan et al. (2013), Daioglou et al. (2015), Kriegler et al. (2015a), Fujimori et al. (2016), Kreidenweis et al. (2016), Leibowicz et al. (2016), Vaughan and Gough (2016), Favero et al. (2017), Fujimori et al. (2017), Mintenig et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Kober et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Rickels et al. (2018), Sanchez et al. (2018), Séférian et al. (2018), Strefler et al. (2018), van Vuuren et al. (2018), Winning et al. (2018)
Technology specific	T3	Food_price	The deployment of BECCS increases food prices due to land competition between energy and food biomass feedstocks. However food prices would still be high without BECCS because other		26	Riahi et al. (2007), Azar et al. (2010), Azar et al. (2013), Edmonds et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Calvin

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
			bioenergy-based mitigation technologies would increase in importance.			et al. (2014), Klein et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), Kreidenweis et al. (2016), Muratori et al. (2016), Vaughan and Gough (2016), Favero et al. (2017), Mintenig et al. (2017), Popp et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Bertram et al. (2018), Emori and Takahashi (2018), Obersteiner et al. (2018), Séférian et al. (2018), van Vuuren et al. (2018), Yamagata et al. (2018)
Technology specific	T5	BECCS_Versatile	BECCS is a versatile technology that can generate a variety of energy types (e.g. electricity, synthetic liquid fuels, hydrogen) from diverse biomass feedstocks (e.g. crops, grass, wood).		13	Obersteiner et al. (2002), Azar et al. (2003), Riahi et al. (2007), Azar et al. (2010), Klein et al. (2011), Humpenöder et al. (2014), Klein et al. (2014), Rose et al. (2014a), Fujimori et al. (2016), Muratori et al. (2016), Bauer et al. (2017), Mintenig et al. (2017), Vaughan et al. (2018)
Technology specific	T9	Technological_c-hange	Technological change is crucial to any technology and will be needed to push NETs to the commercial stage. This process could take decades and could be hampered if diffusion in developing regions follows past trends.		7	Azar et al. (2001), Makihira et al. (2003), Rao and Riahi (2006), Luckow et al. (2010), Lemoine et al. (2012), Leibowicz et al. (2016), van Vuuren et al. (2017)
Earth System/NET interactions	E1	Environmental_i-mpacts	The large-scale deployment of NETs will impact the environment. This is particularly true for land-based CDR which strongly interacts with a number of environmental factors (e.g. air, natural ecosystems, soils, water bodies). The large-scale deployment of AR and BECCS could lead to biodiversity and natural ecosystems loss, increased eutrophication resulting from fertilisation with nitrogen, water shortages, and a variety of climate impacts and feedbacks.		38	Obersteiner et al. (2001), Schlamadinger et al. (2001), Sohngen and Sedjo (2006), Tavoni et al. (2007), Canadell and Raupach (2008), Keller et al. (2008), Luckow et al. (2010), Chen and Tavoni et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Calvin et al. (2014), Calvin et al. (2014), Humpenöder et al. (2014), Popp et al. (2014), Sands et al. (2014), Selosse and Ricci (2014), Fujimori et al. (2016), Kreidenweis et al. (2016), Vaughan and Gough (2016), Manoussi et al. (2017), Mintenig et al. (2017), Popp et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Obersteiner et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Séférian et al. (2018), Strefler et al. (2018), van Vuuren et al. (2018),

