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(Mis)conceptions about modeling of negative emissions technologies

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LETTER

(Mis)conceptions about modeling of negative emissions technologies

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Abstract

Intentionally removing carbon from the atmosphere with negative emission technologies (NETs) will be important to achieve net-zero emissions by mid-century and to limit global warming to 2 °C or even 1.5 °C (IPCC 2018). Model scenarios that consider NETs as part of mitigation pathways are still largely restricted to afforestation and bioenergy with carbon capture and storage (BECCS), while the '[f]easibility and sustainability of [NETs] use could be enhanced by a portfolio of options deployed at substantial, but lesser scales, rather than a single option at very large scale' (IPCC 2018, p 19). Here, we show the results from an anonymous expert survey, including 32 Earth-System-Model (ESM) experts and 18 Integrated-Assessment-Model (IAM) experts, about the role of NETs in future climate policies and about how well the various technologies are represented in current models. We find that they strongly support the view that technology portfolios are required to achieve negative emissions, however, the responses show that the number and range of NETs that can be assessed in IAMs is small and that IAMs and ESMs are rather applied to analyze technologies separately than in combination. IAM experts in particular consider BECCS as part of a future NETs portfolio; but at the same time, all experts judge the constraints BECCS would face regarding future overall feasibility and more particularly regarding resource competition to be the highest. Regarding the assessment of constraints the ESM experts are much more skeptical than the IAM experts; they also think that the BECCS carbon removal pathways are less sufficiently represented in ESMs compared to what the IAM experts thinks about the representation in their models. Despite the perceived need for NETs portfolios, the range of NETs which can be assessed in IAMs is rather small and ocean NETs have, so far, mostly been overlooked by the IAM experts.

1. Introduction

Intentionally removing carbon from the atmosphere with negative emission technologies (NETs) will be important to achieve net-zero emissions by the middle of the century and to limit global warming to 2 °C or even 1.5 °C (IPCC 2018, Minx *et al* 2018, Strefler *et al* 2018, van Vuuren *et al* 2018). However, to what extent and when the various NETs will be utilized to complement emission reductions in future climate policies is still unclear. Recent assessment reports provided for example by the Royal Society (2018) or the National Academies of Sciences, Engineering, and Medicine (2018) discuss a broad set of potential technologies while current process-based Integrated Assessment Model (IAM) analyses predominantly restrict their attention to reforestation, afforestation and bioenergy with carbon capture and storage (BECCS) as part of the climate policies. Earth System Model (ESM) analyses on the other hand, still predominantly focus on stylized, large-scale scenarios. In scenarios for afforestation or ocean alkalinity management it is assumed that the entire Australian hinterland will be planted, that global forest will increase by 8 million km^2 (all 'marginal' land), or that alkaline minerals are utilized on the order of (or many

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magnitudes beyond) the global coal industry mining activities (Keller *et al* 2014, Sonntag *et al* 2018).

Both, ESM- and IAM-based analyses consider so far specific technologies rather in isolation and not as part of a broad portfolio of NETs. However, the implementation of portfolios of NETs (also over time, given the different saturation levels of different NETs) is considered to increase the feasibility, reduce the side-effects, and in turn improve the sustainability of carbon dioxide removal in climate policies compared to the large-scale application of a single technology (Fuss *et al* 2013, IPCC 2018). Whether or not either type of model can adequately simulate NETs singly or as a portfolio, even in idealized scenarios, is an important question. Simulating the climate and carbon cycle today, and in the recent past, where we have observations and can assess model performance, is challenging and we know that the representation of many key processes needs to be improved. When it comes to simulating NETs these difficulties may be exacerbated, potentially in unknown ways as we have never observed how the Earth system responds to intentional CO_2 removal. Our current understanding suggests that intentionally removing carbon from the atmosphere by enhancing natural carbon sinks, engineering new carbon sinks, or combining natural uptake with engineered one would not linearly extend the carbon budget because in an interacting carbon cycle their net contribution will be strongly influenced by feedbacks and saturation effects (Fuss *et al* 2014, Tokarska and Zickfeld 2015, Jones *et al* 2016, Keller *et al* 2018). Accordingly, an important question is how strong is the asymmetry between net carbon emissions and removal in an interacting carbon cycle under different removal deployment scales and under different climate and carbon concentration background conditions and how well are these accounted for the model-based assessment of NETs.

Here, we present the results from an anonymous expert survey, including 32 ESM experts and 18 IAM experts, designed to provide insights into (i) how important the two communities consider NETs for ambitious climate policies, (ii) what they consider as the main constraints for the various technologies, (iii) how well the various technologies are represented in their models, and (iv) what kind of (modeling) improvements and exchange is viewed necessary to come up with more realistic estimates for the future climate mitigation contribution of the various NETs.

The article is structured as follows. Section 2 explains the survey. Sections 3 and 4 present and discuss the results, respectively, before the article ends with some concluding remarks.

2. Methods

In an expert survey, we asked ESM and IAM experts about their conceptions of the future role of NETs, including questions related to factors constraining the feasibility of the technologies, and how well the various technologies are represented in current models. The survey ran from 22 November 2018 to 2 January 2019 and was an anonymous online questionnaire (that means we cannot link the responses to individual experts, but we have the information whether invited experts have responded). We invited 115 experts to the survey (USA: 29; Germany: 16; France 10; Japan: 8; UK: 8; Netherlands: 6; Canada: 5; Finland 5 and 28 further from Sweden, Austria, Switzerland, Norway, China, Italy, Greece, Spain, India and Australia). To assemble the invitation list, we identified the most common models (24 ESMs, 25 IAMs) and at least 2 experts per model. The specific IAMs and ESMs covered by in our invitation list can be found in the supplementary information A and the complete questionnaire in supplementary B, both available online at stacks.iop.org/ERL/14/104004/mmedia.

