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Abstract

Carbon dioxide removal from the atmosphere (CDR)—also known as 'negative emissions'—features prominently in most 2 °C scenarios and has been under increased scrutiny by scientists, citizens, and policymakers. Critics argue that 'negative emission technologies' (NETs) are insufficiently mature to rely on them for climate stabilization. Some even argue that 2 °C is no longer feasible or might have unacceptable social and environmental costs. Nonetheless, the Paris Agreement endorsed an aspirational goal of limiting global warming to even lower levels, arguing that climate impacts—especially for vulnerable nations such as small island states—will be unacceptably severe in a 2 °C world. While there are few pathways to 2 °C that do not rely on negative emissions, 1.5 °C scenarios are barely conceivable without them. Building on previous assessments of NETs, we identify some urgent research needs to provide a more complete picture for reaching ambitious climate targets, and the role that NETs can play in reaching them.

1. Introduction

In 2015, the international community adopted the 'Paris Agreement' at the 21st Conference of the Parties [1], focusing international climate policy on keeping global warming 'well below' 2 °C above pre-industrial levels, and to pursue further efforts to keep the temperature increase below 1.5 °C. Scenario analysis suggests that the 1.5 °C [2, 3] and 2 °C targets [4] are technically and economically feasible. However, it remains uncertain whether future emissions will decline fast enough to be consistent with the requirements of low temperature targets, while trying to achieve other ambitious sustainability targets (e.g. biodiversity conservation) and development goals (e.g. food security). Most scenarios consistent with 2 °C [4], and all of them consistent with 1.5 °C [3], require large-scale carbon dioxide removal (CDR) using negative emission technologies (NETs), defined here as any anthropogenic activities that deliberately extract CO_2 from the atmosphere.

Activities commonly considered to create negative emissions include large-scale afforestation, bioenergy combined with carbon capture and storage (BECCS), direct removal of CO_2 from the ambient air by means of chemical reaction, enhanced weathering, biochar formation, and soil carbon sequestration. Research on NETs has been conducted for almost two decades [5–13], but the topic has received more attention since the IPCC's AR5 [4] and beyond [14–17].

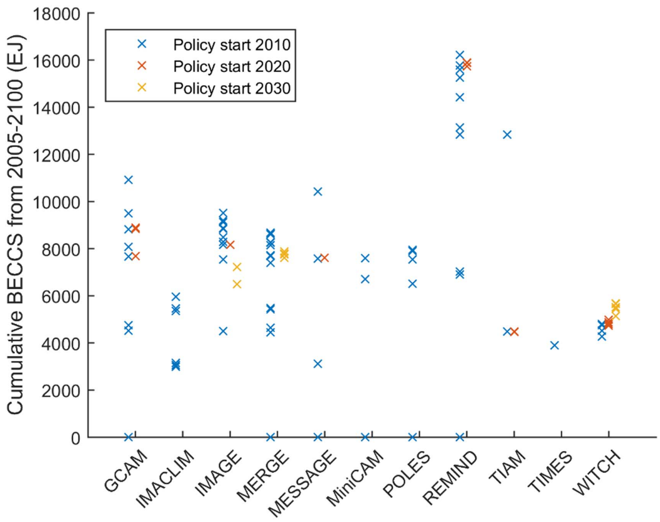

Figure 1. Cumulative BECCS from 2015 to 2100 in 2 °C scenarios (430–480 ppm CO_2-eq in 2100, IPCC AR5 DB). The 11 IAMs using BECCS are shown; different colors refer to different start dates of global uniform climate policies (shifted in the axis to avoid overlap). In each start date, some scenarios can overlap; all BECCS scenarios are shown—irrespective of whether they have technology restrictions or not. Data source: IPCC AR5 Database [20]. Note: ideally, the quantity of CO_2 stored in bioenergy production systems should be used instead of cumulative energy. However, given that this variable is not available in the AR5 Database, cumulative BECCS is used as a proxy.