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
						Vaughan et al. (2018)
Earth System/NET interactions	E3	Climate_feedbacks	CDR could lead to different climate dynamics than with GHG emission reductions because negative emissions would drive the climate system in a different direction. In addition CDR induces a number of negative feedbacks such as changes in precipitation patterns, ocean outgassing. Ocean outgassing, that is the release of CO2 from the oceans back to the atmosphere, would reduce the effectiveness of CDR but would decrease ocean acidification.		10	Chen and Tavoni et al. (2013), Fuss et al. (2013), Tavoni and Socolow (2013), van Vuuren et al. (2013), Blanford et al. (2014b), Manoussi et al. (2017), Tavoni et al. (2017), Keller et al. (2018), Obersteiner et al. (2018), Rickels et al. (2018)
Earth System/NET interactions	E4	Tipping_points	Temperature overshoot associated with NET deployments increasing the risks of triggering climate tipping points. High temperature overshoot decreases the probability of meeting climate targets.		8	Azar et al. (2006), Lemoine et al. (2012), Tavoni and Socolow (2013), Blanford et al. (2014a), Mintenig et al. (2017), Heck et al. (2018), Obersteiner et al. (2018), Strefler et al. (2018)
Earth System/NET interactions	E6	Climate_impacts	Climate change could impact NETs thereby reducing their effectiveness. In a warming climate the increased risks of droughts and fires could limit the potential of land-based CDR such as afforestation and BECCS.		5	Vaughan and Gough (2016), Favero et al. (2017), Popp et al. (2017), Keller et al. (2018), Lehtilä and Koljonen (2018)
Earth System/NET interactions	E7	Carbon_cycle	The carbon cycle is a complex dynamic system that needs to be accounted for in IAMs. The lifetime of CO2 in the atmosphere has an effect on the optimal level of deployment of NETs.		4	Azar et al. (2006), Blanford et al. (2014b), Keller et al. (2018), Rickels et al. (2018)
Earth System/NET interactions	E10	Substitution_effect	There is a substitution effect between emission reduction and CDR, and the extra CDR required to compensate for carbon cycle feedbacks.		1	Rickels et al. (2018)
Others	O1	Important	NETs are often reported important technological options for stringent climate goals such as the temperature goals of the Paris Agreement (i.e. 1.5 °C, well-below 2 °C). The reasons are: effectiveness of reaching these targets and lower mitigation costs.		79	Azar et al. (2001), Obersteiner et al. (2002), Azar et al. (2006), Rao and Riahi (2006), Sohngen and Sedjo (2006), Riahi et al. (2007), Tavoni et al. (2007), van Vuuren et al. (2007), Blanford et al. (2009), Clarke et al. (2009), Krey and Riahi (2009), van Vliet et al. (2009), Azar et al. (2010), Edenhofer et al. (2010), Leimbach et al. (2010), Luckow et al. (2010), Klein et al. (2011), Lemoine et al. (2012), Azar et al. (2013), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Kriegler et al. (2013a), Luderer et al. (2013), Tavoni and Socolow

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
						(2013), Bibas and Méjean (2014), Calvin et al. (2014), Griffin et al. (2014), Humpenöder et al. (2014), Johnson et al. (2014), Klein et al. (2014), Koelbl et al. (2014), Krey et al. (2014), Kriegler et al. (2014), Luderer et al. (2014), McCollum et al. (2014), Popp et al. (2014), Rose et al. (2014a), Sands et al. (2014), Selosse and Ricci (2014), van der Zwaan et al. (2013), van Sluisveld et al. (2013), van Vliet et al. (2014), Bertram et al. (2015), Bosetti et al. (2015), Daioglou et al. (2015), Eom et al. (2015), Calvin et al. (2016a), Kreidenweis et al. (2016), Leibowicz et al. (2016), Luderer et al. (2016b), Vaughan and Gough (2016), Favero et al. (2017), Manoussi et al. (2017), Marcucci et al. (2017), Mintenig et al. (2017), Popp et al. (2017), Riahi et al. (2017), Selosse and Ricci (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Akimoto et al. (2018), Bertram et al. (2018), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Méjean et al. (2018), Mori et al. (2018), Mousavi et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Sanchez et al. (2018), Séférian et al. (2018), Strefler et al. (2018), van Vuuren et al. (2018), Vaughan et al. (2018), Winning et al. (2018)
Others	O2	Risk	Planning for large-scale NET deployment while postponing near-term GHG abatement, as in most 2C scenarios showed in AR5 could turn out to be an ineffective tool for reducing climate risk. The associated overshoot in GHG concentration (and perhaps temperature) would increase the risk of not meeting the PA targets and potentially lead to climate change irreversibility. This is all the more relevant given the large dependence envisaged in these scenarios. From a socio-economic perspective, NETs add another layer of risks by increasing competition for land, water, energy and financial resources.		26	Obersteiner et al. (2002), Azar et al. (2006), Lemoine et al. (2012), Ricci (2012), Chen and Tavoni et al. (2013), Fuss et al. (2013), Tavoni and Socolow (2013), Blanford et al. (2014a), Klein et al. (2014), Krey et al. (2014), McCollum et al. (2014), Riahi et al. (2015), Vaughan and Gough (2016), Mintenig et al. (2017), van Vuuren et al. (2017), Bertram et al. (2018), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Méjean et al. (2018), Mousavi et al. (2018), Obersteiner et al. (2018), Sanchez et al. (2018), Strefler et al. (2018)