In the questionnaire, we first asked about the type of model respondents mainly use and which specific NETs can be assessed with this model. At this point IAM and ESM experts were filtered into similar but slightly different sets of questions about the representation of carbon removal pathways and carbon cycle feedbacks for five of the most commonly discussed NETs: artificial ocean alkalinization (AOA), afforestation (AF), enhanced weathering on land (EW), BECCS, and direct air capture of CO_2 with storage (DAC). Clearly, we could have included additional NETs, and in particular the prominent role of soil carbon sequestration in currently discussed NETs proposal would have also warranted its inclusion (Minx *et al* 2018). However, we decided to restrict the questions regarding the removal pathways to five technologies to keep the survey manageable for our time-constrained experts. Furthermore, we aimed for including a broad range of technologies which cover geological, terrestrial, and ocean carbon storage via chemical and biological reactions. As BECCS and AF have already similar pathways, we decided to include EW instead of soil carbon sequestration at this stage.

ESM experts answered the question for all five technologies, IAM experts only for the technologies that their model can assess. We also asked which factors need to be improved to obtain a better representation of the specific NET's removal pathway and (if applicable) the ocean carbon cycle response and the terrestrial carbon cycle response. We provided respondents with a schematic picture with the removal pathways and carbon cycle responses for each method (for the case of BECCS, see figure 1, the corresponding figures for the other NETs can be found supplementary information B).

In the final section ESM and IAM experts were asked the same question about the relevance of NETs for climate policy, in general and regarding specific NETs (i.e. which technology would you include in a portfolio). Here, we extended the NETs listed above by

soil carbon sequestration (SC), biochar (BC), artificial ocean upwelling (AOUp), ocean iron fertilization (OIF), and blue carbon (BLC) to have a more comprehensive coverage of technologies currently discussed (National Academies of Sciences, Engineering, and Medicine 2018, Royal Society 2018). Asking for all of these technologies about the representation of carbon removal pathways and carbon cycle feedbacks would have simply made the questionnaire too long. Furthermore, we believe that the selected five NETs listed above provide a sufficient representation of carbon cycle pathways and feedbacks affected by carbon dioxide removal. We also asked whether the respondents' models are capable of simulating NETs portfolios and concluded the questionnaire with a set of questions about the constraints for the deployment of specific NETs resulting from non-CO_2 forcing, climate feedbacks, environmental and human health side effects, resource competition, carbon cycle responses and feedbacks, physical CO_2 removal capacity, political feasibility (including acceptance), and cost effectiveness. Throughout the survey, the respondents had the opportunity to obtain information about the specific NETs and could in addition to selecting between options also give free-text answers.

The response rates of IAM experts was rather low compared to ESM experts (27%, i.e. 18 responses from 66 invitations compared 65%, i.e. 32 responses from 49 invitations). Furthermore, four IAM and nine ESM respondents dropped out at some point during the survey. We used the recorded answers of the drop-outs in the analysis as far as possible. Of the 18 IAM-respondents, 16 indicated that they use detailed process IAMs and 2 use benefit-cost IAMs. Of the 18 IAM-respondents, 5 indicated that they rely on impulse-response functions to represent the global carbon cycle in their model, 5 indicated that they rely on nonlinear box-type representations, 3 indicated that they rely on linear box-type representations, 2 indicated that they rely on combinations (of impulse response and (nonlinear) box-type representations, and 3 indicated 'do not know'.

Of the 32 ESM respondents, 22 indicated that they use ESMs of full complexity, 7 use ESMs of