Most mitigation strategies that depend on the large-scale use of negative emissions begin deployment as soon as CCS becomes available, but only achieve net negative emissions (i.e. net removal of carbon from the atmosphere at the global level) in the second half of this century. While there are some temperature stabilization pathways associated with a more than even chance to keep average global warming below 2 °C (i.e. without overshoot), current 1.5 °C scenarios all feature a temporary overshoot [3]. In these scenarios, net negative emissions would need to offset this temporary overshoot later in the century [18, 19]. Negative emissions also offer flexibility for sectors that are difficult to decarbonize completely, e.g. greenhouse gas emissions from food production (i.e., methane, nitrous oxide). However, negative emissions should be viewed as part of a wider mitigation portfolio, and not as an alternative to deep cuts in emissions in the near term [14], as unabated emissions of CO_2 would have all associated side effects, such as ocean acidification, and would increase the risk of ultimately not achieving the target.

Of the 116 scenarios, that were assessed in the IPCC's AR5 [21] consistent with a high probability of achieving the 2 °C target [4, 22], 104 scenarios use BECCS and most of them at a large scale, with an IAM median in 2100 of 160EJ/year and one of the models using as much as 300EJ/year in the second half of the century. The scatter between the data points and models shown in figure 1 represents different preferences for BECCS in the IAMs and scenarios, many of which include limited technology portfolios (e.g., no CCS, limited bioenergy, no nuclear, etc). A subset of the IAMs were run assuming global climate policy starting in 2010 and in 2020 [23] or 2030 [24]. Except for one model, there is no clear signal that delay in global climate policy leads to more BECCS, which may be due to the limited availability of bioenergy in the IAMs, as is the case when comparing 1.5 °C and 2 °C scenarios [3]. Comparisons across IAMs and scenarios is hampered by the lack of model and scenario diversity, particularly in scenario subgroups (e.g., full technology portfolio with climate policy starting in 2020). The large spread between IAMs underlines the need for further investigation to obtain a better understanding of the underlying dynamics and the demand for negative emissions.

Large uncertainties and knowledge gaps remain in all NET areas including supply (the actual negative emissions potential that can be realized), demand (the negative emission requirement to achieve a climate target), and implications (the intended or unintended socio-economic and environmental costs and consequences of deploying large-scale NETs). The four dimensions of uncertainty we consider in this article are outlined in figure 2: sustainable and available potentials (1) dictate the rate and maximum supply, which feeds back to achievability of the target and the optimal mix of mitigation options. This potential needs to be assessed through the lens of all sustainable development goals (SDGs), i.e., go beyond the climate dimension. Mitigation pathways (2) inform about how to stay within the quota in a cost-optimal way given a set of mitigation options and deployment rates. Earth system modeling, (3) considers the carbon cycle and determines the total carbon quota to achieve a temperature target, but does not determine how to stay within budget, i.e., there is no distinction between net or gross positive or negative emissions. Governance (4) encompasses society's choice about what is

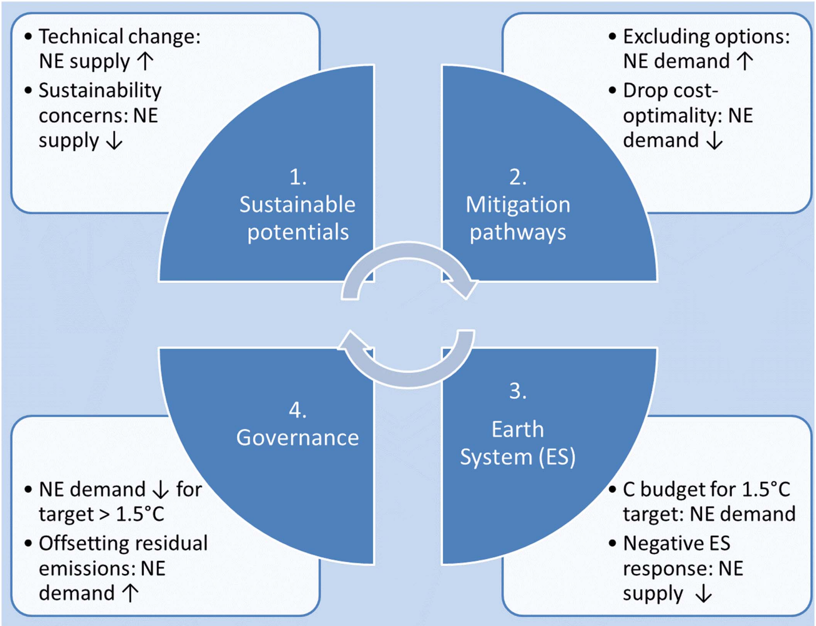

Figure 2. The four components of a consistent climate strategy interact to determine supply and demand of negative emissions motivated by economic, technical, sustainability, governance and Earth System factors (adapted from [14] with examples).