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Others	O3	Uncertainty	NETs are subject to many uncertainties. These include uncertainties in the climate stabilisation targets and climate sensitivity, uncertainties in CDR potentials (including storage capacity and bioenergy), costs and side-effects, uncertainties in environmental constraints, carbon-climate system feedbacks, economic impacts and legal issues′.		24	Obersteiner et al. (2002), Azar et al. (2006), Fuss et al. (2013), Tavoni and Socolow (2013), van Vuuren et al. (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Klein et al. (2014), Kriegler et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), van der Zwaan et al. (2013), Mintenig et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Akimoto et al. (2018), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Lehtilä and Koljonen (2018), Mousavi et al. (2018), Rickels et al. (2018), Sanchez et al. (2018), Strefler et al. (2018)
Others	O4	Challenges	The deployment of NETs is subject to a wide array of challenges, which can be technology specific. These include: NET upscaling, governance, political, policy, legal and finance aspects, social acceptance, food security, technological limits, reservoir leakage, environmental impacts, and climate and carbon cycle feedbacks.		23	Canadell and Raupach (2008), Strengers et al. (2008), Edmonds et al. (2013), Fuss et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Kriegler et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), Vaughan and Gough (2016), Gambhir et al. (2017), Marcucci et al. (2017), Mintenig et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Holz et al. (2018), Obersteiner et al. (2018), Sanchez et al. (2018), Séférian et al. (2018), Strefler et al. (2018), Vaughan et al. (2018)
Others	O7	Sustainability	The large-scale deployment of NETs might not be compatible with the Sustainable Development Goals. Strategies for NET deployment should include sustainability criteria (e.g. sustainable production of biomass).		14	Obersteiner et al. (2001), Obersteiner et al. (2002), Riahi et al. (2007), Ricci (2012), Fuss et al. (2013), Kriegler et al. (2013a), Bibas and Méjean (2014), Calvin et al. (2014), Mintenig et al. (2017), Grubler et al. (2018), Lehtilä and Koljonen (2018), Mousavi et al. (2018), Obersteiner et al. (2018), Sanchez et al. (2018)
Others	O8	MultiNETs	When multiple NETs are available, they are deployed by cost order, the low cost technology options coming first (e.g. afforestation, then BECCS and then DACCS). Their deployment can also be affected by if they compete for scarce resources (e.g. land for AR and BECCS, geological storage for BECCS and DACCS).	Figure 2	12	Chen and Tavoni et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Humpenöder et al. (2014), Popp et al. (2014), Kreidenweis et al. (2016), Favero et al. (2017), Marcucci et al. (2017), Popp et al. (2017), Lehtilä and Koljonen (2018), Rogelj et al. (2018a, b), Winning et al. (2018)
Others	O11	Discount_rate	The discount rate, which usual value is 5%, plays an important role in the timing and scale of GHG		9	Sohngen and Sedjo (2006), van Vliet et al. (2009), Lemoine et al. (2012), Chen and Tavoni et al.

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
			emission abatement and NET deployment. When this value is decreased, more GHG emissions are abated in the near-term and less NETs are deployed.			(2013), Fuss et al. (2013), Tavoni and Socolow (2013), Humpenöder et al. (2014), van Vuuren et al. (2017), Obersteiner et al. (2018)
Others	O14	Correlation	A few correlations between global cumulative variables have been reported in the literature. For instance, the amount of radiative forcing overshoot is correlated with cumulative CDR over the century. There is also a relationship between carbon budgets and non-Kyoto forcing.		4	van Vuuren et al. (2013), Kriegler et al. (2014), Rose et al. (2014b), Tavoni et al. (2017)
Others	O15	Warning	Modellers have been cautiously describing the result of introducing NETs in their models. They warn against the direction application of these scenarios which would obstruct near-term mitigation action and could turn out to be a brittle strategy.		3	Azar et al. (2006), Blanford et al. (2014a), Holz et al. (2018)

2050 occurs faster (0.3 [0.0–0.6] $GtCO_2$/year versus 0.2 [0.0–0.4] $GtCO_2$/year expansion[4]) unless climate policy is delayed until 2030 in 2 °C scenarios (Fig. 1a3, b2) D1. In fact, once climate action is delayed until 2030, the negative emissions characteristics of 2 °C scenarios become increasingly similar to the 1.5 °C scenarios with immediate action. It is worthwhile to note that this difference in NET reliance between 1.5 and 2 °C scenarios is predicated on estimates of the climate response that remain similar to the value assessed in AR5, despite recent studies showing the potential for possible changes to climate response (Millar et al. 2017; Tokarska and Gillett 2018).