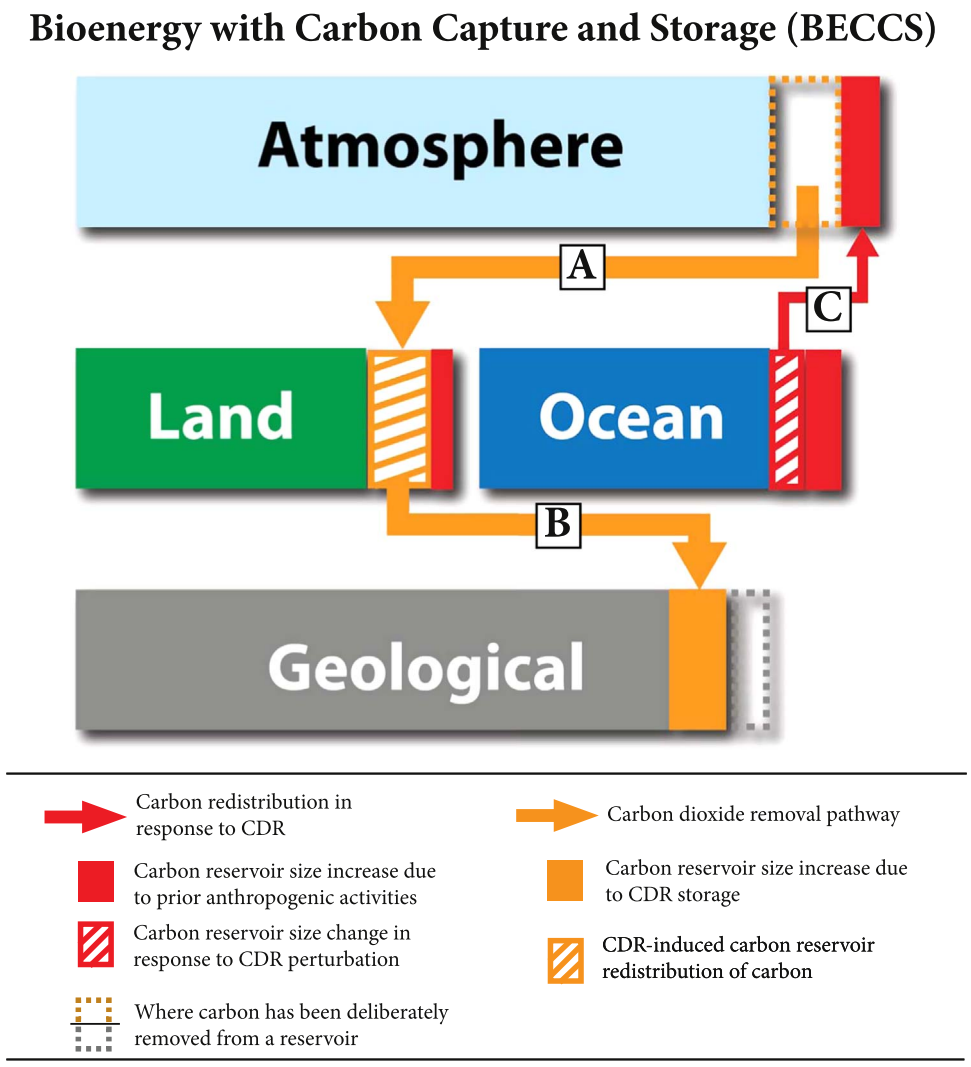

Figure 1. Carbon removal pathways with BECCS (based on Keller *et al* 2018). The figure was used in the survey to ask the experts how well their model accounts for the various pathways and fluxes when modeling BECCS.

intermediate complexity, 2 indicated that they use other models, and 1 indicated 'do not know'. Overall, 21 ESM experts indicated (with multiple answers allowed) that they research one or more components pertaining to the ocean (physics + biogeochemistry + sediments), 15 ESM experts indicate that they research one or more components pertaining to the atmosphere (physics + chemistry), 15 ESM experts indicate that they research the terrestrial biosphere. Table SI.A.T1 in supplementary information A provides further information about the field of research of ESM experts.

3. Results of expert assessment

3.1. Policy relevance of NETs

The majority of respondents strongly supported the view that negative emissions are essential for ambitious climate policy and they indicated that the contribution of NETs is expected to be achieved rather by a portfolio of technologies than by only one or two technologies (figure 2). IAM experts were slightly less pessimistic about conventional emission abatement as only 5 out of 14 IAM experts consider meeting the 2 °C-goal without NETs as very unlikely, compared to 17 out of 25 ESM experts (figure 2, panel (a)). Panel (b) in figure 2 shows that IAM- and ESM experts had similar conceptions of a future NETs portfolio (i.e. a NETs portfolio as part of the climate policy portfolio with mitigation, adaptation, and negative emissions), but it also shows that IAM experts favored land-based NETs, like AF, BECCS, DAC, and BC above ocean-based NETs. While ESM experts ranked the NETs similarly, they more often included ocean-based methods like BLC and AOA. The most striking differences between the two expert groups was observed for AOA: while only 8% of IAM experts ($N = 1$) included this technology, 48% of ESM experts ($N = 11$) indicated that increasing the alkalinity of the ocean should be part of a future NETs portfolio. In contrast, AOUp and OIF were rarely included (only 1 and 3, respectively, respondents included AOUp and OIF). Panel (c) shows that all experts but two actually chose a portfolio (i.e. two or more NETs), and the majority (mode of 8) included six different NETs.

3.2. Constraints for NETs

Experts assessed the extent to which eight different factors could constrain the application and feasibility of ten different NETs. Figure 3 shows the mean constraint ratings, differences in mean ratings between the ESM and the IAM experts, and knowledge gaps (via the share of 'do not know' answers). Across all NETs, experts considered removal efficiency (*physical removal capacity* and *cost effectiveness*) and *political feasibility* to be the strongest constraints. On a scale ranging from 0—no constraint, 1—weak constraint, 2—medium constraint, to 3—strong constraint, they indicated the most severe constraints for BECCS (overall mean, 1.75), which was mainly driven by *resource competition* (2.63), *cost effectiveness* (2.17), and *political feasibility* (2.13). In terms of mean constraints OIF and AOUp follow (1.68 and 1.67, respectively), however, both technologies did not receive support to be included in the future NETs portfolio (see figure 2). Disregarding these two technologies, BECCS is, in terms of severity of perceived constraints, followed by two other land-based NETS, EW and AF (with 1.54 and 1.53 mean assessments, respectively). EW was perceived to be most strongly constrained by efficiency, while AF, like BECCS, was perceived to be mainly constrained by *resource competition*. We found the lowest average constraints for DAC (1.23), SC (1.36), and BLC (1.37). The means for DAC were among the lowest for all constraints except *cost effectiveness*, which was perceived to be the strongest constraint for DAC (2.62). However, there is a considerable spread among experts assessments: only 2 out of 80 constraint-technology combination did not receive at least once the minimum constraint rating of 0 (AOUp and DAC have a minimum constraint rating of 1 in the constraints *carbon cycle responses and feedbacks* and *cost effectiveness*, respectively) and only 3 out 80 contraint-technology combination did not receive at least once the maximum constraint rating of 3 (AOUp, BLC, and OIF have a maximum constraint rating of 2 in the constraint *non-CO_2-forcing*).