'dangerous' climate change and sets a temperature target, decisive in turn for the remaining C budget and the possible mitigation pathways. The rest of the article is organized according to these four dimensions, starting with the potentials on the supply side and ending with governance factors influencing demand.

2. Background

2.1. Overview of negative emissions options

Earlier studies have listed various NETs and assessed their strengths and weaknesses and the potential contribution in creating negative emissions (e.g. [25–27]). A list of the most commonly discussed options includes:

- Bio-energy and CCS (BECCS)—the generation of energy from burning biomass coupled to the capture and storage of carbon dioxide (CO_2) in geological or other reservoirs. Because CO_2 has been captured from the atmosphere during biomass growth, the process delivers net-negative emissions to the atmosphere.
- Afforestation/reforestation and forest management (AR)—the planting of trees which capture CO_2 as they grow, thereby removing CO_2 from the atmosphere and storing it in living biomass.
- Direct air-capture and storage (DAC)—the use of chemicals such as amines or sodium hydroxide to absorb CO_2 from the atmosphere, after which it is mineralized for solid storage or pumped into geological reservoirs.
- Soil carbon sequestration (SCS)—enhancing the sequestration of carbon in soils by increasing inputs or reducing losses, for example by reducing soil disturbance.
- Biochar—the pyrolysis of biomass so that it becomes more resistant to decomposition, which is then added to the soil to store the embedded carbon and, in some cases, enhance fertility.
- Enhanced weathering (EW)—the grinding and spreading of rocks that naturally absorb CO_2 to increase their surface area so that they absorb CO_2 more rapidly. The ground rock can be spread on land or the ocean.
- Ocean fertilization (OF)—the fertilization of the ocean, for example with iron, so that the ocean phytoplankton absorb more CO_2 through photosynthesis, and then potentially sink to the deep ocean and sequester carbon after they die.

These technologies (except for OF; see [28]) were assessed in terms of their negative emissions potential, impacts on land, water and nutrient use, greenhouse gas emissions, energy requirements and investments costs in [15] (for BECCS, AF, DAC and EW) and [16] (for SCS and biochar). Potentials vary from high (BECCS, AR, DAC), to lower (EW, SCS and biochar).

All of these NETs run into their respective limits when implemented at scale [15, 16]. For BECCS, there are significant issues with competition for land if BECCS is implemented at the median rate projected by IAMs, and water use is also significant, while DAC is energy-intensive, for example.

Table 1. Negative emission potentials from BECCS, afforestation (AR), direct air capture (DAC), soil carbon storage (SCS), biochar and enhanced weathering (EW) based on range of 2100 negative emission requirement in AR5 2 °C scenarios (3.67–12.1 $GtCO_2$/year). Data adapted from [15, 16].

Negative emission option	2100 potential ($GtCO_2$/year)
BECCS	3.67–12.1
AR	4.03–12.1
DAC	3.67–12.1
SCS	1.47–2.57
Biochar	1.47–2.57
EW	0.73–3.67

In the following we take a closer look at afforestation and BECCS given they are the only NETs currently used at significant levels in low-stabilization scenarios.

2.2. The role of negative emissions in climate stabilization

Afforestation can lead to negative emissions, but requires land and is thus likely to compete with large-scale biomass cultivation, bioenergy and ultimately BECCS. In assessing its role in a climate change mitigation portfolio, land and other resource requirements, economic costs and potential negative side effects have to be weighed against their carbon benefits.