The prominence of NETs in stringent climate mitigation scenarios is the product of two factors: geophysical requirements and economic incentives, which play very different roles in 1.5 °C and 2 °C scenarios (Minx et al. 2018). As indicated earlier, while carbon dioxide removal deployment in 1.5 °C scenarios is primarily driven by geophysical requirements —for compensating for the overshoot of the allowed carbon budget (Strefler et al. 2018; Kriegler et al. 2018b; Luderer et al. 2018)—this is not the case in 2 °C scenarios. Economic incentives however are an important feature of both 1.5 °C and 2 °C scenarios as depicted by mitigation costs in Table 2. Mitigation costs are a good indicator for understanding the overall mitigation challenge in IAMs: as mitigation costs increase as models move towards their infeasibility frontier (Azar et al. 2006; Luderer et al. 2013). Moving across the columns of Table 2 shows how mitigation costs rise: (a) as long-term ambition increases and (b) as short-term emission reductions get delayed until 2030. Looking across the columns shows the decrease in mitigation costs as NETs are introduced into the models C1 and how models are driven to infeasibility in their absence, as short-term emission reductions get further delayed and long-term ambition increases O11. No single IAM study documents pathways without NETs returning warming to below 1.5 °C by 2100, or limiting warming to well below 2 °C after a delaying action until 2030.

The lowering of mitigation costs resulting from the deployment of NETs has far reaching consequences on mitigation pathways D2. Indeed, regardless of any geophysical requirement, the introduction of NETs in IAM curb emission reductions in the short run and compensates for the carbon budget overshoot towards the end century when carbon prices are high (often reaching thousands of US dollars per ton of CO_2) D2, C2. For example, Fig. 1a2 demonstrates that, until 2060, median net CO_2 emissions in 2 °C scenarios with BECCS exceeds that of the median 2 °C scenario without BECCS. Consequently, this temporal reallocation of CO_2 emissions mitigation by NETs allow for more fossil fuel consumption in the near-term, thus leaving more time for the energy system transition, and a longer utilisation of existing infrastructure in the power, industry and building sectors D5.

Temporal discounting is the main factor driving these dynamics. Indeed, by giving a lower weight to the costs of future mitigation actions, the use of a constant discount rate (generally 5%) during the twenty-first century makes the use of NETs in the second half of the century an economically attractive mitigation option that allow costly near-term emissions reductions to be postponed (van Vuuren et al. 2017; Obersteiner et al. 2018) D9. From these results, it is often concluded that NETs make the timing of climate mitigation policies more flexible D6. Aware of the potential misinterpretation of these findings, modellers described the risks, uncertainties and challenges in following such pathways O2, O3, O4, and have warned policy makers against postponing near-term abatement action O14.

[4] Values preceding the brackets are medians while those in the brackets are minima and maxima.

By the end of the century, negative CO_2 emissions from NETs compensate for past and current residual CO_2 and non-CO_2 emissions D4. Residual CO_2 emissions can arise in the industry, buildings, transportation and land-use sectors and are a function of the ambition level of climate policy (Kriegler et al. 2018b; Luderer et al. 2018). They add to non-CO_2 greenhouse gas (GHG) emissions like CH_4, N_2O and F-Gases, which can represent a large share of total residual GHG emissions depending on the mitigation portfolio represented in models (Kober et al. 2014; Gernaat et al. 2015). When BECCS is available, the power sector is often reported to be essential for decarbonisation and to compensate for these residual emissions (van Sluisveld et al. 2013; Kriegler et al. 2013a). However, other sectors can in principle also contribute since BECCS is a versatile technology which can also be used to produce synthetic fuels, heat and hydrogen T5, O15.

Little attention has been given to portfolios of NETs in IAMs even though there is a growing number of studies that feature two or more NET options—most prominently BECCS and afforestation (AR) (Rao and Riahi 2006; Wise et al. 2009; Calvin et al. 2009a; Edmonds et al. 2013; Humpenöder et al. 2014; Bertram et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018), but also BECCS and direct air capture with carbon sequestration (DACCS) (Chen and Tavoni et al. 2013; Marcucci et al. 2017) or BECCS and enhanced weathering (EW) (Strefler et al. 2015). More recently, Holz et al. (2018) produced scenarios with 6 NETs (i.e. AR, BECCS, biochar, DACCS, EW, soil carbon management). There are a few noticeable findings from these studies O8. Compared to scenarios featuring only BECCS, the availability and use of one or more additional NETs makes emission reductions in the near term even less attractive and further reduces the political costs of achieving the same climate policy objective D9, C1. Indeed, any addition of negative emission potential in scenarios results in an increase in total cumulative CO_2 removal over the twenty-first century and further exacerbates the intertemporal trade-off explained in the previous paragraphs D4, D11. This increase in carbon removal occurs at decreasing rates because of substitution effects. Competition between NETs for land and/or geological storage reduces the individual potential of these technologies. For example, Humpenöder et al. (2014) who examine two land-based NETs (i.e. competing for scarce land) find that the amount of CO_2 sequestered by BECCS over the 1995–2095 period decreases from 600 to 400 $GtCO_2$ when AR is added. Marcucci et al. (2017) find a lower effect of only a few gigatonnes between BECCS and DACCS, which compete for geological storage (see Fig. 2). Holz et al. (2018) also show that the contribution from AR is halved when 5 other NETs are added. These findings suggest that the availability of multiple NETs may help to better balance the various technology risks that are often scale dependent (Fuss et al. 2018). The degree to which this risk can be hedged depends however on technological competition.