In general, ESM experts perceived constraints to be stronger compared to IAM experts: they perceived only 7 out of 80 possible constraint-technology combinations as weaker compared to IAM experts, though these differences are very small in size and not associated with p-values below 0.15 (right panel in figure 3). Ignoring AOUp and OIF, the following three NETs constraints show the largest differences in mean assessments between ESM and IAM experts: *resource competition* on BLC ($\Delta\bar{x} = 1.44$; $p = 0.002$), *non-CO_2 forcing* on SC ($\Delta\bar{x} = 0.94$; $p = 0.010$), and *carbon cycle response and feedbacks* on BLC ($\Delta\bar{x} = 0.86$; $p = 0.035$). This is also partly reflected in the high overall differences for SC ($\Delta\bar{x} = 0.53$) and BLC ($\Delta\bar{x} = 0.54$).

The lower panels of figure 3 reflect knowledge gaps: they display the share of 'do not know'-answers. Two patterns emerge: first, the interaction with and effects on *non-CO_2-forcing* were indicated to be not well known, and second there were large knowledge gaps for ocean-based methods (especially BLC). Many IAM experts did not know about BLC in general and especially about its *physical removal potential*. Moreover, with respect to BLC and *resource competition*, their assessment appeared to be the opposite of what ESM experts indicated. Table SI.A.T2 in the supplementary information displays the number of responses for each constraint-technology combination.

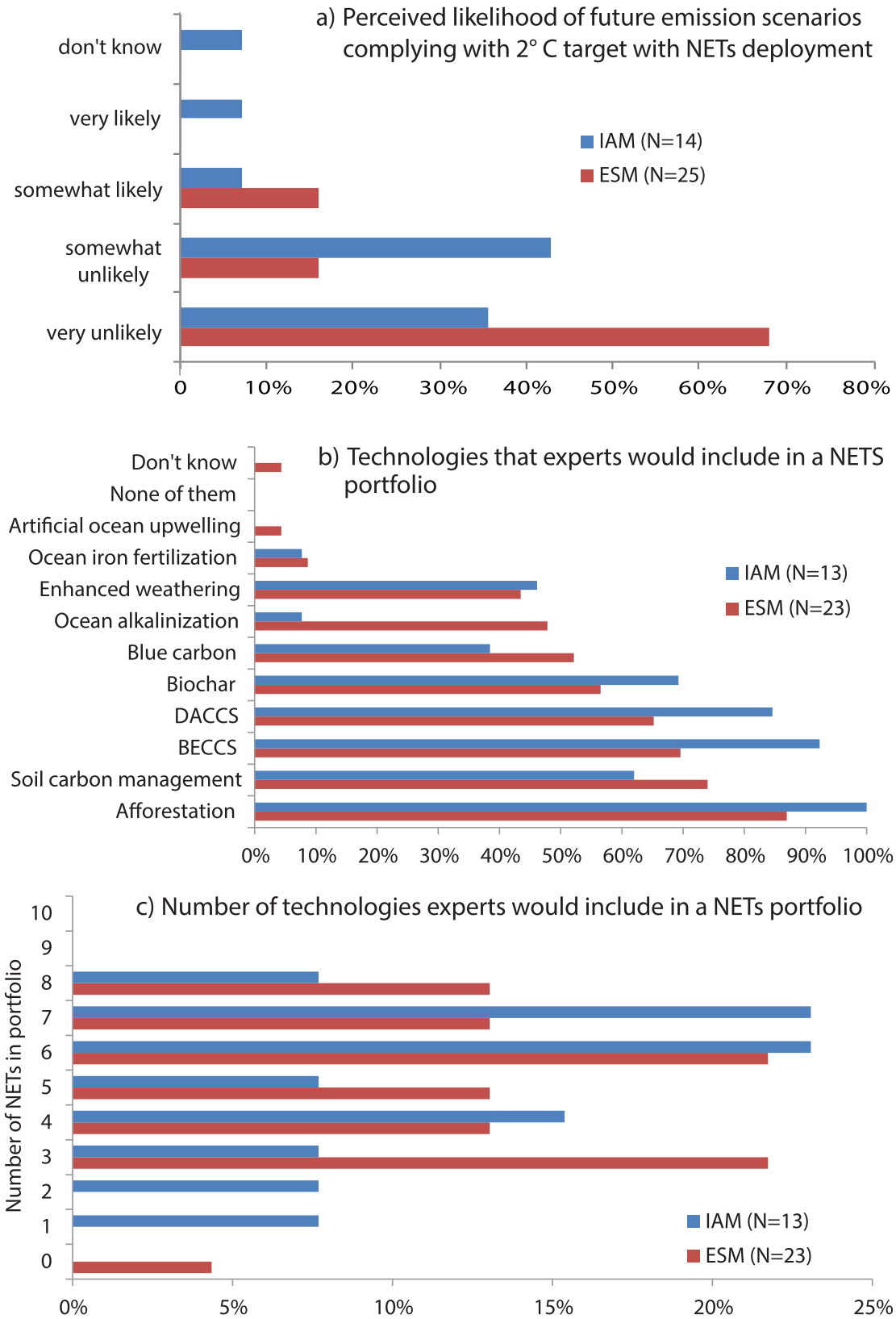

Figure 2. Policy relevance of NETs portfolios. Panel (a): perceived likelihood of future emission scenarios complying with the 2 °C target without NETs deployment, Panel (b): technologies that experts would include in a NETs portfolio, and Panel (c): number of technologies experts included in their preferred NETs portfolio.