BECCS relies on the production of bioenergy, which either is carbon-neutral or emits less carbon than is sequestered by the cultivation of biomass and captured and stored in underground reservoirs. Yet, this mechanism has come under great scrutiny, and scientific assessments vary widely in their estimates of carbon benefit. Concerns with respect to carbon-neutrality include indirect land use change, site-specific barriers, and problems to achieve scale without impacts on the environment [29–31].

Most NETs have not been commercially deployed at large scales as required by low-carbon mitigation scenarios. Afforestation generally already exists at scale [46, 47] and considerable experience exists with implementation and monitoring. However, to achieve negative emissions as indicated in table 1, substantial upscaling would be required. For BECCS, with the individual components of these plants being bioenergy production, capture of CO_2 and storage, only a few projects exist [48, 49].

As summarized by the IPCC [4]—most scenarios contain significantly larger amounts of negative emissions using BECCS compared to afforestation. Afforestation tends to be more cost-efficient for carbon removal at low carbon prices, whereas BECCS becomes more competitive as carbon prices rise [32, 33]. The land requirement for afforestation would also be substantially higher than for BECCS. The assumptions concerning potentials, however, are model and scenario specific: yield assumptions and the dynamics of mitigation strategies vary widely across IAMs [34]. Furthermore, different BECCS technologies can have different consequences for emissions, i.e. the portion of emissions sequestered along the supply chain may vary, and the bioenergy may substitute different technologies (e.g. [35, 36]). Finally, these more aggregated studies will need to be reconciled with more detailed analysis. NETs other than BECCS and afforestation have achieved much less attention in the work of IAMs—although some individual studies exist. For instance, several studies have looked into the consequences of enhanced weathering [37, 38], DAC [39–43], and ocean fertilization [44, 45].

Some individual studies have assessed the implications of negative emissions in shifting the mitigation effort from current to future generations, with the amount of negative emissions being significantly and positively correlated with the discount rate [42]. The use of NETs can allow for an overshoot of as much as 0.5 °C for standard assumptions on climate sensitivity and other physical parameters—provided that temporary overshoot of the target is allowed [11]. However, this has not been fully incorporated in the integrated assessment of NETs, yet. This prevents us from drawing systematic conclusions across models with respect to delay (see figure 1). In any case, a delay in mitigation may prolong our reliance on fossil fuels, although even with CCS, most fossil fuel reserves will need to remain underground to achieve ambitious climate targets [50]. This is particularly important in case of future technology failure, or limited deployment of NETs for social reasons [51]. Uncertainties in negative emissions, combined with future uncertainties in the performance of the natural carbon sinks, have a significant effect on NET deployment [52]. NETs appear to be particularly advantageous in scenarios with delays in mitigation in some key regions [37].

Finally, even if these uncertainties surrounding benefits, costs and risks of NETs could be resolved, the technologies and the large-scale deployment will require the acceptance by the public and thus policymakers ([53, 54] on CCS, and [55] on bioenergy). Currently, there is a vast gap between what is currently being planned and developed and what would be needed based on the low-stabilization scenarios (e.g. [56] for CCS).

3. Negative emissions: research challenges

3.1. Sustainable potentials: focus on BECCS and afforestation

More detailed analysis of optimal land use is needed that allows multi-functional uses for different products (e.g. food and bioenergy feedstock) to be derived from the same land. For example, rice straw is among the most abundant biomass resources with 550 Mt annual production in Asia alone. The majority of this potential feedstock is wasted when burned in the fields for easy disposal [57]. Logistical and financial solutions to utilizing this abundant renewable resource—not competing with food production—are missing. Similarly, palm oil production generates considerable residues and waste that are substantially under-utilized for energy [58]. Clean energy services from oil palm residues and waste provided to surrounding rural areas could be a key contributor to SDG 7 ensuring access to affordable, reliable, sustainable and modern energy for all. Furthermore, breeding of new plants needs more focus on multiple uses. Though not commercially proven, mangrove palm is a promising new feedstock for bioethanol production showing higher productivity than sugarcane and not competing with other crops for agricultural land or freshwater. Planted in suitable areas, it can help to preserve and restore mangrove (e.g. [59]).