Finally, while several studies have eliminated doubts that geological CO_2 storage is a major limiting factor for NET deployment in 2 °C scenarios T1, this is less clear when NET deployment with geological CO_2 storage further increase—like in 1.5 °C scenarios and with the availability of additional NET options with geological storage like DACCS (Meinshausen et al. 2011; Dooley 2013; Edmonds et al. 2013; Tavoni and Socolow 2013; Vaughan and Gough 2016). Even though sequestration rate constraints can limit the amount of CO_2 that can be stored annually, a meta-analysis concludes that 3900 $GtCO_2$ are "practically"[5] available and

[5] In the geological CO_2 storage pyramid (Bachu et al. 2007), "practical" storage capacity is a subset of the "effective" capacity. It includes storage sites that meet additional criteria (i.e. technical, legal and regulatory, infrastructure and general economic barriers to CO_2 geological storage).

13,500 $GtCO_2$ are "effectively"[6] available for storing carbon in onshore and offshore saline aquifers, depleted oil and gas fields, and deep "unmineable" coal basins (Dooley 2013). In a follow-up IAM analysis, Edmonds et al. (2013) made the assumption that 7000 $GtCO_2$ of storage would be available globally. We compare the regional estimates of these two studies to the available 1.5 °C and 2 °C scenario data from the AMPERE (Kriegler et al. 2015b) and LIMITS (Kriegler et al. 2013b) projects (see Fig. 3). The geographical distribution of negative emissions reveals that BECCS is deployed globally (Calvin et al. 2009a; van Sluisveld et al. 2013; Edmonds et al. 2013) but particularly in regions with large biomass potential and/or large geological storage capacity such as USA, China, Former Soviet Union and Middle East D7. Interestingly, biomass trade allows regions without biomass but large geological storage like the Middle East to sequester carbon. This highlights the institutional challenges facing the large-scale deployment of BECCS. Technological change and financial requirements are also concerning particularly for developing countries[7] T9. Nonetheless large discrepancies exist not only in quantities of geological storage but also across model results. For instance, sequestered carbon in 2 °C scenarios can differ by more than 100 $GtCO_2$ in Africa, Europe, Former Soviet Union, India, Latin America, Middle East, USA and up to 200 $GtCO_2$ in China. These differences are much smaller in 1.5 °C scenarios because the results come from a single model. Differences can be attributed to model structures (e.g. general equilibrium model vs partial equilibrium model, regional resolution, etc.) and (regional) modelling assumptions (e.g. geological storage potential, biomass potential, etc.) which can be more or less optimistic about implementable potentials given political, institutional and social acceptance-related constraints O4. It should be noted that IAMs use different estimates of geological storage. For instance, geological storage constraints in Marcucci et al. (2017) are based on Hendriks et al. (2004) whereas estimates used in GCAM are based on Dooley (2013) and Edmonds et al. (2014). In IMAGE, upper limits on geological storage are also based on Hendriks et al. (2004) with updates from Koelbl (2016).

3 Discussion and outlook

IAMs have played a central role in expanding the research frontiers of NETs and helping to discover policy-relevant findings about these technologies. Yet, qualitative evidence so far has not been adequately aggregated into a traceable and updatable body of knowledge and has been disconnected from reviews of quantitative evidence based on large scenario ensembles. In this study, we close this gap by systematically reviewing individual findings in a thematic synthesis of the underlying literature (Boyatzis 1998; Guest et al. 2012) connecting them explicitly to the quantitative ensemble evidence. We argue that such synthesis that systematically connects qualitative and quantitative evidence has been missing so far and impeded a comprehensive and transparent assessment of the role of NETs in climate change mitigation in previous IPCC reports. As such, this paper can help to establish a comprehensive and traceable account of evidence for upcoming IPCC AR6 that can be easily updated.

Table 1 provides an overview of the findings identified during our review. We emphasise that one should not interpret any statement omitted in the previous section as less significant.

[6] Here, "effectively" refers to storage sites that satisfy a range of basic geological and engineering conditions which can be quantified with a fair degree of confidence

[7] The financial requirements of other climate change mitigation technologies in developing countries are also of great concern. This is the case for wind and solar capacities for instance (Hirth and Steckel 2016).