3.3. Current capabilities of modeling NETs

Figure 4 summarizes the conceptions of the experts on modeling AOA, AF, EW, BECCS, and DAC in their own model. The experts were asked whether the removal pathways and carbon fluxes are *insufficiently*, *somewhat sufficiently*, or even *sufficiently* represented. However, IAMs usually apply simplified carbon-cycle and climate system representations, approximating

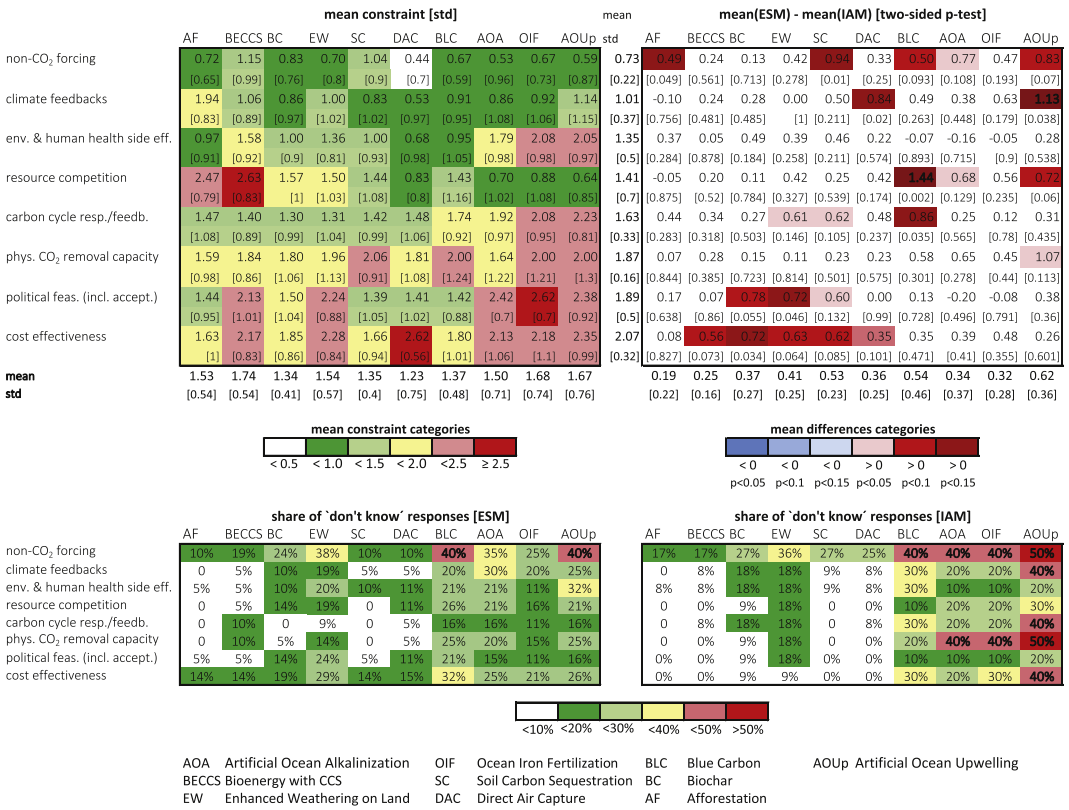

Figure 3. Constraints on the feasibility of NETs. The upper left panel displays the mean constraints (and standard deviation) of the assessment of all respondents (ranging from 0—no constraint, 1—weak constraint, 2—medium constraint, to 3—strong constraint). The upper right panel shows the difference (and *p*-values for a two-sided t-test) in mean constraint assessment between ESM and IAM experts with color coding for different *p*-values. The lower panel shows for both modeling communities the share of 'don't know' answers. High shares of 'do not know' also mean that mean values are based on only few observations, especially among the IAM experts.

various natural fluxes either with box-models or impulse-response functions, whereas ESMs aim at modeling these processes explicitly. Consequently, we applied two filters for the IAM experts. First, they were asked whether their model is capable at all to assess specific NETs and only those who indicated capability were asked about sufficiency. Most IAM experts indicated that their model can assess BECCS, AF, and DAC, only few can assess EW, and one can assess AOA. Second, they were asked whether their model account for the specific removal pathways and carbon fluxes *not-at-all*, *implicitly* or *explicitly*. Only those who indicated *implicitly* or *explicitly* were asked about the sufficiency. For the ESM experts we did not apply any filter and asked all ESM experts about the sufficiency of representation of the removal pathways.

Figure 4 confirms that ESM experts were much more skeptical about the representation of NETs in their models than the IAM experts. One exception is the atmosphere-to-ocean pathway for AOA. Here, the majority of ESM experts considered the pathways to be at least somewhat sufficiently represented in their model. Clearly, the overall numbers of responses from the IAM experts are low, allowing only an indicative interpretation. For example, there are only few responses for AOA ($N = 1$) and EW ($N = 3$) which indicates that the technologies are overall not well represented in IAMs. Furthermore, the models that can assess these technologies either do not include all pathways and responses or do not represent them sufficiently. Most interestingly is the comparison of the two communities for BECCS (which can be assessed by almost all IAMs in our survey).