A major challenge for land-based NETs remains the selection of the optimal feedstock plant species for a given location. Further suitability research is needed—especially with feedstock plants that grow on deforested land and hence have a broad geographic range. Canadell and Schulze [60] warn that many first generation biofuels do not yield net GHG emission savings if their establishment requires the transformation of native ecosystems: carbon debts for different biofuel systems range from 17 years for sugarcane-based ethanol systems replacing Cerrado in Brazil up to 840 years for specific oil palm-based biodiesel systems that replaced original tropical forest on peat in Southeast Asia.

Careful suitability assessments are thus needed to avoid incorrect assumptions and planning mistakes when ramping up a large-scale BECCS system. Palm oil production in particular has expanded greatly, from 6 Mha in 1990 to 16 Mha in 2010. Much of this expansion has come at the expense of biodiversity-rich tropical forests [61]. On the other hand, it is an income source greatly contributing to poverty alleviation. Pirker *et al* [62] found in their global oil palm suitability study that—based on purely biophysical parameters—land used for palm oil production could be doubled without expanding into protected or highly biodiverse forests. Such global suitability guidelines should be paired with continuous efforts to strengthen governance and consumer-driven market tools such as certification of forest and agricultural management [63, 64]. Furthermore, ministerial initiatives such as the 'Bonn Challenge'—a global effort to restore 350 Mha of the world's deforested and degraded land by 2030—can help identify and assess marginal, degraded and abandoned land for restoration with suitable plants for bioenergy feedstock production.

Unlike first generation biofuels, forest-based bioenergy and other ligno-cellulosic short rotation crops/second generation crops such as Miscanthus, poplar, willow and eucalyptus often do not compete directly with food crops [60]. Sustainable management of such systems is already recognized under the REDD+ schemes.

For forest-based bioenergy and BECCS systems, further to (certified) sustainable management [63], the use of wood and harvesting residues is desirable from a technological point of view. Many industries (e.g., pulp and paper, construction, furniture, flooring, biorefinery, etc) compete for wood, which calls for a careful distribution while burning wood for energy should come as late as possible in the cascade (see [65, 66]), unless other valuable services such as CO_2 removal are accounted for. Preference shall be given to long-living products from wood (e.g. for construction) for long-term carbon storage, but permanence remains a challenge for carbon capture for utilization (CCUS) of products (e.g. chemical products, construction materials). Furthermore, wood-forestry-based BECCS systems generally show higher efficiencies than those based on agricultural-herbaceous systems. However, a recent study on the BECCS potential in Brazil for sugarcane ethanol states that CO_2 can be captured twice along the BECCS supply chain—during biofuel generation and combustion [67]. Still, energy penalties that materialize in higher land demand for compensation need to be accounted for [68]. For any technology involving CCS, more large-scale demonstration projects are required to reduce costs and improve efficiencies ahead of larger-scale rollout.

Additional risk management for all land-based carbon mitigation should incorporate wildfires (350 Mha burnt per year globally according to [69]), extreme weather events (storm, hail, drought, flooding, etc) and pests and diseases (infestations by e.g. bark beetles and locust, plant diseases caused by fungi, etc). Pests and diseases are particularly important for monoculture systems, though significant amounts of food are produced in monoculture areas. There is a need to better understand the interdependency between bioenergy production and meteorological processes across time and spatial scales [70, 71].

Negative emissions can be generated through aquatic biomass as well. Green algae could be managed either in floating pools or on land to produce biomass with carbon separation after gasification or combustion [72]. The technology is being developed in many laboratories including with genetically modified organisms but is far from commercialization. The advantage of off-shore schemes would be that the separated CO_2 could be stored in the aquifers under the seafloor as is the case with the Sleipner platform in the North Sea that separates CO_2 from produced natural gas.

Research also needs to examine how possible negative environmental impacts (e.g., effects on water, biodiversity, etc) associated with land-based NETs could be minimized or, in some places, improved. The research needs to include the optimization of locations for future BECCS plants and related logistics for feedstock and CO_2 transportation, with highly resolved geographically explicit studies at regional and national levels [73]. Only the combination of process-based (biophysical and techno-engineering modeling), economic (IAMs) and Earth system models (ESMs) will allow system dynamics to be fully captured.

3.2. Mitigation pathways: benefits and risks of NETs for climate stabilization

A key set of knowledge gaps relates to further quantification and improved representation of the land use and sustainability impacts of large scale NETs in integrated assessments. IAMs already feature energy-land use systems, which can compute the trade-offs of using land to grow bioenergy [74]. Nevertheless, additional focus on modeling the ecosystem and land use impacts of biological NETs is needed to generate more realistic estimates of potentials [60, 75]. Similarly, integration of new knowledge on yield developments and afforestation potential in IAMs will aid the evaluation of the consequences of NETs for the SDGs, as NETs have impacts not pertaining to climate change alone, but also interacting with several of the SDGs, such as poverty and hunger (SDG1 and 2), water and land (SDG14 and 15) and energy (SDG7). By moving mitigation effort in time and space, NETs bring about significant new challenges for equity, for example. The emergence of other NETs—currently not broadly integrated in the assessments—could alleviate some of the unintended negative side effects on other SDGs and still help to deliver sufficient potentials for carbon removal.

Technological uncertainties and the resulting engineering challenges that can influence the mitigation mix and its timing include the ability to deploy large-scale BECCS, in particular with respect to its costs, systems integration, the ability of the technology to deal with a feedstock that may vary in terms of its exact composition and the capture rate. Global biomass-based electricity generation by 2015 reached 464 TWh with an installed capacity of 106 GW compared to more than 1000 GW of hydropower [76] or over 1600 GW of coal-fired power plants. Many of these thermoelectric plants are of small size, which could be an economic disadvantage if combined with CCS. Still, research shows that both in Brazil and the United States larger-scale bioenergy plants are already available [77, 78].

On the storage side, a large-scale CO_2 pipeline network will likely be needed—from power stations and factories to the storage sites, unless BECCS plants are optimally sited to take advantage of *in situ* storage opportunities. In the IAM scenarios, transported volumes are typically quite large, i.e. in the order of up to 10 $GtCO_2$ per year and sometimes even higher (based on the AR5 Database). Such a network would be similar in size to the current natural gas network. Research should focus on the costs and risks that are involved in such infrastructure.

3.3. Earth system: carbon cycle response to negative emissions

The natural carbon cycle—land and ocean—acts as a buffer to excess CO_2 emissions from human activity. More than half of all CO_2 emissions are absorbed by oceans and vegetation on land, thereby slowing by about half the rate of atmospheric CO_2 growth [79, 80]. Although this ecosystem service has largely kept pace with increasing emissions and maintained a mean airborne fraction (AF) of 42% (the fraction of emissions staying in the atmosphere), the efficiency at which natural CO_2 sinks work has declined [81].

The same processes that slow down the CO_2 growth rate will respond to negative emissions in reverse—to buffer the system and partially oppose negative emissions. If more CO_2 is removed from the atmosphere than added, the CO_2 fertilization effect on vegetation will weaken and therefore reduce the land sink. The oceans will reduce their uptake and ultimately even degas CO_2 to equilibrate with the lower CO_2 concentration, also weakening the net ocean sink. This implies that the resulting change in the atmosphere is only a fraction of the amount of CO_2 removed—exactly analogous to the response to positive emissions. [83] analyzed this response under the RCP2.6 scenario across CMIP5 ESMs and found that on long timescales, natural sinks reverse. Therefore, the AF of negative emissions must be treated in the same way as for positive emissions—only a fraction of the CO_2 reduction will persist in the atmosphere. However, there are large uncertainties between ESMs over the magnitude of this response, which hinders the usefulness of projections to policy makers. Models also lack some crucial processes, leading to research gaps and priorities for improving our understanding of the Earth system response to negative emissions.

The highest priority is reducing the large model spread in simulating carbon cycle sensitivity to climate changes. With a focus on low mitigation scenarios, ESMs need to be better evaluated, so that we can more precisely and reliably determine the remaining carbon budget associated with a chosen climate target. For instance, the most up-to-date assessment on the remaining carbon budget to comply with the 2 °C target is 590–1240 $GtCO_2$ [82]. IAMs should continue to draw on ESM outputs for their carbon cycle response, but focus on testing these under low stabilization or even peak-and-decline concentration pathways.

In addition to the overall impact of CO_2 removal from the atmosphere, different methods of extracting CO_2 will also interact differently with the Earth system. For example, land- or ocean-based uptake have effects on the carbon cycle that are very different from DAC and CCS with geological storage [82]. Little is understood about the underlying mechanisms and the magnitudes involved. Yet, these insights can have important impacts on the estimated negative emission needs and their effectiveness in climate stabilization.

Research also needs to understand how reversible the Earth system is and the potential for hysteresis. One question is how to restore CO_2 concentration to the levels before the Industrial era, which is required in scenarios that first overshoot a target before converging to a temperature target using negative emissions. While the atmospheric reservoir may converge to a previous concentration level, it is unlikely that all other carbon reservoirs will be restored. For example, if the tropics have been originally deforested and the same amount has been afforested in the high latitudes, the same CO_2 level may be achieved, but is the system 'reversed'? Similarly, there is to date no robust evidence as to what extent the climate system reverses, whether there are irreversible changes or hysteresis (e.g. ocean overturning or permafrost). Are there some thresholds which can be crossed (e.g. tropical forest dieback) and does the system possess 'temporary resilience' in the sense that we can cross a threshold safely for a few years or even decades before the tipping point is triggered?

3.4. Governance: driver of demand and supply

The importance of governance and society is two-fold for negative emissions. First, governance drives the demand for negative emissions by achieving consensus on temperature targets (figure 2). Second, the lack of governance and societal concerns in the implementation phase can limit the timely supply and reduce the demand for negative emissions, respectively. A further complication is that both climate change and effects of NET deployment raise cross-jurisdictional issues, for which no governance structure currently exists. From here, two major areas of research emerge: first, to better understand the inhibiting factors, their history and potential for change. Second, to determine institutional and governance structures required to ensure the trial and eventual large-scale deployment of NETs.

Indicative of the current lack of commitment to NETs is their complete absence in any of the Intended National Determined Commitments (INDCs) submitted in support of the Paris Climate Agreement. Furthermore, CCS is only mentioned as a priority area in three INDCs [84]. At the same time, investments from the private sector are too low compared to what would be needed at a short timescale [85] and CCS is far behind earlier projections [56, 86]. In contrast, 90 INDCs mention renewable energy, and there is constant government, civil society, and media attention to the faster than expected growth in renewable energy, except for bioenergy, which is the basis for BECCS [75]. A possible explanation for this contrast is that subsidizing some sources of renewable energy is seen as politically expedient, while investing in CCS, NETs, or other large-scale technologies is seen as having a high political risk. NETs are also causing a strong debate in civil society, where BECCS has been unpopular in many countries for two reasons: (1) bioenergy has been one of the main culprits in the public debate during the food price crisis in 2008, and (2) CCS has been associated with environmental and safety issues such as risks of leakage [87], and earthquakes [88], and with prolonging the reliance on fossil fuels [89]. There is a lack of understanding of how policy makers and society receive and interpret information from emission scenarios, and why they favor certain technologies over others.

There are currently no institutional or governance structures for dealing with some of the NETs, particularly with the one most widely used in climate stabilization scenarios, BECCS. Key issues for which new developments are needed include biophysical and economic constraints [15], sustainability risks [17], and even legal risks with respect to liability in the case of leakage from geological storage or other negative side effects. As described in the previous subsections, many of these areas represent key knowledge gaps that need to be addressed. On the practical side, these knowledge gaps are also associated with the current lack of consistent emission accounting rules for all types of NETs. In the case of BECCS, biomass harvest, combustion and capture, and storage can occur in distinct countries, and while accounting rules do exist, there are long-standing debates about their effectiveness, particularly for bioenergy [90].

Finally, the right set of policy instruments is needed to economically incentivize R&D, demonstration and ultimately large-scale, sustainable deployment (e.g. [86, 91]). BECCS has an added advantage with a dual purpose to generate energy and remove carbon, while other NETs only remove carbon. It is currently not clear what policies would lead to the ramp-up of NETs, particularly at the scale needed. Whether incentivisation best works through a combination of carbon pricing (as in the IAMs) and sustainability standards or short-run financial support to get specific technologies on the road should be the subject of further research. What could be the role of debt finance in the face of negative interest rates? To what extent should we support fundamental research and development, as opposed to actual capacity development? Since many NETs require CCS to work, it appears to be important to align policies supporting CCS with the need for BECCS and DAC.

3.5. Cross cutting issues

At the operational level, there are some cross-cutting research needs emerging in all four dimensions (figure 2). In particular, it is important to define a set of 'system level' indicators to assess unintended negative consequences of the expected large-scale deployment of NETs. In addition, there are trade-offs between NET impacts and climate impacts. To stabilize temperatures at low levels may require substantial NETs, but the aggregated unintended negative impacts of NETs may be greater than the climate impacts. On the other hand, there can be also positive consequences unrelated to carbon benefits such as new business opportunities in bioenergy or carbon revenues from afforestation offsets. The aggregation and comparison of impacts between climate and NETs is likely to be controversial. Metrics of the carbon cycle response—e.g. AF—are easy to interpret, but might not always be useful or even meaningful, whereas 'process level' metrics such as sink efficiency [81] may be more meaningful to process experts, but not necessarily useful for policy makers. The transient climate response to cumulative emissions (TCRE) is a metric used to relate surface air temperature increases to cumulative emissions, and is often used to give a remaining 'quota' [82, 92] before a given temperature level is exceeded. Recently, studies have begun to use the TCRE approach to relate carbon budgets directly to impacts such as heatwave occurrence [93] or regional temperature and precipitation extremes [94]. However, if a temporary overshoot in the cumulative carbon budget and temperature is accepted for a period that is sufficiently long [18, 19], then the NETs in the long-term have to, at least partially, compensate for excess CO_2 emissions in the near-term. It is unclear whether the TCRE/budget approach is sufficiently robust when high levels of NETs allow the budget to be temporarily exceeded. Some progress has been made to assess indicators for the risks to sustainability of climate change mitigation in general [95]. Economic indicators, such as policy costs with and without negative emissions, can readily be extracted from the IAMs, but societal preferences are generally underrepresented. For example, there are only few studies looking into public acceptability of technologies and location-specific political realities coming up with comparable metrics.

4. Conclusion

We have set out a research agenda across four dimensions, which interact to determine the demand for and supply of negative emissions. The intersection—and whether there is one—is not only determined by technological parameters, but also by societal preferences, timing issues, economics, carbon cycle dynamics and risks to sustainability. An interdisciplinary approach is needed to comprehensively tackle these interactions.

The research priorities emerging from our analysis of the literature across the four dimensions of figure 2 start with the potential capacities. Here, two research and development areas require major advances. On the one hand, CCS research, development and deployment is behind what roadmaps recommend particularly for 2 °C-compatible pathways; on the other hand, sustainable large-scale supply of second-generation bioenergy will need to be ensured. In addition, due to the limitation of individual NETs, more research and development of NETs other than BECCS and afforestation is needed. Currently, these two options are the only ones used to a large extent in stabilization pathways. However, if energy supply can be largely decarbonized and costs brought down, DAC and other NETs could add to the total negative emissions potential at a negligible land footprint. Furthermore, carbon cycle dynamics under net negative emissions need to be examined in detail. Questions of reversibility and asymmetry of processes as CO_2 concentrations rise and fall are central to this topic area. Finally, spanning from potentials over mitigation pathways to governance challenges, further model development is needed to incorporate multiple criteria for large-scale deployment of NETs that achieves consistency not only with climate change mitigation aspirations, but also other SDGs.

It needs to be reiterated that short-term abatement is a necessary, but not sufficient, condition to meet the most ambitious climate targets (e.g., 1.5°C and most likely 2°C). The research agenda set out here prioritizes the necessary biophysical and socio-economic aspects required to initiate the deployment of negative emission technologies in the short-term that is necessary to reach a scale capable of removing excess CO_2 from the atmosphere in the longer term. Without sufficient short-term emission reductions, however, negative emissions will also prove ineffective in enabling climate stabilization at ambitious targets.

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