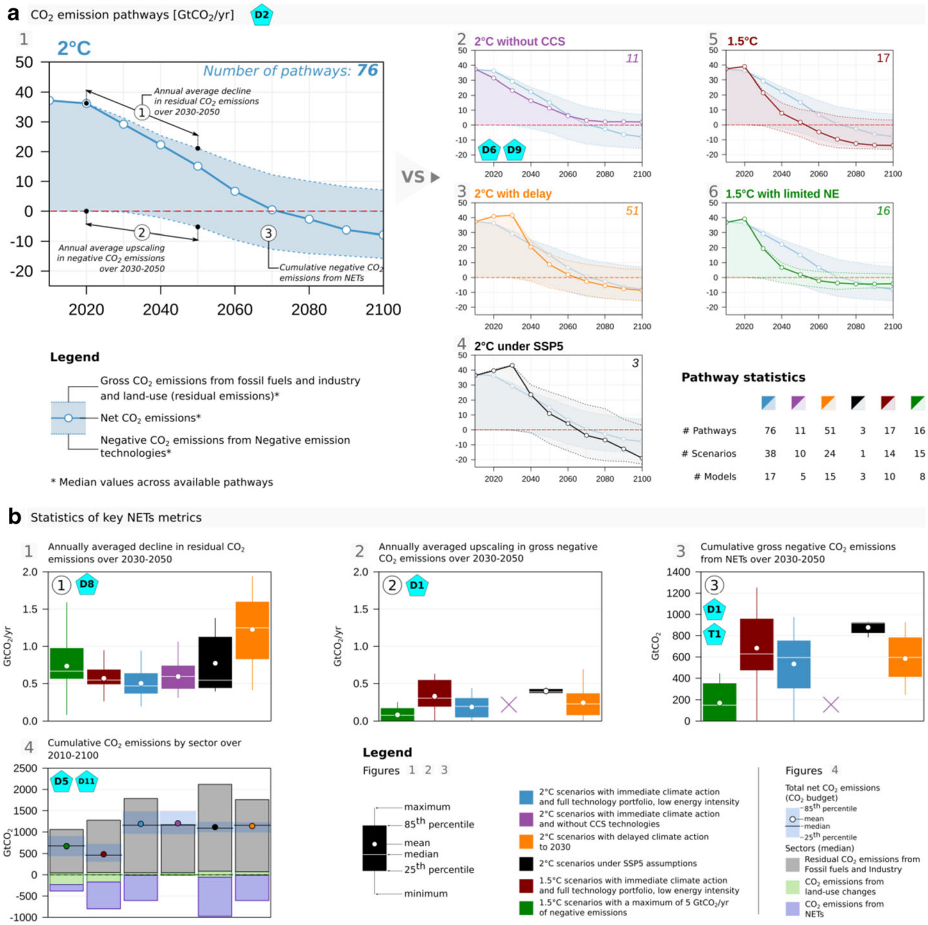

Fig. 1 The role of NETs in meeting international climate targets under various technological and policy constraints and societal choices. Part B shows key statistics. The number of pathways, models and scenarios are provided in Figure **1a**. The colour scheme used to differentiate scenario categories in Figures **1a** and **1b** are the same that is blue for 2 °C pathways with immediate action and full technology, purple for 2 °C pathways without CCS technology, orange for 2 °C pathways with delayed action to 2030, black for 2 °C pathways under SSP5 assumptions, red for 1.5 °C pathways with immediate action and full technology and green for 1.5 °C pathways with limited CDRavailability (< 5 $GtCO_2$/year). The cyan pentagons refer to the qualitative findings in Table 1

Instead we selected statements according to the focus of this review, i.e. the role of NETs in 1.5 °C and 2 °C scenarios, respectively. As such, it serves as a template for bridging qualitative and quantitative evidence systematically. For example, we did not discuss the role that BECCS can play in increasing food prices T3. Although the large-scale deployment of BECCS requires hundreds of millions of hectares to grow bioenergy T1, food prices would still be high in a world without BECCS because bioenergy would increase in importance as a mitigation technology[8] D10. Similar choices will be required in upcoming climate change assessments that are inherently space constrained. The key point here is that comprehensive, traceable accounts of both quantitative and qualitative evidence are required to do make informed and transparent choices in this process (Huppmann et al. 2018).