While the majority of IAM experts indicated that the representation of removal pathways is sufficient, the ESM experts were much more pessimistic. Among them, 7 considered the atmosphere-to-terrestrial pathway insufficiently represented (out of 23) and 13 considered the terrestrial-to-geological pathway insufficiently represented (again out of 23). The stronger confidence in the capabilities of their own model among the IAM experts compared to ESM experts became also apparent in the question about modeling portfolios of NETs. While 70% of the IAM experts indicated that their model can simulate portfolios at least decently, only 50% of the ESM experts conceived their model to be capable of achieving this task at least decently (see figure SI.A.F1 in the supplementary material A).

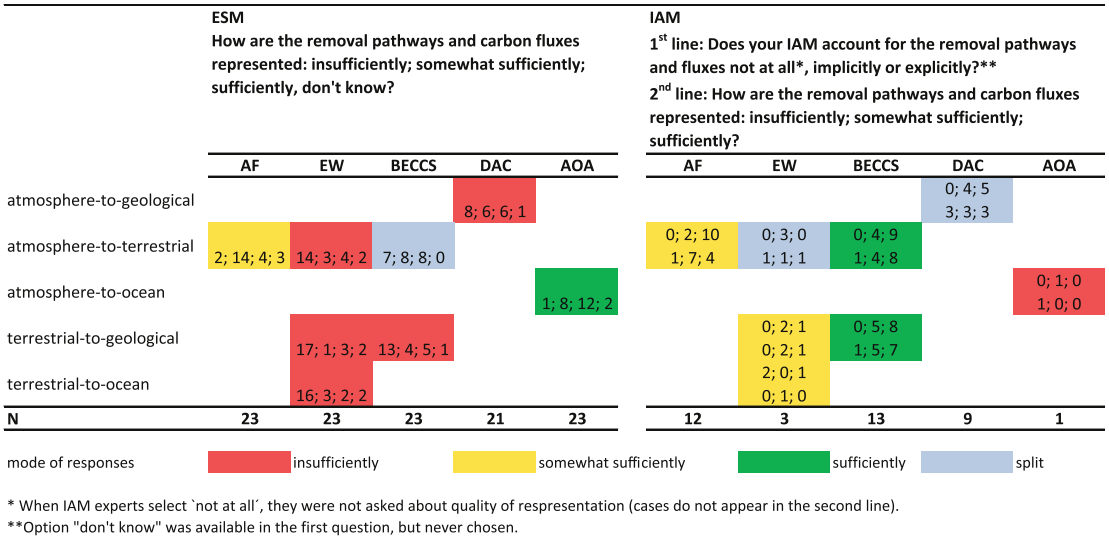

Figure 4. Conceptions about the representation of carbon removal pathways and fluxes in ESMs and IAMs. The left panel shows the number ESM experts assessing the removal pathways and carbon fluxes in their model to be insufficiently, somewhat sufficiently, or sufficiently represented, and the last number indicates the number of 'do not know' responses. The right panel shows the responses of the IAM experts, who initially indicated whether the removal pathway or carbon flux is not all, implicitly or explicitly represented in their model (first line). The option 'do not know' was available, but never chosen by IAM experts. When IAM experts answered the first question with 'not at all', they were not asked about the sufficiency of representation (second line).

Table 1. Factors requiring improvement to better simulate the terrestrial carbon cycle response to AOA and DAC.

	AOA		DAC	
	Mean	*N*	Mean	*N*
Disturbances (fires and pests)	1.59	22	1.67	18
Representation of land-use changes	1.77	22	1.79	19
Hydrology and inland waters	1.79	19	1.72	18
Permafrost	1.95	22	1.89	18
Vegetation representation	2.10	20	2.32	19
Soil carbon cycling	2.27	22	2.21	19
CO_2 fertilization parameterization	2.50	22	2.53	19

Note. 0 not at all important; 1 somewhat unimportant; 2 somewhat important; 3 very important (do not know option available).

3.4. Improvements required for modeling NETs

ESM experts indicated which factors need to be improved to better simulate the ocean or the terrestrial carbon cycle response for assessing specific NETs. More specifically, the experts were asked about factors related to the non-enhanced carbon reservoir(s), i.e. the one(s) that may lose carbon in response to prolonged net negative emissions (see Keller *et al* 2018). Accordingly, table 1 represents the mean assessment for AOA and DAC with respect to the terrestrial carbon response and table 2 represents the mean assessment for AF, EW, BECCS, and DAC.

In free text comments (see for a more detailed summary SI.A4) ESM experts pointed out that climate-carbon cycle feedbacks (controlled by the factors in tables 1 and 2) are one of the most uncertain aspects of ESM simulations, something that has been well discussed within the community (Friedlingstein *et al* 2013, Jones *et al* 2016), and that these uncertainties are exacerbated when simulating carbon removal via NETs, i.e. if we are unsure of how something like terrestrial CO_2 fertilization will respond to increasing CO_2, then we are even more uncertain of what the response will be to increasing and then decreasing CO_2 (in a scenario with negative emissions). Thus, improving the representation of the factors in tables 1 and 2 remains a high priority for ESM experts. The ESM experts also pointed out that many models lack the necessary processes and resolution to realistically simulate NETs. This is why almost all ESM–NETs studies have been performed in an idealized manner. For example, ocean alkalinization studies often simply increase ocean total alkalinity, which is in itself an idealized biogeochemical tracer representing many ions and acid-base species (Wolf-Gladrow *et al* 2007, Orr *et al* 2017), but do not explicitly simulated all of the chemical reactions that actually occur when alkaline minerals are added to seawater. Several experts also pointed out that their model could not simulate a method like (terrestrial) EW. This is because many models do not include adequate (or sometimes even any) sub-components at the right resolution to simulate (for the example of enhanced weathering) soil chemistry or hydrology, as well as biogeochemical cycling along the land ocean continuum. Obviously, in these cases improvements are needed to perform even idealized NETs simulations. Only for DAC, did experts state that they were confident that their simulations of the method were adequate, and even then, some questioned whether or not they should explicitly simulate CCS and any potential leakage. Overall, these responses indicate that most experts feel that much

Table 2. Factors requiring improvement to better simulate the ocean carbon cycle response to AF, EW, BECCS, and DAC.