Table 2 The role of NETs in decreasing mitigation costs. Mitigation costs are the discounted sum of all costs associated with climate mitigation action over the period 2010–2100, calculated here for a 67% confidence level of limiting warming to below 2 °C (well below 2 °C case), or a 50% confidence level of limiting end of century warming to 1.5 °C by interpolating between respective scenarios. Red crosses indicate infeasible scenarios. Costs represent discounted and aggregated consumption losses (i.e. differences in consumption between a baseline and a climate policy scenario) as a share of discounted and aggregated GDP (in the climate policy scenario). A discount rate of 5% is used. Results adapted from Luderer et al. (2013)

Increasing long-term ambition →

Decreasing negative emissions potential ↓

	Well below 2°C		1.5°C	
	Decreasing short-term ambition →		*Decreasing short-term ambition →*	
Start of global climate action ▶	2010	2030	2010	2030
Unconstrained	1.44%	2.16%	2.26%	3.34%
Limited BECCS	1.90%	3.30%	4.10%	×
No BECCS	2.30%	×	×	×

Our approach could be extended in the future. First, it does not represent the entire universe of scenarios on climate change mitigation. A more comprehensive identification and selection of qualitative evidence based on a structured search in bibliographic databases such as Web of Science or Scopus could be a first step in addressing the longstanding concern of selection bias in IPCC assessments of scenario evidence (Haddaway and Macura, 2018). Second, although we are confident that our table of statements includes the major findings of the literature, our search could be extended to capture more peripheral topics (e.g. geological storage, food price). Third, our compiled scenario database contains important data gaps as all model output is not consistently made available publicly. This selection could introduce biases in our numerical results due to model and scenario design sampling. More comprehensive reporting and data provision requirements seem crucial. The qualitative findings presented here however are in good agreement with the list of major statements from the literature. Fourth, while our assessment can robustly identify and reflect insights from the available scenario literature on NETs, it is much harder to identify whether any pervasive scenario assumptions might bias these statements in a particular direction, and whether there are specific conditions under which these insights would apply.

Despite these shortcomings, synthetic research efforts within the scientific community like this study are increasingly valuable (Kowarsch et al. 2016, 2017), particularly in times of exponentially growing scientific publications on climate change (Grieneisen and Zhang 2011;

[0] The importance of bioenergy may decrease in future scenarios if the deployment of electric vehicles continues to gather momentum worldwide.

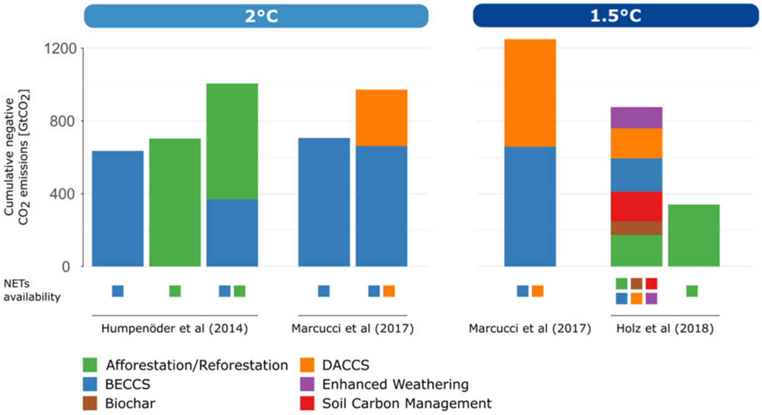

Fig. 2 The role of small NET portfolios in meeting the 1.5 °C and 2 °C climate goals. Each bar represents a scenario. NET availability is indicated by a small square below the bars. Data from Humpenöder et al. (2014) are cumulated over 1995–2095 while that of Marcucci et al. (2017) and Holz et al. (2018) are cumulated over 2010–2100

Haunschild et al. 2016; Minx et al. 2017b). Not engaging in such efforts could exacerbate the difficulty for assessment bodies like the IPCC to meet their often ambitious mandates (Minx et al. 2017a). While such computer-assisted synthetic methods (Westgate et al. 2018; Nakagawa et al. 2018; Lamb et al. 2019) still require laborious inputs from and verification by humans, it allows for a more efficient and better evaluation of the veracity of findings by linking them directly to supporting studies. It may also reduce the risk of bias and misinterpretations by policymakers, who would be in a better position to confront arguments based on cherry-picking and infrequently-made claims.

Importantly, this review allowed us to identify important research gaps, some of which have been underscored in Fuss et al. (2018) and Rogelj et al. (2018b). First, it seems