	AF		EW		BECCS		DAC	
	Mean	*N*	Mean	*N*	Mean	*N*	Mean	*N*
Air-sea gas exchange parameterization	1.15	20	1.24	17	1.39	18	1.42	19
Marine sediments	1.20	20	1.74	19	1.41	17	1.35	17
Sea ice representation	1.37	19	1.33	15	1.31	16	1.31	16
Carbonate chemistry	1.42	19	1.74	19	1.63	19	1.44	18
Biology and biological pump	1.70	20	1.88	17	1.83	18	1.61	18
Ocean physical transport	1.85	20	2.00	17	1.95	19	1.84	19
Biogeochemistry along the land-ocean continuum	2.21	19	2.56	18	2.00	17	1.59	17

Note. 0 not at all important; 1 somewhat unimportant; 2 somewhat important; 3 very important (do not know option available).

needs to be improved to adequately simulate NETs in ESMs.

Given these various limitations in the current ESM simulation of NETs, a central question arising from the IAM experts was in how far net carbon emissions and net carbon removal lead to a symmetric response from the ocean (see for a more detailed summary SI. A4). IAM experts emphasized that improved parametrization of ocean carbon outgassing is required, in particular as function of the amount and speed of carbon dioxide removal, accounting for dynamic, non-equilibrium states of the global carbon cycle. However, the concerns from the IAM experts were not restricted to the ocean but also include issues related to the terrestrial carbon fluxes. Here, like the ESM experts, improved parametrization of the CO_2 fertilization and temperature feedback were considered to be important issues for improved modeling. Furthermore, specific issues like improved soil carbon dynamics, spatially depend forest carbon densities and spatially defined re-growth curves, both for mature or recovered forests were indicated as areas where improvement is required. Yet, as responses in the previous section already indicated, IAM experts also indicated confidence regarding the capabilities of their IAMs. In particular experts who rely in their model on a link to MAGICC indicated that the latest research on carbon cycle fluxes is represented in their model, implying for example that they properly account for ocean carbon outgassing. Jones *et al* (2016) show that (detailed process) IAM simulations relying on a link to MAGICC are general capable of simulating carbon and climate dynamics similar to current state-of-the art ESMs, concluding that these IAMs are not systematically wrong in their estimates of NETs requirement in their scenarios. However, the capability of MAGICC to properly capture all relevant removal pathways and fluxes was not a unanimous view among IAM experts.

4. Discussion

With our invitation list we aimed at a broad representation of currently used models for the assessment of NETs. Given the specificity of the questions, it is possible that experts that are already more familiar with NETs were more likely to respond; this should actually increase the quality of responses. At the same time, the results for our question about which NETs are represented in the IAMs reflects the information from the model descriptions in the supplementary information to chapter 2 in IPCC SR15 (Rogelj *et al* 2018) very well. Furthermore, table SI.A.T1 indicates for ESM respondents a balanced representation of research foci relevant for the assessment of carbon removal pathways. The fact that fewer IAM experts responded compared to ESM experts might be an indication that the IAM community is still less familiar with NETs.

Our results are a glimpse into the conceptions of the experts who actually responded and their models. The results should thus not be extrapolated to all modelers and all models but rather to those who actually model NETs. We therefore only use statistical tests at one instance where we compare ESM and IAM experts. The rather low number of responses obtained from the IAM community limits the possibilities for statistical interference; this means that low *p*-values derived in section 3 should not lead readers to ignore the remaining uncertainty about the 'true' beliefs and conceptions in the IAM community (and similarly in the ESM community); but also means that higher *p*-values should not lead readers to overlook interesting differences in the conception of the two communities (Wasserstein *et al* 2019). Overall, we are confident that our results are helpful for the interpretation of model-based NETs assessments for climate policy and for future model and scenario development with respect to NETs.

This holds in particular true given the differences in the conceptions about NETs between the two expert groups. Two of the most striking differences occur for the assessment of AOA and BLC: while only 1 IAM expert included AOA, about half of the ESM experts indicated that increasing the alkalinity of the ocean should be part of a future NETs portfolio. This does, however, not speak to a general reservation against ocean-based NETs, as 38% of IAM experts would include BLC in a NETs portfolio (compared to 52% of

ESM experts). Looking more closely at the assessment of factors that could potentially constrain the use of the NETs, we furthermore found that IAM experts perceived the physical removal capacity a much smaller constraint for BLC deployment compared to ESM experts (1.63 compared to 2.2 with 3 indicating the maximum constraint). In the assessment reports by the Royal Society (2018) and the National Academies of Sciences, Engineering, and Medicine (2018) AOA has an estimated annual removal potential of 40 Gt CO_2 compared to 0.13 Gt CO_2 for the case of BLC. The large physical potential of AOA does not necessarily translate into a large economic potential and in turn the rather low share attributed to this technology by IAM experts might be based on such kind of economic reasoning. Still, taking into account that IAM-based assessments of NETs predominantly focus on reforestation, afforestation and BECCS, it appears that ocean NETs have so far mostly been overlooked by the IAM community.

The current focus on BECCS appears somewhat surprising because our experts indicated that this technology faces the strongest constraints in terms of feasibility. However, it might just because BECCS has already been researched and discussed in more detail (including for example also public acceptance research); and thus problems and constraints are simply better understood. Accordingly, other NETs with a lower technology readiness level might have received less attention and consequently less scrutiny; this could mean that their assessment is still too optimistic.

However, the pessimistic assessments of BECCs could also indicate that intrinsic conflicts regarding land and water competition are considered to be almost insurmountable, significantly limiting the application of the technology in the future. This becomes also apparent when comparing BECCS with DAC—the latter being assessed by the experts to be much less constraint in terms of resource competition, suggesting that the carbon capture and (geological) storage aspect of BECCS is not necessarily considered to be a limiting factor for BECCS. Furthermore, comparing BECCS with BC and SC (the latter being among the most research NETs since 1990, Minx *et al* 2018), it becomes apparent that land and water conflicts are considered to be limiting BECCS because BC and SC were not only considered to be less constraint overall but also in terms of resource competition.

Only 62% of IAM experts included SC in their future NETs portfolio, compared to 92% who included BECCS. ESM experts included SC just as often as BECCS in their NETs portfolio (74% and 70%, respectively, see figure 2). Experts seem to be aware that annual carbon removal rates at the potential scale of BECCS cannot be achieved via SC indefinitely because of soil saturation (Royal Society 2018): they assessed the physical removal capacity for SC as its most limiting constraint. SC was assessed to face also the highest constraint on removal capacity compared to the other terrestrial and (partly) biological-based NETs.

Among all constraints, NETs were assessed to be strongest constrainted by cost effectiveness. Excluding DAC from the list of NETs, cost effectiveness remains the strongest constraint, closely followed by political feasibility (averaging to 2.07 and 1.89 versus 2.01 and 1.95 with and without DAC, respectively). Even with cost effectiveness included as constraint, DAC was assessed by experts to face the lowest constraints. Consequently, the actual contribution in terms of carbon removal by DAC in future NETs portfolio could be significant if recent cost estimate updates, suggesting that the cost could drop below 100USD/tCO_2 (Keith *et al* 2018) (compared to previous estimates of about 600 USD/tCO_2) prove to be achievable in practice.

In general, ESM experts perceived constraints more pessimistically when compared to IAM experts: they perceived only 7 out of 80 possible constraint-technology combinations as weaker compared to the IAM experts (see right panel in figure 3). These (and other differences) might be driven by diverging conceptions of the technologies or different levels of knowledge in the two communities. ESM experts might misjudge socio-economic factors. For example, it appears surprising that ESM experts considered the political feasibility of BC and EW to be a much stronger constraint than the IAM experts. On the other hand, IAM experts might lack knowledge about biogeochemical processes, e.g. of likely side effects, which could lead them to underestimate certain constraints as well.

A similar pattern can be observed regarding the question how well the expert's own model captures aspects of the global carbon cycle relevant for NETs. While the majority of IAM experts indicated that the representation of removal pathways is sufficient, the ESM experts were much more pessimistic. Among them, 7 considered the atmosphere-to-terrestrial pathway insufficiently represented (out of 23) and 13 considered the terrestrial-to-geological pathway insufficiently represented (again out of 23). Again, this might be explained by different modeling paradigms in the two communities. While ESM experts often aim to explicitly model the various underlying physical, chemical, and biological processes, IAM experts are rather interested in properly measuring the net contribution to climate change mitigation than the exact representation of a pathway. Furthermore, ESM experts spend a lot of time validating their models against historical observations, providing them with more knowledge about how 'bad' their models are. Consequently, the representation of carbon removal pathways in IAMs might not necessarily be worse compared to the representation in ESMs. However, they are probably still insufficient to reliably answer the question about the optimal future shares of specific NETs because the ESMs that are used to calibrate

simple climate-carbon models in IAMs also still fail to properly answer the question.

5. Concluding remarks

Our results emphasize that we need to understand the limitations and implications of a broad set of NETs and their interactions in technology portfolios as soon as possible, to conceive realistic climate mitigation pathways. Current ESM- and IAM-based investigations still focus on rather stylized scenarios or are restricted to afforestation, reforestation, and BECCS, respectively. A reason for the latter may be that planting trees is perceived as a benign method and hardly met with public resentment (Braun *et al* 2018) even by those who are against the use of NETs. Yet, this approach ignores a large number of potential NETs under discussion, and limits the study of portfolios and interactions between different NETs. Current IAM-based climate policy advice appears to potentially overestimate the future negative emissions potentially achievable via BECCS, in particular because experts themselves consider resource competition, cost effectiveness, and political feasibility to be strong constraints for future BECCS deployment. IAMs rarely investigate NETs portfolios, implying that the future negative emission contribution via NETs portfolios is potentially underestimated, in particular because IAM-based assessments neglect the contribution of ocean NETs. Also many carbon removal simulations in ESM are rather idealized, missing some important pathways and components and allowing answering only basic questions. Specific NETS like enhanced weathering or biochar cannot be adequately simulated in ESMs. In the process of improving both, ESMs and in turn IAMs, stronger exchange between the ESM and IAM community would be beneficial for a more comprehensive assessment of NETs. Ideally such exchange is part of joint research programs on model development and comparison.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available for ethical reasons.

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