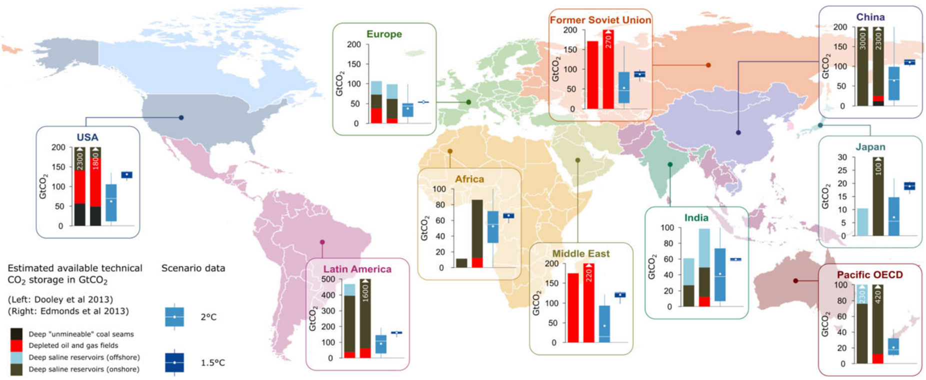

Fig. 3 Regional geological CO_2 storage capacity and CO_2 sequestered by BECCS. Geological CO_2 storage data correspond to the "practical" category from Dooley (2013) which totals 3900 $GtCO_2$ (left bar) and the modified version by Edmonds et al. (2013) which totals 7000 $GtCO_2$ (right bar). Scenario data are from AMPERE (Kriegler et al. 2015a, b, c), LIMITS (Kriegler et al. 2013a, 2013b), RoSE (Kriegler et al. 2016) and Luderer et al. (2013). Scenario data for Canada and Southeast Asia were missing and so could not be included here. Similarly 1.5 °C scenarios for the Pacific OECD region are unavailable

crucial to better understand large NET deployments frequently observed in the literature (Fuss et al. 2018; Rogelj et al. 2018b). Initial evidence suggests that this is directly related to the cost-effectiveness framework (and discount rate) underlying the models studied here, and that, even though CDR would also be large in a cost-risk analysis (Mintenig et al. 2017), a consideration of climate impacts in a cost-benefit mode would substantially decrease CDR deployments (Blanford 2013). Since climate impacts could also affect the potential of NETs, accounting for these effects in IAMs would allow identifying important trade-offs and provide additional insights on the optimal timing and levels of NETs (Rogelj et al. 2018b) E3, E4, E6, E7, E10. Second, as the wider discourse on NETs highlights that even some of the more modest deployment levels are unlikely to be reached with BECCS as a single NET, a deeper exploration of NET portfolios and their ability to hedge against some of the deployment risks are crucial O8. This would also require further exploring the adequacy of introducing NETs that have been neglected[9] by the IAM community so far (e.g. blue carbon) as well as the synergies and trade-offs between NETs. Third, considering and understanding what benefits, risks and societal trade-offs these options could provide would be important. A number of recent studies have also highlighted the potential role of non-CO_2 GHG removal technologies (Stolaroff et al. 2012; Lomax et al. 2015; Ming et al. 2016; de Richter et al. 2016, 2017). A large fraction of residual emissions at the end of the century come from non-CO_2 GHG, some of which are stock pollutants that accumulate in the atmosphere. For these species, GHG removal appears a promising avenue for future research. Fourth, not only do large-scale deployments of NETs impact regional economies, energy systems and carbon budgets but they can also lead to food price increases (Wise et al. 2009; Calvin et al. 2009a; Reilly et al. 2012; Kreidenweis et al. 2016), local air and water pollution, water overuse and biodiversity losses (Williamson 2016) T3, E1. Consequently, NETs should be examined under a broader spectrum of societal and environmental goals. To that end, Planetary Boundaries and Sustainable Development Goals provide useful frameworks for future research E8, O7. Finally, net negative CO_2 emissions, which could amount to a few tens of gigatonnes of CO_2 by the end of century when carbon prices are high, would require substantive and sustained support from financing bodies (e.g. governments) O4. In an intertemporal optimisation framework, this can be financed by a banking and borrowing scheme. However, whether such large-scale financing product could see the light in reality is unclear at the moment. Therefore, it would be essential to investigate the role of NETs in an intergenerational modelling framework and from a political and business perspective.

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[9] An exception is Holz et al. (2018)

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Affiliations

Jérôme Hilaire[1,2] • Jan C. Minx[1,3] • Max W. Callaghan[1] • Jae Edmonds[4] • Gunnar Luderer[2] • Gregory F. Nemet[5] • Joeri Rogelj[6,7,8] • Maria del Mar Zamora[1]

Jan C. Minx
minx@mcc-berlin.net

[1] Mercator Research Institute on Global Commons and Climate Change, Torgauer Straße 12-15, EUREF Campus #19, 10829 Berlin, Germany

[2] Member of the Leibniz Association, Postdam Institute for Climate Impact Research (PIK), Potsdam, Germany

[3] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

[4] Pacific Northwest National Laboratory – Joint Global Change Research Institute, 5825 University Research Court, College Park, MD 20740, USA

[5] La Follette School of Public Affairs, University of Wisconsin–Madison, 1225 Observatory Drive, Madison, WI 53706, USA

[6] ENE Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

[7] Grantham Institute for Climate Change and the Environment, Imperial College London, London SW7 2AZ, UK

[8] Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland