Governing large-scale carbon dioxide removal: are we ready?

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CLIMATE ANALYTICS

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Summary

In 2015, Parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to limit global temperature increase to well below 2°C above pre-industrial levels and to pursue efforts to limit the increase to 1.5°C . This goal is to be operationalized in part through achievement of a balance between anthropogenic emissions by sources and removals by sinks, as stated in Article 4 of the UNFCCC's Paris Agreement.

In 2018, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (IPCC SR 1.5°C) warned that the impacts of warming at 2°C would be significantly worse than those at 1.5°C. This IPCC report also found that that all pathways to achieve 1.5°C with limited or no overshoot project the use of Carbon Dioxide Removal (CDR) in the order of 100–1000 $GtCO_2$ over the 21st century.

In short, IPCC SR 1.5°C bolsters the case for pursuing the lower end of the Paris Agreement's temperature goal, and makes clear that it is no longer sufficient to reduce emissions alone — CO_2 will also need to be removed from the atmosphere, on a scale never previously attempted.

Is the international community prepared for the implementation of CDR options at this unprecedented scale? Can the sustainability challenges, risks and trade-offs inherent in large-scale CDR efforts be managed? What governance tools would need to be in place to deploy CDR options at the levels the IPCC says are needed? Can provisions under the current climate change regime support implementation at scale, or will further provisions and incentives be needed?

This report represents a first effort to address these questions. It is primarily aimed at negotiators in the UNFCCC process, recognising that some degree of reliance on CDR options is now inevitable to achieve the Paris Agreement's long-term temperature goal, as a direct result of the international community's delay in making the necessary transition to a low-carbon economy.

The top-line finding is that while a number of reporting rules and accounting practices are already in place with direct applicability to the implementation of CDR options, many governance gaps remain.

This report is intended to start a discussion focused on three key issues: how much CDR is needed to avoid or limit any overshoot of the 1.5°C temperature goal; are there governance mechanisms in place that can begin to address CDR at the necessary scale; and what governance gaps remain to be filled.

The scale of the CDR governance challenge is daunting. The good news, however, is that many of the governance systems needed to support the necessary acceleration in emission reductions under the Paris Agreement will also take us a good way toward filling the gaps needed to govern large-scale CDR. Addressing large-scale CDR and reducing global emissions cannot be seen as separate activities; they are intimately related, both are needed and their governance goes hand in hand.

Key insights

1. The scale of Carbon Dioxide Removal needed to limit global warming to 1.5°C depends on the speed of emissions reductions

According to IPCC SR 1.5°C, to avoid or limit any overshoot of the 1.5ºC temperature goal, CO_2 emissions will need to be phased out almost entirely by 2050 while the "*balance*" cited in Article 4 would need to be reached by 2070.[1] Current levels of ambition in the Nationally Determined Contributions (NDCs) fall far short of what is needed.

The pace of global efforts in the near-term is therefore critical: the longer it takes to reduce emissions, the more large-scale carbon dioxide removal will be needed.

- Substantial amounts of CDR will likely be needed over the remainder of the 21st century even if NDCs are ratcheted up substantially given insufficient global mitigation action to date;
- If the international community succeeds in ratcheting up NDCs only modestly, an extremely large contribution from CDR will be needed; if NDCs are ratcheted up only marginally, limiting temperature rise to well below 2°C and 1.5°C will be out of reach completely;
- A broad portfolio of CDR options will be required to satisfy the overall need for CDR, to avoid running into limitations inherent in any single CDR option;
- CDR activities and technologies will need to be rolled out sooner rather than later, as delay in deployment and hence capacity to rapidly scale-up a portfolio of options creates substantial future risk.

If Parties bring forward new and updated NDCs by 2020 that are substantially more ambitious in the reductions they deliver for 2030, this can reduce future reliance on CDR to a scale that may be economically feasible and avoid jeopardizing sustainable development.

2. A number of existing provisions under the UNFCCC, Kyoto Protocol and Paris Agreement address governance aspects of Carbon Dioxide Removal

Provisions under the UNFCCC, Kyoto Protocol and Paris Agreement address the reporting and accounting of CO_2 removals. The IPCC has also provided guidance relevant to BECCS and substantial guidance on CCS. The development of a new rule set under the Paris Agreement provides a valuable, near-term opportunity to address a number of governance challenges and legacy issues that have not been adequately addressed through existing provisions, or that have arisen due to the scale of CDR that is now required.

For example, the presentation of consistent and comparable GHG inventory data across all Parties, at an appropriate level of granularity in connection with CDR, would help the international community assess progress toward the necessary "*balance*" between anthropogenic emissions and removals. Similarly, consistency in reporting Parties' NDCs would help project 2030 emission levels and aid in CDR planning, and the adoption of robust accounting rules would address some concerns over environmental integrity.

1 This applies to a 50% chance to limit warming to 1.5°C (median) or with a limited overshoot to 1.6°C, accounting for uncertainties in the climate system, non-CO2 greenhouse gases, aerosol pollutants and carbon cycle. Zero emissions would need to be achieved earlier for a 66% chance to limit warming to 1.5°C (a "likely" chance in IPCC terms). Further, the underlying energy-economic pathways show rapid global GHG emissions reductions from 2020 until the point of zero emissions, with the cumulative emissions until that point consistent with total cumulative emissions budgets, calculated using geophysical relationships. Obviously, if global emissions were not reduced and were growing, or kept constant at present-day levels, the emissions budget would be exhausted much earlier.

UNFCCC, Kyoto Protocol and Paris Agreement contexts		Selected provisions*	Key points
Existing provisions from which lessons can be learned	UNFCCC	• Annex I Reporting Guidelines (Decision 24/CP.19) • Non Annex I Reporting Guidelines (Decision 17/CP.8) • Biennial reporting and review guiidelines for developed and developing countries (Decision 2/CP.17) • REDD+ (Decisions 1/CP.16, 2/CP.17, 12/CP.17, 9/CP.19, 10/CP.19, 11/CP.19, 12/CP.19)	Consideration of gaps within and differences between UNFCCC and Kyoto Protocol provisions form a starting point for the Paris Agreement rule-book and highlight the need to move towards consistent and comparable GHG inventories and robust accounting rules for all Parties
	Kyoto Protocol	• Land use, land use change and forestry (Decisions 16/CMP.1, 17/CMP.1, 18/CMP.1) • Afforestation and reforestation under CDM and sink enhancement under JI (Decisions 5/CMP.1, 9/CMP.1, 13/CMP.1, 15/CMP.1) • CCS as CDM project activities (Decisions 10/CMP.7, 5/CMP.8) • The Cancun Agreements: Land use, land use change and forestry (Decision 2/CMP.6) • Second commitment period (Decisions 2/CMP.7, 1/CMP.8, 2/CMP.8, 5/CMP.8)	
Paris Agreement provisions to be built upon	Land sector	• Decision 1/CP.21 • Articles 4, 5, 13, 14	Robust reporting and accounting guidance for NDCs, robust accounting rules for Article 6 transfers, development of land sector accounting rules, an enhanced transparency framework and an effective global stocktake all needed as part of an effective CDR governance architecture
	Assessment of progress toward temperature goal / balance between emissions and removals	• Decision 1/CP.21 • Articles 2, 4, 13, 14	
Existing IPCC guidelines to be built upon	IPCC Guidelines relevant to A/R, CCS and BECCS	• Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories • IPCC Special Report on Land Use, Land-use Change and Forestry, 2000 • Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, 2000 • IPCC Good Practice Guidance for Land Use, Land-use Change and Forestry, 2003 • IPCC Special Report on Carbon Capture and Storage, 2005 • 2006 IPCC Guidelines for National Greenhouse Gas Inventories • 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands	Aditional guidance is needed for reporting lifecycle emissions and removals from bioenergy (with and without CCS) and DACCS. The forthcoming special Report on Climate Change and Land (due in 2019) is expected to provide an updated assessment of the role of land in meeting Paris Agreement objectives

* This listing is not intended to be inclusive, but rather to point to key decisions, provisions and documents.

3. Despite existing provisions, many key governance gaps and challenges remain for large-scale CDR and will need to be addressed

While existing provisions and guidance under the UNFCCC, Kyoto Protocol and Paris Agreement already cover a number of governance issues related to CDR (as above), many key governance challenges remain. These gaps revolve around 4 key issues:

- The scale and speed of implementation required, and the associated challenges for research and development and for monitoring deployment;
- The substantial incentives that will be needed to scale-up potential CDR options, as sufficient incentives do not at present exist under the UNFCCC or other legal frameworks;
- The trade-offs between, and interactions with, a range of Sustainable Development Goals (SDGs) e.g. food security, water security, that may follow from large-scale implementation intended to achieve climate ends; and
- The risks to the climate system and to the SDGs that will follow if CDR options are not implemented at the pace or scale required, or if large-scale reversals follow large-scale CDR efforts.

The report identifies ten particular areas with remaining governance challenges for the implementation of large-scale CDR:

- **Rapid pace of CDR scale-up required to limit warming to 1.5°C**: many potential CDR options are at a low level of technology readiness, and it may take decades to achieve widespread deployment for these options.
- **Responsibility and ethics of implementation**: to date there has been no clear assignment or acknowledgement of responsibility for development and deployment of CDR options among Parties to the UNFCCC and/or Paris Agreement.
- **Incentives for CDR deployment:** direct funding and economic incentives will be needed for the deployment of CDR at the pace and scale required to achieve the Paris Agreement's long-term temperature goal.
- **Access to information needed to monitor progress:** a significant challenge that will arise once CDR starts to be deployed at scale is how best to monitor progress towards the goal of balancing emissions and removals.
- **Safeguards for sustainable development**: there are constraints on the sustainable potential of BECCS and A/R due to limits on resource availability.
- **Challenges for measuring, reporting and verifying CO_2 removals:** measurement and verification of the scale of removals from CDR presents substantial governance challenges, in particular in the context of terrestrial sinks.
- **Issues of storage: permanence, leakage and saturation:** a key criterion for successful CDR deployment is that carbon removals are durable. Potential CDR options that store carbon in geological reservoirs and terrestrial reservoirs have different degrees of "*permanence*".
- **Planning for and monitoring the biophysical effects of deployment**: for land-based CDR options, deployment can have biophysical impacts beyond CO_2 removal that require consideration.
- **Liability and redress**: Safeguards need to be put into place to address physical risks and accounting risks related to reversals of removals and storage.
- **Public awareness**: public awareness and acceptance of CDR will be important for its development and roll-out. At the broadest level, public acceptance of CDR as a concept is influenced by the ethics of pursuing CDR and the perceived risk of moral hazard.

4. Priority gaps on mitigation, information, accounting, knowledge and incentives can be addressed in the near-term, both inside and outside of the UNFCCC process

Certain priority areas for governance can be addressed in the near-term. These include **mitigation gaps, information gaps, accounting gaps, knowledge gaps, and incentive gaps.** Some can be addressed through the ongoing negotiating processes under the Paris Agreement, while others will require decisions and interventions outside the UNFCCC process.

Key governance challenges and gaps that can be addressed in the near-term:

Governance challenges and gaps	Entity or entities	Options for adressing them
1. Narrow the mitigation gap to reduce possible future reliance on CDR options	UN Secretary General	• Maintain momentum from the Talanoa Dialogue and the IPCC SR 1.5°C • Encourage more ambitious NDCs by 2020, in view of the IPCC SR 1.5°C and SDGs • Encourage new and updated NDCs by 2020, with enhanced emissions reduction targets • Encourage communication of 2050 strategies, consistent with 1.5°C pathways by 2020 • Encourage a shift to economy-wide NDCs • Facilitate greater collaboration between treaty Secretariats
	UNFCCC Executive Secretary	
	Parties	• Enhance NDCs by 2020, to avoid extreme reliance on CDR options • Communicate 2050 Low Emission Strategies by 2020 including consideration of CDR needs • Provide information necessary for clarity, transparency and understanding of existing NDCs
2. Improve inventory data and information management systems	IPCC	• Develop IPCC Guidance on biomass energy lifecycle emissions for inclusion in national emissions inventories • Develop IPCC Guidance on emission inventory and reporting for DACCS.
	IGOs, NGOs, CSOs	• Explore how external datasets can be used to verify sectoral emissions data (e.g. through atmospheric measurements) • Support capacity building initiatives
3. Put in place robust accounting rules	Paris Agreement Work Programme	• Adopt robust GHG accounting rules • Elaborate land sector accounting rules (including for Harvested Wood Products, Natural Disturbances) • Elaborate robust rules for Article 6 transfers
	UNFCCC Executive Secretary	• Collaborate with IMO, ICAO, CORSIA and Montreal Protocol to enable sharing of emissions data, to ensure no double counting of emission reductions and ensure work is not at cross-purposes

4. Create incentives to accelerate research, investment and implementation	Research community	• Design incentives to support accelerated deployment • Consider role of public / private partnerships, particularly where existing infrastructure and plans can be utilized • Identify inexpensive no-regrets options for immediate implementation
	Parties	• Review previous guidance on CCS in the CDM and REDD+ under the UNFCCC and consider relevance for governing CDR in the Paris Agreement context
5. Engage the research community in scoping specific CDR options and necessary incentives	Research community IEA, IRENA, IIASA	• Build scenarios around specific CDR options, value chains and their sustainability implications (e.g., BECCS linked to existing and new CCS sites, DACCS linked to renewable energy, other land-based options with sustainability benefits) • Research into environmental aspects of CDR options and portfolios, including storage permanence and leakage • Regional, bottom up studies to identify realistic, sustainable removal potential
6. Improve public awareness of potential CDR options, risks and trade-offs in planning processes	IGOs, NGOs, CSOs	• Create a registry of existing BECCS, CCS, DACCS initiatives and projects, with scale and location, to track the progress and achievements in tonnes removed / avoided / sequestered • Provide information from external datasets to facilitate tracking of CDR deployment, e.g. on forest cover, clearing, natural disturbances, from satellite data
7. Improve international collaboration and cooperation	Paris Agreement Work Programme	• Agree common GHG reporting guidelines, metrics, GWPs • Adopt common GHG reporting formats to facilitate aggregation • Agree to sources of input for the Global Stocktake that would enable the assessment of collective progress in balancing emissions and removals and in following a 1.5°C consistent mitigation pathway
	ICAO and IMO	• Data sharing and enhanced collaboration with UNFCCC • Develop long-term vision for zero emissions in their sectors
	IPCC	• Evaluate the implications of geophysical feedbacks and other issues for emission pathways and CDR needs consistent the Paris agreement long-term temperature goal, for inclusion in assessment reports that will inform the Global Stocktake
	Climate Action Tracker & UNEP	• Expand tracking of NDCs and current policies to include CDR deployment

Introduction

In 2015, Parties to the UN Framework Convention on Climate Change agreed ***to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels.*** The Parties adopted this goal in express recognition that "*climate change represents an urgent and potentially irreversible threat to human societies and the planet and thus requires the widest possible cooperation by all countries*."[2] When adopting the agreement, Parties invited the Intergovernmental Panel on Climate Change to provide a special report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways.

This *Special Report on Global Warming of 1.5°C* (IPCC SR 1.5°C) has now been released. It is an eye-opening read for Heads of Government and policymakers around the world. The report makes absolutely clear that getting the world on a 1.5°C consistent pathway is necessary to avoid irreversible impacts of climate change on human, social, ecological and economic systems. It also makes clear that this effort will require unprecedented levels of mitigation ambition, international coordination, and international cooperation if we are to realize the deep reductions in global emissions needed. A key element of the mitigation requirements confirmed in the IPCC SR 1.5°C is the need for large-scale Carbon Dioxide Removal — or CDR. The longer it takes for truly ambitious mitigation action to get underway, the greater the need will be to turn to existing and proposed methods and technologies that would aim to remove CO_2 directly from the atmosphere, through biological and technological means — termed "*Carbon Dioxide Removal*" options.

This paper aims to help senior climate change negotiators and other relevant stakeholders better appreciate some of the current gaps in international governance that would need to be remedied for potential CDR options to contribute to 1.5°C-consistent pathways at the scale and pace required.

The term **Carbon Dioxide Removal (CDR)**[3] as used in this paper, follows the definition provided in the recently accepted IPCC SR 1.5°C and its approved *Summary for Policy Makers (SPM)*, reproduced below:

> "*Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities*".

IPCC SR 1.5°C points to important sustainability and other concerns with CDR, but also shows some reliance on CDR options is now inevitable. All 1.5°C-compatible[4] model pathways considered by the IPCC SR 1.5°C (see Figure 1) rely to varying degrees on a contribution from potential CDR options,

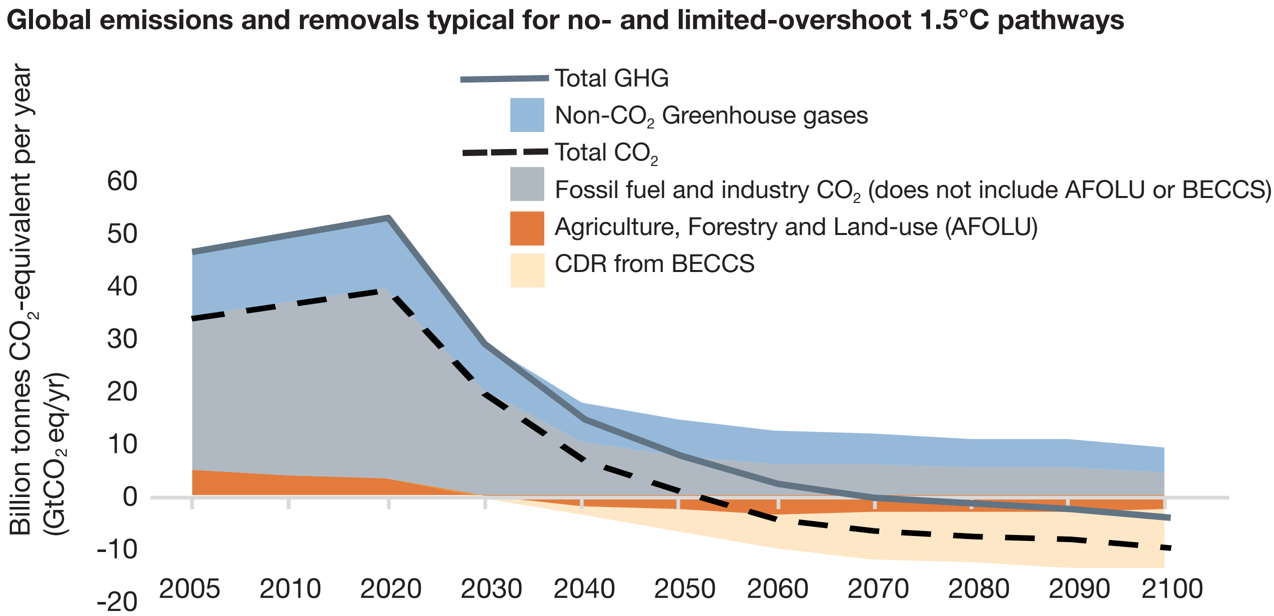
2 Decision 1/CP.21, preamble.

3 The IPCC SR 1.5°C definition of *"anthropogenic removals"* is the *"withdrawal of GHGs from the atmosphere as a result of deliberate human activities. These include enhancing biological sinks of CO2 and using chemical engineering to achieve long-term removal and storage. Carbon capture and storage (CCS) from industrial and energy-related sources, which alone does not remove CO_2 from the atmosphere, can reduce atmospheric CO_2 if it is combined with bioenergy production".* Removals commonly refer to CO_2, as very little data and literature is available on anthropogenic removals of other GHGs (for an exception see Ming et al. 2016) the average global temperature will still increase during this century. A lot of research has been devoted to prevent and reduce the amount of carbon dioxide (CO_2).

4 Following the IPCC SR 1.5°C these are defined as pathways with no or limited overshoot of 1.5°C in that they give at least 50% probability based on current knowledge of limiting global warming to below 1.5°C ('no overshoot') and/or limit warming to below 1.6°C (maximum 0.1°C overshoot) and return to 1.5°C or below by 2100 ('limited-overshoot').

though the extent of this reliance varies across pathways. CDR also plays a major role in the vast majority of scenarios that limit global temperature rise to 2°C.

Figure 1. Total global CO_2 and GHG emissions for 1.5°C-compatible pathways in IPCC Special Report on 1.5°C (IPCC SR1.5). These pathways typically require substantial levels of Carbon Dioxide Removal (CDR) to limit global warming to 1.5°C, both to compensate for limited mitigation action to date and to compensate for remaining CO_2 and non-CO_2 in sectors where the scientific literature shows reaching zero emissions will not be feasible. CDR is achieved in these pathways at a global level via Afforestation/Reforestation — leading to global CO_2 removals in the sector of Agriculture, Forestry and Land-Use (AFOLU) — as well as via BioEnergy combined with Carbon Capture and Storage (BECCS). All emissions and removals where calculated from the median emissions levels across the 46 pathways in the IPCC SR1.5 scenario database that are 1.5°C compatible and that reported data for all variables included here (Source: IPCC SR1.5 scenario database https://data.ene.iiasa.ac.at/iamc-1.5c-explorer, accessed 22 October, 2018)



A number of potential terrestrial CDR options have been identified (see Table 1), but these are at different stages of maturity and few examples currently exist of successful large-scale CDR operations, aside from Afforestation and Reforestation. The rapid scaling-up of large-scale CDR options is untested and will require international governance systems capable of addressing a range of sensitive issues and challenges, e.g., responsibility for funding and hosting possible CDR options; accounting, monitoring, reporting and verification of CDR; systems for managing, minimizing and avoiding environmental and social impacts; systems to share benefits among actors and costs among beneficiaries; systems to manage future liability; and systems and models for international cooperation. Consideration needs to be given to geophysical, environmental, technological, economic, social-cultural and institutional enabling conditions. International cooperation can be expected to play a role, particularly in developing countries, in supporting and creating the necessary conditions for large-scale initiatives.

In this study we consider the potential scale and pace of CO_2 removals needed to meet the Paris Agreement goals, existing and emerging provisions under the UNFCCC rules and Paris Agreement governing anthropogenic CO_2 removals and then identify significant governance gaps and challenges at the international level that policymakers need to address as soon as possible. Framing considerations for identifying challenges include ensuring that scaling-up CDR measures are sustainable and can be governed equitably and effectively.

We will focus on three specific CDR options:

1) Afforestation and Reforestation (A/R)[5];
2) Bioenergy with Carbon Capture and Storage (BECCS); and
3) Direct Air Capture with Carbon Capture and Storage (DACCS).

5 Although we specifically address Afforestation and Reforestation (A/R), large-scale land restoration would raise similar governance challenges at scale.

We focus on these options due to their potential for low-cost up-scaling (A/R), their potential to create sustainability challenges at various level of governance (A/R, BECCS), their unique governance challenges in the context of transboundary transfers (BECCS, DACCS) and their need for investment and incentivization to support commercialization (BECCS, DACCS).

Table 1 below shows options identified in the scientific literature that achieve net Carbon Dioxide Removal and their definitions, as included in IPCC SR 1.5°C. Note that other options exist. The scientific literature that achieve net Carbon Dioxide Removal, showing definitions as included in IPCC SR15. Note that this IPCC list is not an exhaustive list and other options exist, such as CDR by ecosystem restoration. the scientific literature identifies a number of additional potential options for enhancing terrestrial sinks exist beyond A/R, including ecosystem restoration (both on land and along coastlines) and soil carbon sequestration. These options are often low cost, and could be more rapidly deployed than technological CDR options such as BECCS and DACCS, although their potential falls far short of what is needed in terms of CDR. Many would raise similar governance challenges to A/R when deployed at large-scale (e.g., issues related to monitoring, reporting and verification, permanence) and they are not a specific focus of this report.

Table 1. Options identified in the scientific literature that achieve net Carbon Dioxide Removal, showing definitions as included in IPCC SR 1.5°C.[6] Note that this IPCC list is not an exhaustive list and other options exist, such as CDR by ecosystem restoration.

IPCC SR 1.5°C Glossary
Afforestation Planting of new forests on lands that historically have not contained forests.
Reforestation Planting of forests on lands that have previously contained forests but that have been converted to some other use.
Bioenergy with carbon dioxide capture and storage (BECCS) Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility.
Direct air carbon dioxide capture and storage (DACCS) Chemical process by which CO_2 is captured directly from the ambient air, with subsequent storage. Also known as direct air capture and storage (DACS).
Biochar Stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Biochar may be added to soils to improve soil functions and to reduce greenhouse gas emissions from biomass and soils, and for carbon sequestration.
Soil carbon sequestration (SCS) Land management changes which increase the soil organic carbon content, resulting in a net removal of CO_2 from the atmosphere.
Enhanced weathering Enhancing the removal of carbon dioxide from the atmosphere through dissolution of silicate and carbonate rocks by grinding these minerals to small particles and actively applying them to soils, coasts or oceans.

6 IPCC SR 1.5°C Glossary also includes a definition of ocean fertilization. However, it is not included in the table here, since Chapter 4 in the IPCC SR 1.5°C notes that "*The London Protocol of the International Maritime Organization has asserted authority for regulation of ocean fertilisation (Strong et al. 2009), which is widely viewed as a, de facto moratorium "on commercial ocean fertilisation activities*". For completeness, the IPCC SR 1.5°C Glossary definition is "*Deliberate increase of nutrient supply to the near-surface ocean in order to enhance biological production through which additional carbon dioxide from the atmosphere is sequestered. This can be achieved by the addition of micro-nutrients or macro-nutrients. Ocean fertilisation is regulated by the London Protocol.*" Substantial doubt has also been raised by the scientific community in relation the efficacy of ocean fertilisation — see for example Williamson, P. et al., 2012.

1) What scale of removals is needed to meet Paris Agreement goals?

In the Paris Agreement of 2015, the international community adopted an ambitious long-term temperature goal, resolving to strengthen the global response to the threat of climate change, by *"[h]olding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels."*[7] This goal is operationalized in Article 4.1 of the Paris Agreement *inter alia* via a global emissions pathway whose key parameters are to be determined based on the best available science:

> " *In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, to undertake rapid reductions … in accordance with best available science, to achieve a balance between anthropogenic emissions by sources and [anthropogenic] removals by sinks of greenhouse gases in the second half of this century, in the context of sustainable development and efforts to eradicate poverty*" (Art. 4.1).

With these Paris Agreement goals in place, attention turns to how the required temperature limit and the emissions pathway required under Art. 4.1 can be operationalized, including defining how, and when this "*balance*" is to be achieved. The IPCC 1.5°C Report makes clear how rapidly reductions need to be achieved to avoid or limit any overshoot of the 1.5°C temperature limit — CO_2 emissions will need to be approximately halved by 2030, and reach zero, or lower, by 2050.[8] The report also shows that total GHG emissions will need to peak by around 2020 and be significantly below present levels by 2030 to reach zero by about 2070, thereby defining the timeframe within the second half of this century by which a balance has to be achieved.[9] As a consequence, systems will need to be found to generate "*negative emissions*" in connection with the basket of GHGs that contribute to global warming.[10] All emissions pathways in the literature show that some GHG emissions cannot be reduced to zero (e.g. remaining nitrous oxide and methane emissions from agriculture — Rogelj et al, 2018). Accordingly, the "*balance*" in Article 4 implies that some level of continuous anthropogenic CO_2 removal will be required to offset the residual GHG (CO_2 and/or non-CO_2) emissions that cannot be reduced below zero, in order to reach global net-zero GHG emissions.

7 See UNFCCC Decisions 10/CP.21 (adopting this goal under the Convention) and 1/CP.21, Annex (embedding this goal in Article 2.1 of the Paris Agreement).

8 IPCC SR 1.5°C, SPM-15, SPM-19.

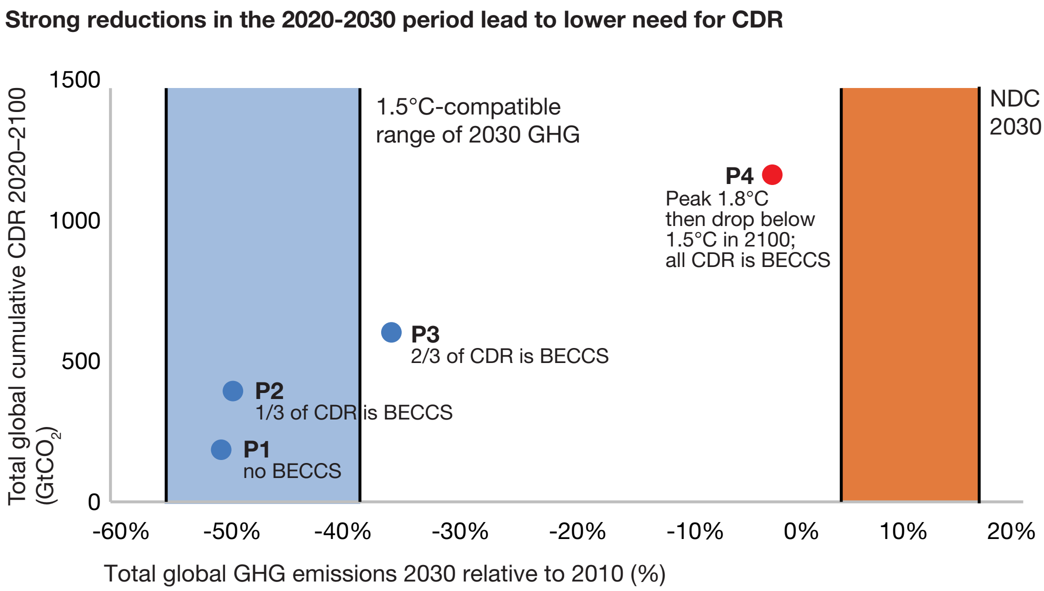
9 This applies to a 50% chance to limit warming to 1.5°C (median) or with a limited overshoot to 1.6°C, accounting for uncertainties in the climate system, non-CO2 greenhouse gases, aerosol pollutants and carbon cycle. Zero emissions would need to be achieved earlier for a 66% chance to limit warming to 1.5°C (a "likely" chance in IPCC terms). Further, the underlying energy-economic pathways show rapid global GHG emissions reductions from 2020 until the point of zero emissions, with the cumulative emissions until that point consistent with total cumulative emissions budgets, calculated using geophysical relationships. Obviously, if global emissions were not reduced and were growing, or kept constant at present-day levels, the emissions budget would be exhausted much earlier.

10 In the background literature of emissions pathways, total greenhouse gas emissions are calculated as the GWP-100 weighted total of individual GHG emissions (see, e.g. IPCC AR5 WGIII).

In addition to the need for CDR to ensure the "*balance*" in Article 4.1, substantial efforts will be necessary to achieve the deep emissions reductions necessary to hold warming well below 2°C and limit it to 1.5°C. The slow pace of emissions reductions to date makes achievement of Article 2.1's long-term global temperature goal challenging. Indeed, most Paris Agreement (PA)-consistent emissions pathways[11] assessed in the recent IPCC SR 1.5°C exceed a warming level of 1.5°C above pre-industrial levels by a small amount (up to 0.1°C), before dropping down to below 1.5°C at the end of the century and typically reach around 1.3°C by 2100. All of these PA-consistent pathways rely on a contribution from potential CDR options, though the extent of this reliance varies across pathways, ranging from 100 to 1,000 $GtCO_2$ cumulatively over the 21st century.

The IPCC SR 1.5ºC frames some of its considerations of feasibility and sustainability using four "*illustrative*" pathways (P1-P4), which are represented by dots in Figure 2. These four pathways vary greatly in their reliance on CDR options as a function of the global emissions reductions achieved by 2030. The global total GHG emissions reduction achieved by 2030 will of course be a prime indicator of the overall mitigation ambition level represented by NDCs (represented by the orange bar in Figure 2). There are no mitigation pathways in the scientific literature that reach the PA goals from these NDC-consistent 2030 emissions levels[12]. Continuing the level of ambition represented by NDCs submitted so far would result in over 3°C warming by 2100, and still rising into the next century[13], and hence currently submitted NDCs in aggregate fall far short of what is needed to reach the PA goals. NDCs to 2030 need to be enhanced substantially by 2020 to bring expected global GHG emissions by 2030 down to levels represented by the P1-3 pathways in Figure 2.

Figure 2. Total global GHG emissions in 2030 and cumulative Carbon Dioxide Removal (CDR) in the four "illustrative" pathways (P1-P4) in IPCC SR 1.5°C. These pathways require increasing levels of CDR to limit global warming to 1.5°C as 2030 GHG emissions levels are higher — with increasing relative shares of total CDR supplied by Bioenergy with Carbon Capture and Storage (BECCS). Note the P1 pathway was developed specifically to limit global warming to 1.5°C without CCS (and hence without BECCS). P4 is labelled red to indicate that it is not consistent with limiting global warming to 1.5°C, as it exceeds 1.5°C around mid-century by as much as 0.3°C. (Source: IPCC SR 1.5°C SPM (2018); Rogelj et al. (2018) Supplementary Information; Grubler et al. (2018))



11 We define PA-compatible pathways here as those that are referred to in the IPCC SR 1.5°C with no or limited overshoot. See IPCC SR 1.5°C Box SPM 1: Core Concepts Central to this Special Report. The report also assessed pathways where global warming exceeds 1.5°C by as much as 0.4°C before reaching 1.5°C by 2100, which is typified as "high overshoot". Given their peak warming at 1.9°C, this is not considered to be "well below 2°C" and hence not considered here as consistent to the Paris Agreement aim. For a broader discussion of emissions scenarios in the context of the Paris Agreement, see Schleussner et al (2016).

12 *In extremis*, this would lock in substantial overshoot of the 1.5° warming level, and would lead to the requirement for much larger levels of CDR then presently seen in the cost optimal integrated assessment models, and which would exceed sustainability boundaries.

13 See https://climateactiontracker.org/global/cat-thermometer

While these "*illustrative pathways*" make it immediately clear that stronger global GHG emissions reductions by 2030 lead to a smaller need for CDR over the 21st century to achieve the long-term temperature goal, the need for CDR is still substantial. The P4 illustrative pathway relies on CDR at even larger scale than the other pathways to get back to 1.5°C by 2100, but is not consistent with limiting global warming to 1.5°C as it exceeds this limit around mid-century by as much as 0.3 °C.

The relationship between 2030 mitigation ambition and CDR reliance is an essential one to understand in considering the governance-related dimensions of CDR — the core subject of this briefing. Current NDCs are recognized as insufficient for consistency with the Paris Agreement's long-term temperature goal. At the same time, CDR options raise questions of social acceptability and environmental sustainability, food security and feasibility of large-scale deployment amongst other issues. If Parties bring forward new and updated NDCs by 2020 that are substantially more ambitious in the reductions they will deliver for 2030, this can reduce future reliance on CDR options that are untested at scale.

What is also clear from Figure 2 is that the relative contribution of different CDR options, approaches and technologies differs substantially between these four pathways, depending on GHG emission levels in 2030. The primary CDR options built into the underlying models that limit warming to 1.5°C are BECCS and Afforestation & Reforestation (A/R) (IPCC SR 1.5°C SPM at C3.1). Both BECCS and A/R are explicitly represented at a process level in the models. This means various vegetation types and their carbon-cycle characteristics are resolved, as are the life-cycle emissions of harvest and decay, as well as uptake by re-growth, efficiency of bioenergy as a feedstock for power plants. As illustrated in Figure 2, not only does the total cumulative CDR reliance increase depending on the 2030 emissions level, but also the share of BECCS in total CDR and in absolute terms.

Historically, most existing model scenarios rely largely on BECCS[14] and A/R for CDR, because these options have been studied the most, considered to be the most plausible and estimated to be cost effective at scale. However, concerns over the sustainability of large-scale biomass energy, the CCS components of BECCS and A/R deployment (see section 4), as well as growing research on other potential CDR options, mean that the scientific community is starting to build in other options, including additional land-based approaches and DACCS. The next generation of modelling will undoubtedly include a wider range of options, both land-based and technology-based, to expand the portfolio of approaches available to meet climate targets and sustainability boundaries.

The declining cost of renewable energy technology and advances in electrolysis and related technologies have led to a resurgence of interest in DACCS which may have cost-effective applications in high penetration renewable energy systems.[15] Recent studies indicate potential for this at scale (Wohland et al., 2018).

For 1.5°C-compatible[16] pathways in IPCC SR1.5°C, annual rates of BECCS deployment range from 0-1, 0-8, and 0-16 $GtCO_2$/yr in 2030, 2050 and 2100 respectively, while A/R ranges from 0-5, 1-11 and 1-5 $GtCO_2$/yr in those years. By mid-century, values at the upper end of these ranges exceed the assessed potential for BECCS of up to 5 $GtCO_2$/yr and for A/R of up to 3.6 $GtCO_2$/yr, if sustainability concerns and land-use priorities are accounted for.

At the higher end, potential CDR numbers are comparable in magnitude to the present-day net CO_2 uptake by the global terrestrial biosphere (due to natural processes rather than direct human impacts) of around 11 $GtCO_2$/yr (average for 2007-2016; (Le Quéré et al., 2018)). To place these numbers into the context of human-induced emissions, the current net emissions from land use, land use change and forestry are about 1.3 $GtCO_2$/yr; these emissions will have to be brought to zero and then reversed in the next 1-2 decades. This is an important illustration of the scale of the CDR governance task.

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14 See for a historical perspective: https://www.carbonbrief.org/beccs-the-story-of-climate-changes-saviour-technology

15 https://www.carbonbrief.org/combining-renewables-with-direct-air-capture-for-net-negative-emissions

16 Meaning Paris Agreement-consistent pathways such as P1-P3 — but not "high-overshoot" pathways, such as P4, which relies on higher levels of CDR.

Avoiding or limiting overshoot will be essential to minimize climate change impacts. High-overshoot pathways, such as the P4 pathway mentioned above, return warming to 1.5°C by 2100, but achieve this after an overshoot to as much as 1.8°C, which is clearly not "*well below 2°C*" as specified in PA Article 2.1 and would be associated with climate risks, impacts and damages close to 2°C. These pathways are therefore not compatible with the Paris Agreement long-term temperature goal. Indeed, IPCC SR1.5 SPM notes:

> "*Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (high confidence).*"

We draw four key conclusions from this brief assessment:

1. Substantial amounts of CDR will likely be needed over the remainder of the 21st century even if NDCs are ratcheted up substantially, given insufficient global mitigation action to date.
2. An even more significant contribution from CDR would be needed if NDCs were only *modestly* ratcheted up; if NDCs were ratcheted up only *marginally*, limiting warming to 1.5°C without a substantial overshoot for an extended period of time may be out of reach completely.
3. A broad portfolio of CDR options would be required to meet the overall need for CDR, to avoid dependence on any single option that would have its own limitations at scale and/or unsurmountable sustainability concerns at larger scale.
4. CDR activities and technologies will need to be rolled out sooner rather than later, as delay in deployment and hence capacity to rapidly scale-up a portfolio of options creates substantial future risk due to policy failure and the need to compensate for carbon cycle feedbacks such as melting permafrost (Comyn-Platt et al., 2018) or heat and drought induce loss of carbon from the terrestrial biosphere.

2) How do current provisions under the UNFCCC, Kyoto Protocol and Paris Agreement address removals?

International governance for CDR currently lies largely under the United Nations Framework Convention on Climate Change (UNFCCC) and its related processes. **Decisions taken under the UNFCCC provide for the use of IPCC guidelines for the development of greenhouse gas inventories; IPCC guidelines in turn address reporting on anthropogenic removals in the land sector and CCS in the energy sector. Decisions taken under the Kyoto Protocol set out how removals in the land sector contribute to emissions reductions targets ("accounting").** However, these provisions were not designed for the scale of removals required for the Paris Agreement's long-term temperature goal, nor are they appropriate for all potential options for CDR, and a number of governance gaps remain. The adoption of the Paris Agreement and the release of the IPCC's SR 1.5°C brings new focus on the need for international governance of CDR that addresses the potential scale of CDR in fulfilling the objective of the Paris Agreement, and existing governance gaps in global measuring, reporting and accounting systems.

The rules being developed under the Paris Agreement draw from the differing provisions related to removals under the UNFCCC and Kyoto Protocol. It is useful to consider the legacy effects of these different rule sets, including the gaps they have created, for example, between developed and developing country inventory reporting of removals. This section describes existing provisions under the UNFCCC, the Kyoto Protocol and the Paris Agreement, noting the existing challenges for assessing whether progress is being made toward a balance between anthropogenic emissions and removals, either at the country or collective level. It then very briefly identifies specific IPCC reporting guidance related to A/R, BECCS and CCS.

1. UNFCCC reporting on emissions and removals

The UNFCCC requires all Parties to *"[p]romote sustainable management, and promote and cooperate in the conservation and enhancement of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans, as well as other terrestrial, coastal and marine ecosystems*"(Art 4.1(d)). Each Party is required under Article 4 to regularly communicate a national inventory of anthropogenic ***emissions by sources*** and ***removals by sinks*** using comparable methodologies, and each Party reports inventories both including the land sector and excluding the land sector. The Convention places differentiated reporting obligations on developed countries, in recognition of their national capacities and circumstances.

Since 2015, developed countries ("*Annex I*" Parties) have been required to report their GHG inventories annually, using the **2006 IPCC Guidelines,** as well as ***the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories,*** and the ***IPCC Good Practice Guidance for Land Use, Land-use Change and Forestry (GPG-LULUCF).***[17] Emissions are reported on a gas by gas basis, in tonnes of CO_2-equivalent emissions, applying 100-year global warming potential (GWP-100) values from the IPCC's Fourth Assessment Report.[18] Emissions and

17 Decision 24/CP.19

18 Decision 24/CP.19, Annex III.

removals are allocated to different source and sink categories according to prescribed Common Reporting Format tables,[19] with emissions by sources listed separately from removals by sinks, except in cases where it may be technically impossible to separate information on sources and sinks from Land use, Land-use Change and Forestry (LULUCF). Reporting on the land sector under the Convention by Annex I Parties is "*comprehensive*", meaning that all categories of land use and all carbon pools are to be reported (Iversen et al., 2014).

Annex I Party national communications, containing annual GHG inventory reports, are supplemented by **Biennial Reports (BRs)**, through which these Parties report on progress made in achieving their quantified economy-wide emission reduction targets under the Convention, and emission projections for 2020 and 2030.[20] They are asked to state the role of LULUCF in their base year and target year (included or excluded), and whether the contribution of LULUCF is calculated using a ***land-based approach, activity-based approach or other specified approach***,[21] acknowledging the difference in accounting treatment applied by Parties under the Convention and those Convention Parties that are also Annex B Parties to the Protocol. National GHG Inventories and biennial reports are subject to technical reviews.

Developing countries ("*Non-Annex I Parties*"), in contrast, submit GHG inventories every four years,[22] and update these inventories every two years through **Biennial Update Reports (BURs)** which also include information on their mitigation actions. Inventories are to be no older than four years prior to the year of submission, with more recent years submitted if available.[23] Least developed country Parties and small island developing States may submit BURs at their discretion.[24]

Developing country inventory updates use the IPCC's **1996 Guidelines** and ***GPG-LULUCF***. Most developing countries use GWP values from the IPCC's Second Assessment Report. Developing countries are encouraged to use tabular reporting formats for the land sector but are not required to produce information in an equivalent format as that for developed countries, or at a similar level of detail.[25] Those developing countries that aim to receive "*results-based finance*" for mitigation efforts related to Reducing Emissions from Deforestation and Forest Degradation and related measures (REDD+) apply specific REDD+ guidance, which addresses, among other issues, a range of sustainability concerns.[26] Unlike developed country inventories and BRs, which undergo a technical review, developing country inventories and BURs are subject to technical analysis.[27]

Although reporting and review obligations for developed and developing countries have moved closer together in recent years, the differences in these obligations continues to present a fundamental challenge for any assessment of progress toward global goals. Inventory data still cannot be readily aggregated across all Parties due to a series of issues that perpetuate differentiation in the treatment of inventory data. These include: differing reporting requirements for developed and developing country Parties; use of different IPCC reporting guidelines (2006 and 1996); application of different GWPs to the underlying GHG data reported; different frequency of inventory reporting; different treatment of the land sector by developed and developing countries (land-based v. activity based for Kyoto Parties); and the absence of common reporting format tables used by all Parties (Annex I Parties use Common Reporting Format software consistent with Annex I reporting guidelines and Kyoto land sector accounting rules; developing countries do not use this common software).

The absence at present of equivalent coverage across different countries for the land sector, as well as across other inventory categories is a challenge to adequate governance of CDR measures globally. Understanding what CDR is happening requires comparable levels of reporting to enable country based and aggregated assessments of CDR, taking into account a full range of sectors within each country.

19 Decision 24/CP.19, Annex II.

20 Decision 2/CP.17, Annex I.

21 Decision 19/CP.18.

22 Decision 1/CP.16, para 59.

23 Decision 2/CP.17, para 41.

24 Decision 2/CP.17.

25 Decision 2/CP.17.

26 See e.g. Decisions 1/CP.16, 2/CP.17, 12/CP.17, 9/CP.19, 10/CP.19, 11/CP.19, 12/CP.19

27 Decision 2/CP.17, Annex IV.

2. Kyoto Protocol provisions related to the land sector and CCS

Reporting and accounting rules for the land sector

The Kyoto Protocol takes an "*activity-based*" approach to the land sector for Parties with quantified mitigation targets, as contrasted with the Convention's comprehensive "*land-based"* approach for developed country Parties.

Parties that take quantified mitigation targets agree to reduce or limit their future emission levels relative to their base year emission levels over a fixed commitment period. In accounting for their targets, Parties must add to their sectoral emissions (from energy, industrial processes and solvent use, agriculture, waste) their net changes in emissions by sources and removals by sinks from direct human-induced land-use change and forestry activities limited, under Article 3.3 of the Protocol, to ***afforestation, reforestation and deforestation*** since 1990, measured as verifiable changes in carbon stocks in each commitment period. Under Article 3.4 of the Protocol, Parties could also elect to include net emissions and removals from certain additional "*activities*" — ***forest management***, ***cropland management***, ***grazing land management*** and ***revegetation*** — if they so chose. This list was expanded in the second Kyoto commitment period (2013-2020) to make forest management a mandatory activity for accounting purposes, and to include wetlands drainage and rewetting as another activity which could be elected for accounting by Parties, in a move toward more inclusive coverage.[28]

In effect, Protocol Parties were given the flexibility to use net removals from mitigation efforts in the land sector to offset emissions in other sectors of their economies. Parties with net removals could issue "*removal units*" (RMUs) that they could use to offset emissions in other sectors for purposes of complying with their quantified targets. However, due to concerns with estimation uncertainties in the land sector, and concerns that net removals achieved in a given period might be re-emitted into the atmosphere, limits were placed on the amount of units that could be used for demonstrating compliance and Parties were prevented from carrying over surplus units to use against future quantified targets. [29] So while the Kyoto Protocol accounting system provided ***incentives*** to Parties to undertake activities in the land sector, these incentives were also limited.

LULUCF accounting rules for the first commitment period were criticized among other things for not offering sufficient incentives in the forest sector, and for creating accounting loopholes that undermined environmental integrity by permitting asymmetric accounting — allowing Parties to choose to include only beneficial activities (Krug, 2018). In partial response, rules for the second commitment period made forest management accounting a mandatory activity.[30] To accommodate different national circumstances (such as harvesting cycles or legacy effects of previous management), Parties were permitted to propose *"forest management reference levels (FMRLs)"* against which they would compare their performance.[31] FMRLs were established using a variety of approaches, but all were subjected to technical review. While FMRLs provided an incentive structure for forest-based mitigation that had been lacking in the first commitment period, they also allowed some anthropogenic emissions included under these reference levels to go unaccounted towards national emissions targets.

Under the Protocol, Parties report and account for emissions and removals from carbon stocked in harvested wood products (HWPs) such as timber and fuelwood. Parties are permitted, under certain conditions to exclude from accounting emissions from natural disturbances (e.g., provided they do not to account for subsequent removals in the land excluded from accounting due to natural disturbance), under the rationale that emissions from natural disturbances do not reflect human

28 See *Kyoto Protocol second commitment period User-friendly document Consolidated decisions from the second commitment period* 23 February 2016, available at https://unfccc.int/sites/default/files/kp_2nd_cp_userfriendly_doc_23feb2016_final_2.pdf

29 Kyoto Protocol Reference Manual (UNFCCC) at 98; Krug, 2018)

30 See Decisions 1/CP.16 and 2/CMP.7, setting out accounting rules for the LULUCF sector for the KP second commitment period.

31 See Decisions 2/CMP.6 and 2/CMP.7.

intervention. Emissions from HWPs are reported and accounted for by the producing country. Where HWPs are moved across borders between two Kyoto Protocol Parties with quantified emissions targets, imported HWPs are not accounted for by the importing country, to avoid double-counting.[32]

The asymmetric accounting possibilities created under the Kyoto Protocol via the activity-based approach for land accounting would, if propagated to the Paris Agreement, create serious challenges for the adequate governance of CDR activities globally. Structural asymmetric accounting creates the possibility, and indeed incentive, to count only beneficial activities (carbon storage) and omit activities that lead to CO_2 releases. Under the Kyoto Protocol architecture this can occur for a variety of reasons, ranging from the structure of activities reported through to the discounting of natural disturbance-induced carbon losses from managed land for which credits have already been accounted.

Project-based mechanisms under the Kyoto Protocol

The Kyoto Protocol established two project-based mechanisms that provided ***further incentives*** for CDR approaches. Parties were allowed to use units generated from emissions reductions achieved in other Parties toward their own targets under Articles 6 (Joint Implementation (JI) and 12 (the Clean Development Mechanism (CDM). Methodologies for ***Afforestation and reforestation*** (A/R) project activities and for ***carbon capture and storage*** activities were developed.

Relatively few A/R projects have been registered,[33] in part because removals associated with A/R activities are potentially non-permanent, and it was agreed that the units resulting from these projects would only be valid for a specific period of time, thus having to be replaced by another type of CDM project. The substantial political problems encountered by the Kyoto Protocol, and related low demand for the emission removal units generated by A/R activities, seem to be the most likely explanation for the lack of use of the methods agreed.

No CCS projects have ever been approved, despite procedures to manage a range of physical and accounting risks, including risks of seepage and liability.[34] As with A/R activities the most likely explanation for lack of use of the CCS methodologies is lower than expected carbon price (Dixon et al., 2013) and hence lack of incentive to actually deploy CCS technologies in practice: CCS has not yet been deployed at scale in the power sector, where most demand would ultimately be.

The methodologies developed for A/R and CCS under the Kyoto Protocol are generally viewed as robust and if adapted to the Paris Agreement may assist in some of the governance challenges identified in this report for CDR.

3. Paris Agreement provisions related to the land sector

The *Paris Agreement* now requires each Party to communicate a nationally determined contribution (NDC) every five years, setting out its planned domestic mitigation efforts. Each successive NDC is to represent a progression beyond the previous NDC and represent highest possible ambition.[35] Developed countries are expected to take the lead by undertaking economy-wide absolute emission reduction targets; developing countries are encouraged to move over time towards economy-wide emission reduction or limitation targets.

Article 4 of the Paris Agreement requires Parties to pursue domestic mitigation measures, with the aim of achieving these objectives. In addition, Article 5 of the Agreement specifically provides that

32 Decision 2/CMP.7, para 26-27.

33 See UNEP DTU CDM Pipeline, http://www.cdmpipeline.org/cdm-projects-type.htm#1, accessed October 27, 2018 (A/R projects in developing countries constituted 71 projects in total, 0.8% of registered CDM project activities and 0.7% of issued certified emission reductions (CERs).; A/R and avoided deforestation projects in developed countries constituted 3 projects in total, 0.4% of JI project activities and 1% of issued emission reduction units (ERUs)).

34 See Decision 10/CMP.7.

35 Article 4.3.

Parties should take action to conserve and enhance, as appropriate, sinks and reservoirs of GHGs.[36] Parties are encouraged to implement and support, **including through results-based payments,** policy approaches and positive incentives for activities relating to reducing emissions from deforestation and forest degradation, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries.

Because Parties were given little guidance on how to present their intended NDCs before adoption of the Paris Agreement, NDCs address the land sector in many different ways. Nevertheless, as under the Kyoto Protocol, ***each Party is required to account for its NDC target*** **(Art. 4.13).** The challenge is that the Agreement contains no defined rules on what aspects of LULUCF need to be accounted, how they should be accounted or which methods are to be applied (Krug, 2018).

Article 4.13 does provide, however, that *"[i]n accounting for anthropogenic emissions and removals corresponding to their nationally determined contributions, Parties shall promote environmental integrity, transparency, accuracy, completeness, comparability and consistency, and ensure the avoidance of double counting,"* in accordance with guidance to be adopted by the Parties to the Paris Agreement. These so-called "TACCC" principles (transparency, accuracy, completeness, comparability and consistency) have already been defined in developed country reporting guidelines under the Convention. Paris Agreement Parties have also agreed to account for anthropogenic emissions and removals in accordance with methodologies and common metrics assessed by the IPCC and adopted by the Parties to the Paris Agreement.[37] Parties are to strive to include all categories of anthropogenic emissions or removals in their NDCs, and once a source, sink or activity is included, Parties must continue to include it. Accounting guidance will only be mandatory in the second NDC period, though it may be applied voluntarily to Parties' first NDCs.[38]

The Paris Agreement maintains a clear distinction between the ***reporting of Parties' GHG inventories*** — including removals — on the one hand, and ***accounting for Parties' NDCs*** on the other. This distinction is particularly important because NDC efforts are not co-extensive with emissions inventories. Many developing country NDCs, for example, do not present absolute reductions relative to a base year, many are not economy-wide, many do not encompass all inventory sectors or align with these sectors, and many do not cover all Kyoto gases (Herold et al., 2018). Different metrics have also been presented to calculate their climate impacts. Significantly, not all NDCs specify whether their land sector is included, or if it is, how emissions and removals from the land sector will be accounted (e.g., through a land based approach, activity-based approach or other) (Herold et al., 2018). So while reported GHG inventories are expected to give a comprehensive picture of a Party's emissions and removals, at present, for many Parties, the emissions and removals that must be accounted toward these NDC targets under Article 4.13 remain unclear and will not be co-extensive with emissions inventories. These aspects make it challenging to aggregate these planned efforts to determine their future impact.

The Parties have agreed to adopt common guidance for reporting and review as part of the Paris Agreement's "*Enhanced transparency framework"*, with built-in flexibility to take into account Parties' different capacities, which will build on and supersede the existing framework. As part of this enhanced framework, all Parties are required to provide national inventory reports *at least* biennially (though they must maintain at least the frequency and quality of their reporting under the Convention[39] — thus annual inventories must continue to be presented by developed country Parties), and all Parties are required to provide information necessary to track progress made in implementing and achieving their NDCs.[40] Submitted information will be subject to a ***technical expert review*** and each Party will participate in a multilateral process that considers its progress in implementing and achieving its NDC. A *Capacity Building Initiative for Transparency* will support

36 The UNFCCC defines "sink" as "any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere"; "reservoir" is defined as "a component or components of the climate system where a greenhouse gas or a precursor of a greenhouse gas is stored."

37 See Decision 1/CP.21, para 32.

38 Decision 1/CP.21, para 32.

39 Decision 1/CP.21, para 92.

40 Article 13.7

developing countries in meeting enhanced transparency requirements.[41] ***A Global Stocktake*** every five years will assess the overall effect of Parties' NDCs as well as collective progress in the context of the Agreement's global temperature increase limitation goal, to inform the ambition of Parties' successive NDCs.

Unlike the Kyoto Protocol, Parties no longer account for domestic targets through allowances calculated from their quantified targets. However, opportunities remain for using reductions achieved in other Parties towards domestic targets. Parties are mandated to develop guidance for ***"cooperative approaches***" under Art. 6.2 that involve the international transfer of mitigation outcomes between Parties, to ensure that corresponding adjustments between Parties reflect the accounting impacts of these transfers and avoid double counting.[42] Article 6.4 establishes a mechanism with centralized oversight that will contribute to the mitigation of GHG emissions and support sustainable development. It also aims to deliver an "*overall mitigation in global emissions*", though how this is to be operationalized is not specified.

4. Challenges for assessing progress towards the Paris Agreement long-term temperature goal

The Paris Agreement takes a step forward, moving to more regular inventory reporting by all Parties, accounting by all Parties and a process for the aggregation of GHG inventories and efforts across both developed and developing Parties (Mace, 2016). This aggregation of GHG inventories to the global scale, as well as aggregation of the effects of policies and NDCs, is critical to assessing progress towards the Paris Agreement's long-term temperature goal and critical for assessing whether GHG anthropogenic emissions and removals are progressing globally towards the balance needed by around 2070. Significant challenges nonetheless remain for aggregation at the country and collective levels:

- **Current NDCs are presented with different timeframes, use a range of reference years and apply different GWPs** — and there is no guidance yet in place for common timeframes or on common features of future NDCs.
- **NDCs are not yet co-extensive with GHG inventories —** many Parties' NDCs cover only a subset of their GHG emission profiles, NDC sectors may not map on to inventory sectors neatly, and NDCs often lack a clear articulation of their relationship with Parties' inventories.
- **GHG inventories do not cover all emissions within the scope of the Paris Agreement** — the Agreement implicitly covers emissions from international aviation and maritime transport, but systems are needed to ensure that these emissions are included in assessing progress toward Paris Agreement goals, and that the same emission reductions are not counted under multiple treaty processes, undermining treaty aims (e.g, counted under both the PA and as offsets by aviation operators under ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which aims to maintain international aviation emissions at 2020 levels).
- **Accounting for the land sector within and across NDCs** — some NDCs do not address the land sector, or present unquantified policies and measures in the land sector. Where the land sector is clearly included, it may not be clear how Parties intend to account for emissions and removals and common accounting approaches for the land sector have not yet been agreed.
- **NDC accounting guidance will remain voluntary for the first NDC period** — though Parties are required to account for their NDC-related emissions and removals under Article 4.10.
- **Time lags in reporting and review** — developing countries are required to report inventories for calendar years no older than 4 years prior to the date of inventory submissions; developed countries report for calendar years no older than 2 years prior. This will lead to delays in aggregating the results of reviewed inventories. Reviews of inventories and progress reports may also be delayed or become out of synch, due to the number of Parties involved.
- **Accounting balances** — there is a need to keep reporting of progress on implementation and achievement of NDCs distinct from ongoing inventory reporting; "*accounting balances*" and "*structured summaries*" have been proposed as a tool for facilitating the tracking of emissions

41 Decision 1/CP.21, paras. 24-25.

42 Decision 1/CP.21, para 36.

and removals in the land sector and tracking transfers of ITMOs, but no format has yet been agreed.[43]

- **Common reporting formats** — common formats and tables can facilitate calculation of progress toward net-zero emission levels at the national and international levels, but are not required of all Parties' inventories.
- **Capacity challenges** — many developing countries face capacity challenges in producing regular, reliable and complete GHG inventories; how the necessary flexibility will be built in to the enhanced transparency framework has yet to be established.
- **Avoidance of double counting** — In the absence of robust accounting rules, potential exists for emission reductions to be counted by multiple Parties, multiple stakeholders, multiple programmes and possibly multiple treaty processes (for example, in offsets under Article 6, or in connection with ICAO's CORSIA).
- **2050 net zero low emission strategies** — Parties have been invited to submit 2050 strategies by 2020, but few Parties have done so. These strategies can be an opportunity to address the need for scaling up CDR and at the same time address sustainability and governance issues.

5. IPCC Guidelines relevant to A/R, CCS and BECCS

The IPCC provides the scientific authority for national greenhouse gas inventories under the Convention and reporting under the Kyoto Protocol and has a Task Force on National Greenhouse Gas Inventories for this purpose.[44] To date the IPCC has responded to reporting and accounting needs under the Convention and Kyoto Protocol, and there is considerable guidance for the land sector. There is also guidance for CCS and bioenergy, however as yet there is no guidance for reporting net removals from DACCS or other more novel forms of CDR.

Beyond reporting guidance, the IPCC has assessed the available literature on CDR in its assessment reports and in the IPCC SR1.5°C. The IPCC has also started work on the *Sixth Assessment Reports*, which will include an assessment of information on potentials, governance, risks and impacts of GHG removal techniques, as well as a chapter on international cooperation that will cover "*transparency and accountability frameworks*".

This section provides a brief outline of existing IPCC guidance as well as the anticipated products from the ongoing Sixth Assessment Cycle that are relevant for CDR governance.

Afforestation / Reforestation and the land sector

As described above, countries report their inventories using either the 1996 Guidelines (developing countries) or the 2006 IPCC Guidelines (primarily developed countries) as well as IPCC guidance on uncertainty management and Good Practice Guidance on LULUCF (GPG-LULUCF). A Wetlands Supplement has been produced to complement reporting of sources for which no reporting methodology was available in the 2006 IPCC Guidelines. For the second period of the Kyoto Protocol, the IPCC also produced an update of the GPG-LULUCF with supplementary methods and good practice guidance for reporting emissions and removals from LULUCF activities.[45]

The IPCC SR 1.5°C includes a definition of CDR[46], which is helpful in addressing the challenge of distinguishing between anthropogenic and non-anthropogenic removals. The definition clearly states that CDR comprises *anthropogenic* activities, and does not include any indirect CO_2 uptake (for example, due to the higher CO_2 concentrations in the atmosphere) or any outgassing from ocean and terrestrial reservoirs, although these indirect effects do have an impact on the amount of CDR

43 Submission by South Africa to the Ad Hoc Working Group on the Paris Agreement and Subsidiary Body for Scientific and Technological Advice on Accounting across Articles 4, 6 and 13 of the Paris Agreement (2018); Submission by Austria and the European Commission on behalf of the European Union and its Member States, Views on Accounting — Proposal for a Structured Summary. Vienna (2018)

44 https://www.ipcc-nggip.iges.or.jp

45 Available here: https://www.ipcc-nggip.iges.or.jp/public/kpsg/index.html

46 See Introduction, above, for this definition.

required in modelled scenarios.[47] The IPCC's forthcoming *Special Report on Climate Change and Land* — due for publication in August 2019 — will further explore the mechanisms behind CO_2 removals in the terrestrial biosphere[48], providing an updated assessment of the role of land in meeting the Paris Agreement objectives.

Carbon Capture and Storage

The Revised IPCC 1996 Guidelines, which are referenced in the Non-Annex I reporting guidelines and BUR guidelines, do not explicitly mention GHG storage, but allow for it to be addressed.[49] The 2006 IPCC Guidelines, used by developed countries and encouraged for use by developing countries, do explicitly cover carbon capture and storage in a dedicated chapter of the volume on energy.[50]

In 2005, the IPCC's Special Report on CCS considered whether CCS should be accounted for on the side of emissions, with CCS systems treated as ***mitigation options*** to reduce emissions to the atmosphere, or as ***sink enhancements*** by analogy to the treatment made to CO_2 removals by sinks in the LULUCF sector (Metz et al., 2005).[51] The first option was considered to offer transparency benefits, because it would enable emissions from captured CO_2 to be tracked through capture, transport, injection and storage, tracked from many sources and tracked across borders. It was also recognized that the second option would require new definitions not available in the UNFCCC or the framework for preparing inventories.[52]

As a result, under the IPCC 2006 Guidelines emissions from industrial processes and energy that are captured may be reported as "*not emitted*", provided they are subsequently stored and subjected to long-term monitoring and reporting.[53] The volume of **CO_2 captured** is reported as a memo item in the CRF sectoral report on energy and not counted toward emission totals. This reporting on CO_2 capture is broken down into "*for domestic storage*" and "*for storage in other countries*." Parties report on Table 1.C as information items the total amount captured for storage, total amount of imports for storage, total amount of exports for storage, total amount of CO_2 injected at storage sites, and total leakage from transport, injection and storage.[54]

Where CO_2 from biomass and CO_2 from fossil fuel emissions are combined for storage, there is no distinction made between the two in accounting. Emissions and storage of both biogenic and fossil carbon will be estimated and reported as memo items in the sectoral report on energy.[55] In the case of release, both are counted in the same way.

It is IPCC good practice to treat capture and storage on a per plant or facility basis. Guidance addresses reporting for cross-border operations. Kyoto Protocol Decision 10/CMP.7 provides project level guidance in the context of the Clean Development Mechanism, addressing site selection and

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47 For every tonne of CO_2 emitted by burning fossil fuels, about half ends up in the atmosphere, while the rest is distributed between the oceans and terrestrial biosphere. When CO_2 is removed from the atmosphere, this process goes into reverse: CO_2 concentrations in the atmosphere drop, causing some outgassing of CO_2 from the oceans and terrestrial biosphere (Jones et al., 2016). Hence the total CO_2 removed from the atmosphere will necessarily be less than the amount of CO_2 sequestered by CDR deployment. In modelled scenarios, the amount of CDR required takes into account the impact of outgassing (as well as changes in atmospheric CO_2 concentrations).

48 The Special Report on Climate Change and Land will include a chapter on interlinkages between land and climate change mitigation. According to the approved outline for this report, it will cover "land-based negative emissions (including the role of forests, soils and the use of biomass) and their role in balancing anthropogenic sources and sinks". At this stage it is not clear how much detail on governance will be included on this topic.

49 IPCC FAQs, Q2-1, https://www.ipcc-nggip.iges.or.jp/faq/FAQ.pdf

50 See 2006 Guidelines, Vol. 2, Chapter 5.

51 IPCC Special Report on CCS Chapter 9, at 366-67.

52 Id at 367.

53 Report to the IEAGHG — GHG Accounting for Bio CCS at 17, citing IPCC Vol. 1, Ch.1, p 1.6.

54 Recycled carbon dioxide (CO_2) for enhanced recovery is excluded from CO_2 transported or injected.

55 See CRF Table 1 Sectoral Report on Energy, n. 1 and CRF Table 1.C Sectoral Background Data for Energy n. 4.

characterization of geological storage sites, risk and safety assessments, environmental and socio-economic impact assessments, monitoring requirements, and systems to account for net reversal of storage (non-permanence).

Given that there are no DACCS reporting guidelines it could be appropriate for the IPCC to engage in this area.

Biomass energy and CCS under current IPCC Guidelines

The IPCC 2006 Guidelines note that "*Negative emissions may arise from the capture and compression system if CO_2 generated by biomass combustion is captured. This is a correct procedure and negative emissions should be reported as such*." [56]

The CRF tables treat **CO_2 emissions from biomass** combustion as a memo item; they are not counted toward energy sector emission totals.[57] The zero-emissions factor applied to biomass results from the assumption that emissions from biomass will be reported in the LULUCF sector at harvest, that biomass is produced in a sustainable manner, and that where biomass is harvested at an unsustainable rate, net CO_2 emissions will be reflected and reported for as a loss of biomass stocks in the LULUCF sector.[58] This assumption may not be valid, for example, if the biomass originates in a country that reports using the default emission factors (tier 1), that may produce a less accurate estimate.

Annex I Parties are required to report biomass-related CO_2 emissions under the LULUCF sector. However, while ***reporting*** by Annex I Parties is intended to be comprehensive, ***lifecycle accounting*** for biomass impacts may not be comprehensive if some Annex I Parties fail to account for certain LULUCF activities, or if biomass is sourced from developing countries that do not provide inventory reports on their land sector emissions annually, or report using a tier 1 approach. Gaps in reporting raise the possibility that the GHG **benefits** of BECCS may count towards GHG commitments of some Parties, while the ***disbenefits of using more carbon intensive biomass*** in BECCS are not visible in the reporting.

The challenge of fully accounting for emissions from bioenergy is not specific to BECCS, but also applies to bioenergy without CCS and the challenges appear likely to be at a similar scale with or without the deployment of CCS coupled to bioenergy. The use of bioenergy has been assessed to be competitive enough to lead to large-scale deployment by 2100 even without any climate mitigation incentives, at a level of deployment comparable to levels reached in 1.5°C and 2°C compatible scenarios by 2050. Critically, this means that reporting and sustainability issues in relation to a growing share of bioenergy in the global energy mix are therefore not a problem unique to 1.5°C scenarios, and need to be addressed under any scenario with or without CDR.

In 2019 the IPCC will release an update to its guidelines for GHG inventories. This will include a refinement to guidance for reporting emissions from harvested wood products used for energy generation, which is relevant for BECCS reporting where the feedstocks are forest residues.

56 2006 IPCC Guidelines at Vol. 2, Ch. 5, 5-8.

57 Table 1, Sectoral Report for Energy, n. 1.

58 Table 1, Sectoral Report for Energy, n. 1.

Table 2: Existing provisions

UNFCCC, Kyoto Protocol and Paris Agreement contexts		Selected provisions*	Key points
Existing provisions from which lessons can be learned	UNFCCC	• Annex I Reporting Guidelines (Decision 24/CP.19) • Non Annex I Reporting Guidelines (Decision 17/CP.8) • Biennial reporting and review guiidelines for developed and developing countries (Decision 2/CP.17) • REDD+ (Decisions 1/CP.16, 2/CP.17, 12/CP.17, 9/CP.19, 10/CP.19, 11/CP.19, 12/CP.19)	Consideration of gaps within and differences between UNFCCC and Kyoto Protocol provisions form a starting point for the Paris Agreement rule-book and highlight the need to move towards consistent and comparable GHG inventories and robust accounting rules for all Parties
	Kyoto Protocol	• Land use, land use change and forestry (Decisions 16/CMP.1, 17/CMP.1, 18/CMP.1) • Afforestation and reforestation under CDM and sink enhancement under JI (Decisions 5/CMP.1, 9/CMP.1, 13/CMP.1, 15/CMP.1) • CCS as CDM project activities (Decisions 10/CMP.7, 5/CMP.8) • The Cancun Agreements: Land use, land use change and forestry (Decision 2/CMP.6) • Second commitment period (Decisions 2/CMP.7, 1/CMP.8, 2/CMP.8, 5/CMP.8)	
Paris Agreement provisions to be built upon	Land sector	• Decision 1/CP.21 • Articles 4, 5, 13, 14	Robust reporting and accounting guidance for NDCs, robust accounting rules for Article 6 transfers, development of land sector accounting rules, an enhanced transparency framework and an effective global stocktake all needed as part of an effective CDR governance architecture
	Assessment of progress toward temperature goal / balance between emissions and removals	• Decision 1/CP.21 • Articles 2, 4, 13, 14	
Existing IPCC guidelines to be built upon	IPCC Guidelines relevant to A/R, CCS and BECCS	• Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories • IPCC Special Report on Land Use, Land-use Change and Forestry, 2000 • Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, 2000 • IPCC Good Practice Guidance for Land Use, Land-use Change and Forestry, 2003 • IPCC Special Report on Carbon Capture and Storage, 2005 • 2006 IPCC Guidelines for National Greenhouse Gas Inventories • 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands	Aditional guidance is needed for reporting lifecycle emissions and removals from bioenergy (with and without CCS) and DACCS. The forthcoming special Report on Climate Change and Land (due in 2019) is expected to provide an updated assessment of the role of land in meeting Paris Agreement objectives
* This listing is not intended to be inclusive, but rather to point to key decisions, provisions and documents.			

3) What governance gaps and challenges exist for CDR at scale?

The central governance challenges for CDR stem from at least four key issues:

- The **scale and speed of implementation required,** and the associated challenges for research and development and for monitoring deployment;
- The **substantial incentives** that will be needed to scale-up potential CDR options, as sufficient incentives do not at present exist under the UNFCCC or other legal frameworks;
- The **trade-offs between, and interactions with, a range of SDGs** (e.g., food security, water security) that may follow from large-scale implementation intended to achieve climate ends; and
- The **risks to the climate system and to the SDGs that will follow if CDR options are not implemented at the pace or scale required,** or if large-scale reversals follow large-scale CDR efforts.

Existing provisions and guidance under the UNFCCC, Kyoto Protocol and Paris Agreement already cover a number of governance issues related to CDR (monitoring, reporting, verification of removals). However, a number of governance challenges remain, and some CDR options have received no specific attention under these frameworks or in the IPCC's reporting guidance (e.g., in what sector should CO_2 capture related to DACCS be reported?).

This section identifies t**en key governance challenges** for the implementation of large-scale CDR:

1. Rapid pace of CDR scale-up required to limit warming to 1.5°C
2. Responsibility and ethics of implementation
3. Incentives for CDR deployment
4. Access to information needed to monitor progress
5. Safeguards for sustainable development
6. Challenges for measuring, reporting and verifying CO2 removals
7. Issues of storage: permanence, leakage and saturation
8. Planning for and monitoring the biophysical effects of deployment
9. Liability and redress
10. Public awareness

1. Rapid pace of CDR scale-up required to limit warming to 1.5°C

By 2050 the median amount of CDR in 1.5°C compatible pathways is already 7 $GtCO_2$/yr, which creates an imperative for a rapid transition from early stages of development to demonstration and deployment. However, many potential CDR options are at a low level of technology readiness, and it may take decades to achieve widespread deployment for these options (Lomax et al., 2015). Most literature to-date has focused on the start of the innovation process, rather than on demonstration and scale-up (Nemet et al. 2018). **Incentives are needed in the near-term for research and development, to boost learning-by-doing and advance less mature options to higher levels of maturity** (Lomax et al. 2015).

The **IPCC SR 1.5ºC** identifies at Table 4.13 a series of knowledge gaps and uncertainties that remain in connection with the scale of CDR required in 1.5°C consistent pathways (IPCC, 2018). These include assessments of environmental aspects for some CDR options; the need for bottom up regional studies on realistically available and sustainable removal potentials, taking into account social issues; issues of governance and public acceptance; impacts of large-scale CDR on the carbon cycle; potential to accelerate deployment and upscaling; and means of incentivisation (IPCC 2018). Many of these challenges are expanded upon below.

2. Responsibility and ethics of implementation

Recent literature has highlighted the need for ethical considerations to be taken into account when developing mitigation scenarios (Lenzi et al., 2018; Minx et al., 2018). The IPCC SR 1.5°C has laid out clearly that delaying mitigation now is not an option, hence the potential availability of CDR options in the future cannot be used to replace near-term inaction without exposing future generations to intolerable risks (Shue, 2018) — risks associated with both climate change impacts from substantially overshooting 1.5°C and the risks of very large-scale CDR. Instead, rapid near-term emissions reductions across all sectors need to be complemented by the development and deployment of sustainable CDR options.

To date there has been no clear assignment or acknowledgement of responsibility for development and deployment of CDR options among Parties to the UNFCCC and/or Paris Agreement, beyond their regional distribution in least-cost model pathways (Peters & Geden, 2017). Parties to the Paris Agreement have not mentioned BECCS nor other technological CDR options in their NDCs, and only a few (about 14) refer to CCS or to CO_2 transport and storage.[59] A number of NDCs do mention A/R activities or other forms of land restoration, pointing to the importance of these options in the near-term. Several of the few long-term strategies submitted to date[60] do include reference to the need for CDR or negative emissions, either explicitly (e.g. Canada, UK, USA), or implicitly, such as in reference to Paris Agreement Article 4.1, or in the definition of concepts like ***"greenhouse gas neutrality"*** (e.g. Germany). However all of these references are limited to the need for such options, not to dimensions of governance.

Treaty overlap is also relevant to discussions of responsibility and ethics. Other treaty processes do contain provisions relevant to CDR, and highlight the need for caution in particular contexts. The Convention on Biological Diversity (CBD), for example, addresses what it terms geoengineeering, which it defines as including both solar radiation modification (SRM) and large-scale CDR.[61] It invites governments to ensure that no climate-related geoengineering that may impact biodiversity takes place until such time as appropriate controls and regulatory mechanisms

59 See Paris Reality Check: https://www.pik-potsdam.de/primap-live/indcs-carbon-capture-and-storage/

60 https://unfccc.int/process/the-paris-agreement/long-term-strategies accessed 22 October, 2018.

61 Definitions of geoengineering differ, and the IPCC refrains from using the term (IPCC, 2018). Under the CBD, geoengineering includes solar radiation management as well as large-scale CDR. There are good reasons for keeping CDR and SRM distinct, see e.g. https://climateanalytics.org/publications/2016/why-negative-co2-emission-technologies-should-not-be-classified-as-geoengineering/. For example, unlike SRM, CDR options address the problem of increased CO_2 concentrations.

are in place and associated risks and impacts have been fully considered.[62] This caution under the CBD was renewed following the adoption of the Paris Agreement, citing an incomplete basis for global regulation and the need for more transdisciplinary research into impacts on biodiversity, ecosystem functions and services, socio-economic, cultural and ethical issues, and regulatory options (CBD, 2012, 2016). Similarly, the London Protocol has asserted its authority over regulation of ocean fertilisation, which is viewed as a *de facto* moratorium on commercial ocean fertilisation activities (IPCC, 2018).

Another element of responsibility becomes relevant once CDR is deployed — responsibility for ensuring that removals are verifiable and that information on these removals is publicly accessible (see liability and redress section below).

3. Incentivising CDR deployment

Direct funding and economic incentives will be needed for the deployment of CDR at the pace and scale required for the Paris Agreement's long-term temperature goal. Currently there are only very weak incentives for CDR (Nemet et al., 2018). To achieve the pace of upscaling anticipated in modelled scenarios, policy packages will be needed in the near-term so that those CDR options that are already mature or being demonstrated can be deployed as soon as possible. Policies will likely need to evolve as more CDR options become available (Lomax et al., 2015).

Policy options could include direct regulation (e.g. a requirement for fossil fuel companies to deploy or finance CDR), subsidies for deployment, government support to reduce investment risks, or the adaptation of existing policy mechanisms (e.g. use of agricultural policy to incentivize soil carbon sequestration or biochar (Lomax et al., 2015; Nemet et al., 2018a). Where benefits of a specific CDR option for sustainable development are identified — such as flood control or improved soil quality in the case of ecosystem restoration, or job creation for deploying and monitoring CDR — this could also provide an incentive.

Further research is needed to improve understanding of how to incentivize early deployment, develop niche markets, and scale-up and maintain CDR activities (IPCC SR 1.5°C). In many cases lessons may be learned from other technologies that have already made the journey to commercialization (Nemet et al., 2018). However, challenges will continue in the longer-term, even after commercialization; once country emissions begin to go net negative, further incentives will be needed to drive ongoing negative emissions. Successful implementation will also require transparent and effective monitoring and verification, and robust reporting and accounting rules (see below).

4. Access to information for monitoring progress

A significant challenge that will arise once CDR starts to be deployed at scale is **how best to monitor progress towards the goal of balancing emissions and removals**. Under the Paris Agreement's transparency framework there are no provisions for separating removals and emissions neatly to feed into this assessment, and there is as yet no detail on accounting rules for LULUCF emissions and removals, resulting in considerable uncertainty in how Parties will monitor progress towards net-zero at the national level. Parties currently report emissions / removals following IPCC guidelines (e.g., for the land sector and CCS), however we have seen in the preceding discussion there are gaps in the IPCC national inventory guidance in relation to reporting negative CO_2 emissions from, for example DACCS, as well as issues to be resolved in terms of ensuring that emissions related to bioenergy are complete. These methodological issues would need to be progressed to enable emission inventories to fully and comparably resolve how far countries are from achieving a balance between sources and removals.

62 See CBP COP 10 Decision X/33 (Parties have been invited to "ensure that, in the absence of science based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach and Article 14 of the Convention, that no climate-related geo-engineering activities** that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts, with the exception of small scale scientific research studies…")

At the global level, the Paris Agreement's **Global Stocktake** will assess collective progress towards the net-zero goal, but the details of which inputs and modalities will be used also have yet to be decided. It is likely that the Stocktake will use information from the NDCs as well as GHG inventories to compare progress with emissions pathways consistent with limiting global warming to 1.5°C (as described in IPCC SR 1.5°C). However, it is not yet clear exactly how the backward-looking emissions / removals that are *reported* in GHG inventories will be used in this exercise, or how the forward-looking emissions / removals in Parties' NDCs will be accounted for in this context. Some effort will need to made to ensure comparability of NDC reporting with inventory reporting, at a minimum to avoid double counting where mitigation outcomes are transferred between Parties. As outlined above in section 4, a key challenge will be the substantial gaps remaining in many developing country inventories and in the sectors and gases covered by the NDCs, most of which are not yet economy-wide. This is particularly problematic for CDR options with multi-national supply chains, such as BECCS. It is likely that **independent datasets** will need to be employed to supplement and verify aggregate GHG inventories in relevant sectors and verify related emission flows.

Fully symmetric reporting and accounting will be needed between countries that are involved in the transfer of mitigation outcomes, to ensure environmental integrity. The relationship between CCS, BECCS and DACCS and any transfers of mitigation outcomes under Article 6 of the Paris Agreement ("*cooperative approaches*") presents an example of where such symmetry will be needed, but has yet to be explored. However, the issue of symmetric accounting also relates more broadly to any transfers between countries (e.g., transfers of biomass between countries destined for BECCS). Where transfers take place between countries, international guidance will be needed to address environmental integrity, the avoidance of double counting and transparency.

Future research efforts and policy design would benefit from access to information on the state of current and planned removals, at local, national and international scales. Currently there is a lack of information on what CDR activities are in place or anticipated, and where. For options that would require CCS, technology-level information would also be lacking: estimating the total contribution of BECCS and DACCS would be difficult because IPCC guidance does not require separate reporting for biogenic emission sources, fossil fuel emissions sources, and removals from DAC injected for storage. Knowing the volumes of each injected and stored would be helpful for considering the contribution of BECCS and DACCS to carbon neutrality.

5. Safeguards for sustainable development

There are constraints on the sustainable potential of BECCS and A/R due to limits on resource availability (land, water, nutrients) that, if exceeded, would negatively impact on sustainable development. For example, large-scale deployment would potentially create risks for food production, biodiversity and social cohesion by driving up land demand, and lead to the over-use of water and nutrient resources. At the same time, in some contexts deployment at smaller scales could lead to local environmental and social benefits, such as improved soil quality and water management, biodiversity conservation, and income generation. Other land-based options such as **ecosystem restoration and soil carbon sequestration could also have substantial benefits for sustainable development**.

Both the negative and positive impacts of most CDR options would be largely determined by the **scale, context and implementation strategy used** (Fuss et al., 2018; IPCC, 2018). This is why a portfolio of CDR options, spreading the negative emissions burden between different CDR options, would likely be more effective at achieving a given amount of CDR sustainably than a focus on one or two options. The size and composition of a potential CDR portfolio that is beneficial for sustainability at the local, national or regional level in one context may look very different to a sustainable portfolio elsewhere.

The potential implications of a CDR portfolio on resource availability and sustainable development also **requires consideration of the wider context of other drivers of land-use change, including land-based options for reducing emissions**. For example, the land available for CDR options would be sensitive to improvements in crops yields, changes in demand for livestock products, changes in the intensity of livestock production and competition with other land uses, all of which depend on socioeconomic conditions and policy choices. The substitution of fossil fuel based liquid fuels with biofuels (without CCS)[63] is an obvious example of a mitigation activity that might compete for land with land-intensive CDR activities: even scenarios with less BECCS use large amounts of bioenergy production for emissions abatement, which has implications for resource use and sustainability.

Managing the interactions between CDR deployment, other land-uses and sustainable development would require strong governance in a number of areas. First, further guided **research into the sustainability of different CDR portfolios at the national and local level** and in different regional contexts is needed to explore potential interactions between CDR options (for example, competition for land or other resources), and to better understand the synergies and trade-offs between CDR deployment and sustainable development goals. **Focused research on the range of contexts in which different potential CDR activities might be sustainably deployed** would bring more clarity on how much each option could contribute to future CDR needs. For example, in the case of BECCS, niche options for bioenergy deployment at the local level may have a greater likelihood of achieving synergies with sustainable development (IPCC, 2018), but the feasibility of combining such small-scale operations with CCS would depend on costs, supply chain and infrastructure requirements.

Second, **safeguards will need to be tailored to prevent adverse impacts of potential CDR options on sustainable development at local, regional and global scales.** To maximize opportunities for socially and environmentally beneficial CDR deployment, incentive mechanisms could be designed to prioritize those CDR activities with net benefits for sustainable development. In addition it would be important to put in place mechanisms to **monitor negative and positive impacts** in an open and transparent manner, in order to allow for public participation and access to information and ensure that CDR deployment does not lead to adverse outcomes.

6. Challenges for measuring, reporting and verifying CO_2 removals

Measurement and verification of the scale of removals from CDR presents substantial governance challenges, in particular in the context of terrestrial sinks. Measurement and verification of the scale of removals from CDR presents substantial governance challenges, in particular in the context of terrestrial sinks. Uncertainties in reported land sector mitigation actions are very high (Grassi et al., 2017; Rogelj et al., 2017), particularly in developing countries where measurement and monitoring capacities are often limited. In the case of bioenergy production, land-use emissions vary considerably between different geographies and different feedstocks, and also depend on the time horizon chosen for measuring net emissions (Daioglou et al., 2017). These uncertainties present substantial challenges for anticipating, tracking and reporting overall progress, for designing results-based incentives to reward success in augmenting carbon stocks, and for the design of market-based approaches that can function credibly in the sector, though progress is being made in developing technologies that can reduce some of these uncertainties.

The estimation and verification of life cycle emissions presents an additional challenge, in particular for land-based options involving multi-sector and/or multi-national supply chains. For example, estimating the net removals for a BECCS project lifecycle (and the net emissions from bioenergy systems in the absence of CCS) would require consideration of emissions and removals due to land-use change and emissions due to the transport, processing and conversion of biomass to bioenergy, which are reported under different IPCC categories. The IPCC 2006 guidelines recommend reporting emissions where the activity took place (**sector-based accounting**), and for bioenergy this means reporting emissions in the land sector at harvest (rather than in the energy sector at combustion). This approach was designed to avoid double counting, but it makes it difficult to track the net effect of projects and flows, and to assess the total net removals achieved through BECCS[64] (Peters & Geden, 2017). Tracking flows and assessing total net removals will be particularly challenging when feedstocks are transported across national borders and emissions and removals from different stages of a project's life cycle are reported in different countries, especially if reporting capacities differ between the countries involved.

63 Note that only bioenergy combined with CCS can be considered as a form of CDR.

64 Note that this is also a challenge for bioenergy deployment without CCS.

Incentive mechanisms will be needed to share the benefits of BECCS between exporting countries (where biomass is harvested), and importing countries (where combustion, CO_2 removal and CO_2 storage take place). This is likely to be particularly important where bioenergy feedstocks are exported from a developing country for combustion and CCS in an industrialised country (Peters & Geden, 2017). Where value chains cross borders, sector-based accounting will present a challenge for incentivizing and rewarding negative emissions.

For some potential CDR options a key challenge is the identification of value chains with the greatest overall climate benefit. For example, the net effect of BECCS (and possibly also DACCS) for removing CO_2 is highly context dependent, and this can lead to investment uncertainty and public acceptability challenges (Nemet et al. 2018). While there are existing certification schemes and frameworks for tracing the origins of biomass and assessing its sustainability, they tend to be regionally focused (e.g. the EU's Renewable Energy Directive, which includes provisions for preventing indirect land-use change) or are voluntary (e.g. the Roundtable on Sustainable Biomaterials).

Distinguishing anthropogenic emissions and removals: The aim of balancing emissions and removals relates to anthropogenic (human-induced) emissions and removals. However, for terrestrial sinks it can be very difficult to distinguish between anthropogenic and non-anthropogenic removals because the same area of land can be simultaneously influenced by both human and natural factors. The IPCC[65] has developed guidance for using emissions / removals on managed land[66] as a proxy for anthropogenic carbon flows, but countries differ in how they apply this tool (Ogle et al., 2018), and other datasets (e.g. FAO and global models) use different methods (Grassi et al., 2018; Pongratz et al., 2014)there is a discrepancy of about 4 GtCO2 yr−1 in global anthropogenic net land-use emissions between global models (reflected in IPCC assessment reports. Further work is needed to develop more robust and accurate methods for distinguishing anthropogenic emissions and removals. A clear, universally applied definition of what constitutes an anthropogenic removal from the atmosphere would be necessary for reconciling different datasets and to enable the assessment of whether progress is being made in achieving a balance between anthropogenic emissions and removals.

Another substantial challenge is to ensure that NDCs are met through verifiable anthropogenic actions, rather than historical legacy effects. Some land sector carbon flows are the result of previous activities, age effects and inter-annual variability; under the KP, accounting rules are used to ensure that only emissions reductions or removals that result from a change in policies or activities are counted towards targets. Accounting rules for LULUCF will be needed to ensure that only anthropogenic efforts are accounted under the Paris Agreement. Where forest reference levels are used, transparent assumptions and verification will be required to ensure that baselines are well-founded.

7. Issues of storage: permanence, leakage and saturation

Permanence: A key criterion for successful CDR deployment is that carbon removals are durable. Potential CDR options that store carbon in geological reservoirs and terrestrial reservoirs have different degrees of "*permanence*". Once CO_2 is captured in a geological reservoir, storage can be considered to be long-term (IPCC (2018) and Fuss et al., 2018). The risk of significant leakage is relatively low, and research has looked into enhancing monitoring, verification and leak detection for geological storage (Fuss et al., 2018). However, for biological sequestration in soils and plants there is a considerable risk that sinks will be reversed through land management decisions or natural disturbances, and the risk of non-permanence will likely increase as climate change impacts are projected to exacerbate droughts, forest fires and other potential drivers of non-permanence (Ciais

65 See the IPCC 2006 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry and Other Land Use, available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

66 Defined as: "Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions". https://www.ipcc-nggip.iges.or.jp/public/mtdocs/pdfiles/0905_MLP_Report.pdf

et al., 2013; Griscom et al., 2017; P. Smith et al., 2014)confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify "natural climate solutions" (NCS. Mechanisms for protecting and enhancing the resilience of terrestrial sinks and stores of carbon and for compensating (and insuring) releases are essential for reducing the risk of sink reversal or loss of CO_2 from CO_2 storage reservoirs at both national and international levels. There are precedents for partially addressing these issues under the Kyoto Protocol.

Careful planning is required to manage these challenges and ensure that the physical impacts of large-scale BECCS, A/R or biochar implementation do not have a negative impact on the local, regional and/or global climate. However, it should be noted that many of these risks also apply to large-scale bioenergy deployment outside of the CDR realm (including the substantial amount of bioenergy in the global energy mix today). Pathways that limit CDR deployment tend to include considerable bioenergy production, so these physical risks present a governance problem for energy services more generally, not just mitigation or CDR.

The IPCC SR 1.5°C definition of CDR includes activities that durably store CO_2 in products, and here the question of permanence is also important. Mechanisms may be needed to monitor durability or to account for re-release over time.

Leakage: Land-intensive CDR options are also subject to the risk of leakage to satisfy other land-use demands. For example, A/R or reduction in deforestation in one location can trigger increased deforestation and/or degradation or harvesting in another, cancelling out benefits of carbon storage and forest restoration or protection. This also applies to many mitigation actions in the land sector. There are existing governance mechanisms for addressing leakage in regional contexts, but the effectiveness of these has been questioned (IPCC (2018))

Storage saturation: All CDR options have a limit to their maximum pace of deployment; for example, for BECCS and DACCS there are theoretical physical limits to the amount of CO_2 storage in geological reservoirs (IPCC, 2018), although other factors (such as cost) will likely be more important. For biological sinks (e.g., AR, soil sequestration) there is a limit to how much carbon can be removed from the atmosphere. Once a biological system reaches a state of "*near*" equilibrium it reduces its ability to remove carbon (Houghton et al., 2015). Therefore, while in the near-term there is a substantial potential for the rapid scale-up of activities for enhancing terrestrial sinks, the role of such activities in the longer-term may decline over time. Focus would instead shift to preserving terrestrial stocks, and if further removals were needed then other forms of CDR would need to be identified. At present, storage limits and saturation are not a limiting factor, but would need to be taken into account when planning long-term CDR deployment (Nemet et al., 2018), and could be further examined in the coming decades.

8. Planning for and monitoring the biophysical effects of deployment

For land-based CDR options, deployment can have biophysical impacts beyond CO_2 removal that require consideration. On a large-scale, changes in how the land surface is used can change the reflectivity (albedo) of the Earth, which in turn affects how much of the sun's radiation heats the Earth and how much is reflected back into space. Large-scale land-use changes for BECCS, AR or biochar deployment could lead to such an albedo effect, depending on the location and type of land used. For example, replacing grasslands with forests at high latitudes darkens the land surface, reducing albedo and leading to warming (Pete Smith, 2016; Pete Smith et al., 2015).

Changing land management practices can also affect local water and heat fluxes through changes in evapotranspiration and the surface roughness of the land. However, these effects will depend on the former use of the land and the local geography, and there is currently limited understanding of the net biophysical effect of bioenergy plantations or large-scale afforestation in different contexts.

Appropriate regulations or safeguards will need to be put in place to prevent any large-scale CDR deployment that might negatively impact local or global climate. On the other hand, in cases where biophysical effects can lead to adaptation benefits (e.g. through increased rainfall or protection against erosion during heavy rainfall events), guidance or incentives may also be needed to ensure that in the design of CDR activities these **local or global climate benefits are realized.** A number of NDCs do include forest-based activities in the adaptation components of their current NDCs, indicating an openness to projects with co-benefits.

9. Liability and redress

Safeguards also need to be put into place to address physical risks and accounting risks related to reversals of removals and storage. This has begun at the international level with Kyoto Protocol rules relating to accounting for land sector removals (e.g., RMUs and temporary CERs) and rules establishing a framework for accounting for CCS as CDM project activities (described in section 3 above).

The modalities and procedures for CCS as CDM project activities address both liability, in connection with the physical leakage or seepage, and responsibility for accounting for net reversals.[67] A Party hosting CCS as a CDM project activity must have a legal framework in place to address liability and to provide redress to affected entities, individuals and communities for damage, including environmental damage and damage to ecosystems from CCS project activities. The CCS rules also contain obligations for addressing **non-permanence** (any net reversal of storage) and for the **transfer of liability** from project participants to the host Party once site monitoring has terminated.

10. Public awareness

Public awareness and acceptance of CDR will be important for its development and roll-out. At the broadest level, public acceptance of CDR as a concept is influenced by the ethics of pursuing CDR and the perceived risk of moral hazard (i.e. whether the availability of CDR would take pressure off emissions reductions activities). The IPCC SR 1.5°C shows that any known model pathways consistent with 1.5°C require CDR in addition to accelerated transitions in all sectors, a rapid drop in emissions and a phase-out of coal power generation by mid-century. Raising public awareness of these findings and emphasizing that CDR does not offer a 'get out of jail free' card may help to enhance public acceptance (The Royal Society and Royal Academy of Engineering, 2018).

For individual CDR options, the potential negative side-effects of large-scale deployment may create challenges for public acceptance. In the case of BECCS, both bioenergy and CCS suffer from a **limited level of public acceptance** in many countries (IPCC, 2018) because of sustainability and CO_2 leakage concerns, among others, which is likely to present challenges for any BECCS deployment. On the other hand, people are still unfamiliar with BECCS, and the combination of CCS with bioenergy or direct air capture rather than fossil fuels may make it more acceptable (Nemet et al., 2018; Wallquist et al., 2012). At the more local level, public acceptance depends on whether users of a CDR measure and those exposed to benefits and risks associated with the measure see value in it (Nemet et al., 2018). For example, the need to transport large quantities of biomass and to install CO_2 pipelines may affect the local acceptability of BECCS. Meanwhile, the potential benefits from soil carbon sequestration or biochar for farmers is likely to raise their acceptance, provided that farmers are aware of these benefits.

In general there is **little existing research on the public acceptance of most CDR options** (Nemet et al., 2018), even though public acceptance may present a considerable barrier to deployment. Researchers and policy makers will need to consider how best to raise awareness of the risks and benefits of particular CDR options and portfolio of options in engaging with the public at local, national and international levels.

67 See Decision 10/CMP.7, Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities. "Liability" is defined as "the legal responsibility arising from the CCS project activity or the relevant geological storage site, with the exception of the obligations arising from a net reversal of storage …, but including all obligations related to the operation of the storage site (e.g., monitoring, remedial measures, etc.) to compensate for or remedy any significant damages, including damage to the environment, such as ecosystem damage, other material damages or personal injury".

4) What governance gaps and challenges could be addressed as a matter of priority?

A number of governance gaps, if addressed now, can help support informed decision-making on the necessary scale and portfolio of CDR options and lay the ground work for upscaling relevant options. They include the gap in mitigation ambition, informational gaps, accounting gaps, research gaps, and incentive gaps.

We have identified priorities based on their significance for CDR scale and planning, their implications for Party accountability, and their near-term achievability. These priorities include: addressing the current 2030 mitigation gap to reduce the necessity for reliance on large-scale CDR options; improving inventory data and information management systems to improve accountability and support the tracking and assessment of aggregate CDR efforts; putting in place robust accounting rules to avoid double counting, including for the land sector; refining reporting and accounting rules for projects involving international transfers related to CCS and BECCS; creating incentives to support CDR research, investment and implementation; developing scenarios and value chains for specific CDR options and combinations of options; enhancing public awareness, and supporting the development of legal and planning frameworks at the national and international levels that can address large-scale CDR options.

Some of these elements may be addressed by policymakers and negotiators through the ongoing negotiating processes under the Paris Agreement Work Programme; others will require decisions and interventions outside the UNFCCC process. Responsibility may be envisaged as follows:

1. Narrow the mitigation gap to reduce possible future reliance on CDR options

As explained in section 2 above, 2030 emission levels are an indicator of the degree to which reliance on CDR will be necessary to meet Paris Agreement goals. Any acceleration of mitigation efforts will help reduce reliance on CDR at a scale that will require very challenging rates of scale-up and that may have substantial implications for sustainability (e.g., food security, resource availability, biodiversity, land tenure, social cohesion).

Paris Agreement Parties have been requested to bring forward new and updated NDCs by 2020. A commitment by Parties at COP 24, in the context of the Talanoa Dialogue and the release of the IPCC SR 1.5°C Report, to consider an increase in the ambition of the NDCs they communicate would help narrow the existing emissions gap and reduce future dependence on CDR. Similarly, the 5-yearly Global Stocktakes that will assess collective progress in implementing the Paris Agreement will provide regular opportunities for Parties to bring forward more ambitious NDCs and move onto a 1.5°C-consistent emissions pathway.

The adoption of economy-wide NDCs by a wider number of developing country Parties would also facilitate consideration of the widest possible array of mitigation initiatives. As discussed in section 3 above, while developed countries have presented economy-wide NDCs, many developing countries currently have NDCs that cover only a subset of their inventory sectors.

Developing countries could be encouraged to move to economy-wide NDC emissions reduction or limitation targets in the new and updated NDCs they communicate by 2020.

Parties have been invited to communicate **2050 long-term low GHG emission development strategies by 2020**.[68] Policymakers could be encouraged to present 2050 strategies that are 1.5°C consistent, that aim to phase out CO_2 by 2050, aim to achieve a balance between emissions and removals, and aim to achieve net negative emissions later in the century. As mentioned in section 4, above, a number of the countries that have communicated 2050 strategies have begun to consider the role of CDR in these strategies.

The UN Secretary General is uniquely placed, using positive momentum from the IPCC SR 1.5°C and the COP 24 Talanoa Dialogue, to encourage more ambitious NDCs, reflecting the findings of the IPCC SR 1.5°C. Throughout 2019, the UN Secretary General and the UNFCCC Executive Secretary might also use this opportunity to **sensitize policymakers and the public** to the scale of the CDR implementation challenge if transformative mitigation action is delayed. Setting out the significance of the sustainability and governance challenges inherent in large-scale reliance on potential CDR options, most of which are currently of limited availability, high cost, resource intensive and/or unproven at scale, may encourage greater near-term mitigation efforts.

2. Improve inventory data and information management systems

Robust and comparable GHG inventory information is a key input for sound planning and decision-making. To facilitate the aggregation of inventories, and the tracking of progress toward the necessary balance between anthropogenic emissions and removals, Paris Agreement Parties could agree, as part of the Paris Agreement Work Programme, to:

- Apply common metrics across all Parties (tonnes of CO2-equivalent emissions)
- Apply a common set of IPCC Reporting Guidelines (e.g., 2006 IPCC Guidelines, as updated)
- Apply a common set of 100-year global warming potentials
- Use common reporting formats to support aggregation of GHG inventories.

Capacity building support to developing countries in implementing data collection and information systems, to support measurement, monitoring and reporting of inventory information will contribute to reliable inventories, and can be supported through, inter alia, the Financial Mechanism, Paris Committee on Capacity Building (PCCB), Capacity Building Initiative on Transparency (CBIT). Improved inventories can support forward planning, and facilitate assessment of progress toward net-zero emissions.

Where NDCS are not currently quantifiable or quantified, Parties might be requested to provide, by 2020, information necessary for clarity, transparency and understanding of the mitigation effects of Parties' current and updated and enhanced NDCs, including on assumptions related to baselines, accounting approaches, planned contribution of the land sector and planned indicators of progress where this information has not been communicated, or has been communicated with an insufficient level of detail.

More granular reporting with respect to A/R, BECCS, and DACCS will also help track progress towards carbon neutrality. It will be helpful in this context to further disaggregate reporting on biomass and CCS. For example, plant-level allocation of CO_2 volumes stored and injected to biogenic sources versus fossil fuel sources will help track BECCS and enable the development of tailored incentives. Ensuring that common reporting formats are applied, and collect geo-referenced information on storage locations will also help track progress in the implementation of CDR options.

The International Maritime Organisation (IMO), the International Civil Aviation Organisation (ICAO) and the Montreal Protocol Secretariats can also be enlisted to supplement UNFCCC

68 Decision 1/CP.21, para. 35

GHG inventory data, for a more complete global picture of emissions and removals. This might include, for example: IMO data related to international bunker fuels and the use of biofuels; ICAO data related to international bunker fuels, the use of biofuels, and the use of CORSIA offsets; Montreal Protocol data related to GHGs, including HFCs; and London Protocol data related to sub-seabed storage

It will also be helpful to verify reported GHG inventory data using emissions flow data and using reliable external data sets and sources (e.g., current information on forest cover and clearing from satellite data and FAO datasets; atmospheric GHG measurements from WMO), ensuring key data sets remain in public domain and recognizing cyber security concerns. **Inter-Governmental Organisations (IGOs), Non-Governmental Organisations (NGOs) and other Civil Society Organisations (CSOs)** can be encouraged to help verify sectoral emissions and removals, bolstering and reinforcing UNFCCC efforts. Moving towards a **common definition of anthropogenic emissions and removals** would be helpful to allow these different datasets to be compared.

3. Put in place robust accounting rules

The Paris Agreement Work Programme is now in the process of considering accounting guidance for Parties' NDCs. **Robust, common accounting rules that support Parties in accounting for their emissions and removals, and avoid the double counting of emissions and removals, will be an important goal of this process.**

In this context, it will be important to **elaborate land sector accounting rules that deliver comparable information from all Parties** — including rules for the establishment of baselines and reference levels, and for reporting on harvested wood products, natural disturbances, and lands identified for purposes of managed land proxy. While some flexibility will have to be provided in recognition of Parties' different circumstances and starting points, a common rule set will support consistency, avoid double counting, minimize the risk of asymmetric accounting, ensure net removals are anthropogenic. These rules could consider limiting the use of removals from the land sector to offset emissions in other sectors, in recognition that reductions are needed from all sectors and in recognition of the impermanence of land sector removals.

The application of **robust accounting rules, and corresponding adjustments between Parties**, will also be important to ensure that international transfers of mitigation outcomes under Article 6.2 and Article 6.4 avoid double counting, deliver symmetric accounting and ensure that uncertainties in measurement in the land sector are not exploited.

Existing accounting rules for CCS activities under the CDM may be useful in informing the development of accounting rules for Article 6 activities under the Paris Agreement. This guidance, found at Kyoto Protocol decision 10/CMP.7, provides systems to account for net reversal of storage, in addition to addressing, inter alia, issues of site selection and characterization, risk and safety assessments, and environmental and socio-economic impact assessments, monitoring and verification. The thinking behind the safeguards established under the CDM will be equally relevant under the Paris Agreement.

4. Create incentives to accelerate research, investment and implementation

It is worth considering how risk and responsibility allocation might be used to support up-front costs associated with incentives and commercialisation, as well as equitable risk sharing along the value chain for emissions, reversals and associated liability, among Parties, and among public and private sector actors. For example, countries well situated for hosting certain CDR options may not be able to put forward the upfront costs needed for research and investment to support the scaling up of CDR options or their commercialization. They may also lack the necessary human or institutional resources. At the same time, it has been noted that some heavily forested developed countries may be challenged in balancing their emissions and removals.[69] Different national circumstances and different cumulative emission profiles suggest that there is room for an equitable division of responsibility in accelerating CDR upscaling.

REDD+ and the Kyoto Protocol flexibility mechanisms managed to catalyze substantial research and investment in developing countries. In both contexts, financial incentives motivated countries and the private sector to seek out low cost mitigation options. Safeguards were designed to manage various kinds of risks. Lessons from these initiatives may be helpful in connection with Article 5 of the Paris Agreement, addressing results-based finance for reducing deforestation and forest degradation (REDD+) and Article 6, addressing cooperative approaches. Similarly, under the Paris Agreement, a planned allocation of risks and benefits may incentivize specific CDR options, or create the space for useful public/private collaboration that may support commercialization of promising CDR options.

Consideration could be given to **how best to incentivize specific CDR options and aspects of their value chains** (e.g., negative emissions in the context of CCS) where domestic incentives may be lacking.

Funding and economic incentives may also need to be found to overcome barriers to low cost no-regrets CDR options that have known co-benefits (e.g., A/R, soil carbon sequestration, ecosystem restoration) and to support the development and commercialization of more expensive CDR options that may become necessary to drive emissions below zero at the international level.

5. Engage the research community in scoping specific CDR options and necessary incentives

The necessary scaling up of CDR options will be facilitated by efforts from the research community to build scenarios around specific CDR options, their associated value chains and their sustainability implications (e.g., BECCS linked to existing and new CCS sites, DACCS linked to renewable energy). This applies equally to those options that have not yet seen widespread consideration in model-based analysis.

Research initiatives might include:

- Modelling specific CDR options and portfolios of options at scale, to identify linkages between potential options and implications for the SDGs
- Performing bottom-up studies at the local or regional level to identify sustainable potentials, potential socio-economic impacts, and governance needs
- Identifying potential locations for implementation of large-scale CDR initiatives, in view of related sustainability concerns
- Identifying potential near-term and niche options that could be rapidly and sustainably expanded
- Identifying measures capable of incentivizing different CDR portfolios in different settings
- Piloting projects through public/private partnerships that can employ existing plans and infrastructure (e.g., CCS storage facilities)
- Identifying pathways for collaboration, cooperation, cost sharing and benefit sharing, as well as options for the allocation of responsibilities and liability
- Public awareness and acceptance surveys of identified CDR options

Where research reveals low cost options that have clear co-benefits (e.g., soil carbon enhancement, erosion prevention, habitat restoration, income generation) and that can be immediately deployed at large-scale (taking into consideration relative maturity, known trade-offs, sustainability challenges, cumulative impacts and interactions between CDR options), these options can be targeted for early implementation.

69 See Regulation (EU) 2018/841 of 30 May 2018, on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU, mentioning Finland in this regard.

6. Improve public awareness of potential CDR options, risks and trade-offs in planning processes

Reliance on CDR options to meet Paris Agreement goals will be inevitable, even if 2030 NDCs improve dramatically. Planning processes with **broad stakeholder engagement** will help build public understanding of the imperative to reduce emissions and enhance removals. This in turn can build momentum for more ambitious mitigation efforts and greater acceptance of potential CDR options, both of which will be needed to achieve Paris goals.

Public awareness efforts might address **cost, risks, uncertainties, sustainability challenges and trade-offs** associated with various CDR options at different scales, as well as their potential role in delivering net-zero emissions by mid-century.

Efforts to implement large-scale CDR options will benefit from the **early incorporation of scoping for CDR options in 2050 low emission strategies and national development strategies**. 2050 strategies could, for example, begin to identify areas or facilities with potential to accommodate large-scale CDR options. As noted in section 4 above, some countries' 2050 strategies have now begun to identify possible CDR options and it can be anticipated that these strategy documents will be updated over time.

Land use and land sector planning documents at various levels (local, regional, national) might consider land set asides for A/R, recognizing standards for sustainability and the need to protect communities from land grabs (The Royal Society and Royal Academy of Engineering, 2018).

IGOs or NGOs might be invited to **develop a registry** of ongoing existing BECCS, CCS, DACCS initiatives and projects to track deployment of negative emission technologies in tonnes removed and sequestered, to increase public awareness.

7. Improve international collaboration and cooperation

Enhanced collaboration between international treaty bodies in connection with the measurement, monitoring, reporting and management of emissions and removals, as well as on issues related to responsibility and liability in connection with CDR options, will help bodies avoid working at cross-purposes (CBD, UNFCCC, MP, London Protocol, ICAO, IMO, FAO, WMO). This enhanced collaboration could be supported by the UN Secretary General working with the UNFCCC Executive Secretary.

As a starting point, collaboration and cooperation will be needed to maintain and improve the information base needed to support sound policy-making. While the UNFCCC process generates GHG inventory data, as noted above, this data suffers from gaps and consistency challenges. The Paris Agreement Work Programme can address a number of consistency issues (see Table 3). **Intergovernmental organisations, non-governmental organisations and other and civil society organisations** can help fill gaps and support greater accountability and transparency by providing external checks on UNFCCC inventory data. For example, satellites and FAO data sets can provide information on forest cover, forest clearing and natural disturbances. The WMO can provide atmospheric GHG measurements. These **external sources can be used both to supplement and verify UNFCCC GHG inventory data and emission flows, to provide a fuller understanding of emissions and removals in country contexts and in aggregate.**

Mutually-reinforcing research agendas can be used to target support to research, development and commercialization of prioritized CDR options, and to research initiatives that solicit stakeholder input and reflect local community concerns and needs regarding sustainability.

As consensus grows on optimal mixes of CDR options and physical locations for the implementation of these options, international collaboration and cooperation can help identify the most effective incentives for deployment, and mobilize resources to support this deployment.

Conclusion

The issue of CDR presents the global community with a dilemma. On the one hand the science is clear that a substantial scale of CDR will be needed to limit warming to 1.5°C, and CDR deployment will be needed soon in order to reach such a scale in the coming decades. On the other hand CDR is not ‘a get out of jail free’ card, and the global community has an interest in ensuring that its ultimate deployment and use are as low as feasibly possible. Deployment of CDR at scale, whether it is based on the land sector, or biomass energy with carbon capture and storage, or new approaches such as direct air capture and storage, all have serious challenges in the sustainability domain.

If 2030 targets do not improve dramatically, the international community will need to rely heavily on CDR options that are as yet unproven at scale, to meet the Paris Agreement’s 1.5°C temperature limit. Even with improvements in current policies and NDCs, significant, if not substantial, CDR will be needed to meet the Paris agreement’s long-term temperature goal. The next decade really is critical — emissions levels in 2030 will determine the portfolio of CDR options that may be needed. If Parties bring forward new and updated NDCs by 2020 that are *substantially* more ambitious in the reductions they deliver for 2030, this can reduce future reliance on CDR to a scale that may be economically feasible, and avoid jeopardizing sustainable development.

More work is needed to develop an appropriate portfolio of CDR approaches that can maximize synergies with sustainable development and minimize trade-offs. Investment is needed for research and for commercialization of promising technologies, and this work is really just beginning.

This report shows that the global community is far from ready to provide incentives for the deployment of CDR, and that there are many gaps in the governance systems that will be needed to manage CDR at scale. In this report, we have begun to ask questions such as:

- Is the international community prepared for the implementation of large-scale CDR options?
- Can the sustainability challenges, risks and trade-offs inherent in large-scale CDR efforts be managed?
- What governance tools need to be in place for an urgent development and upscaling of possible CDR options?
- Can current provisions under the climate change regime support implementation at scale or are further provisions and incentives needed?

Some biological options, such as afforestation, reforestation, and other land management activities, are available at relatively low cost and provide positive co-benefits: these approaches could be pursued as soon as possible. As the scale of these activities grow there will need to be an important strengthening of governance.

To ramp up CDR to the scale needed will require substantial lead time, planning and resources, and governance tools to ensure that CDR can be deployed sustainably, and that progress in achieving net-zero — and ultimately net negative emissions — can be monitored effectively.

In this report we identify key priority governance challenges and gaps at the international level for the development and potential deployment of CDR at a scale consistent with the Paris Agreement goals. These gaps include mitigation gaps, information gaps, accounting gaps, knowledge gaps, and incentive gaps, some of which can be addressed under the ongoing negotiating processes under the Paris Agreement, while others will require decisions and interventions outside the UNFCCC process.

The table below summarises the key governance challenges and gaps that can be addressed in the near-term, what could be done about them, and who could be involved.

Table 3: Key governance challenges identified in this report, and options for addressing them

Governance challenges and gaps	Entity or entities	Options for adressing them
1. Narrow the mitigation gap to reduce possible future reliance on CDR options	UN Secretary General	• Maintain momentum from the Talanoa Dialogue and the IPCC SR 1.5°C • Encourage more ambitious NDCs by 2020, in view of the IPCC SR 1.5°C and SDGs • Encourage new and updated NDCs by 2020, with enhanced emissions reduction targets • Encourage communication of 2050 strategies, consistent with 1.5°C pathways by 2020 • Encourage a shift to economy-wide NDCs • Facilitate greater collaboration between treaty Secretariats
	UNFCCC Executive Secretary	
	Parties	• Enhance NDCs by 2020, to avoid extreme reliance on CDR options • Communicate 2050 Low Emission Strategies by 2020 including consideration of CDR needs • Provide information necessary for clarity, transparency and understanding of existing NDCs
2. Improve inventory data and information management systems	IPCC	• Develop IPCC Guidance on biomass energy lifecycle emissions for inclusion in national emissions inventories • Develop IPCC Guidance on emission inventory and reporting for DACCS.
	IGOs, NGOs, CSOs	• Explore how external datasets can be used to verify sectoral emissions data (e.g. through atmospheric measurements) • Support capacity building initiatives

3. Put in place robust accounting rules	Paris Agreement Work Programme	• Adopt robust GHG accounting rules • Elaborate land sector accounting rules (including for Harvested Wood Products, Natural Disturbances) • Elaborate robust rules for Article 6 transfers
	UNFCCC Executive Secretary	• Collaborate with IMO, ICAO, CORSIA and Montreal Protocol to enable sharing of emissions data, to ensure no double counting of emission reductions and ensure work is not at cross-purposes
4. Create incentives to accelerate research, investment and implementation	Research community	• Design incentives to support accelerated deployment • Consider role of public / private partnerships, particularly where existing infrastructure and plans can be utilized • Identify inexpensive no-regrets options for immediate implementation
	Parties	• Review previous guidance on CCS in the CDM and REDD+ under the UNFCCC and consider relevance for governing CDR in the Paris Agreement context
5. Engage the research community in scoping specific CDR options and necessary incentives	Research community IEA, IRENA, IIASA	• Build scenarios around specific CDR options, value chains and their sustainability implications (e.g., BECCS linked to existing and new CCS sites, DACCS linked to renewable energy, other land-based options with sustainability benefits) • Research into environmental aspects of CDR options and portfolios, including storage permanence and leakage • Regional, bottom up studies to identify realistic, sustainable removal potential

6. Improve public awareness of potential CDR options, risks and trade-offs in planning processes	IGOs, NGOs, CSOs	• Create a registry of existing BECCS, CCS, DACCS initiatives and projects, with scale and location, to track the progress and achievements in tonnes removed / avoided / sequestered • Provide information from external datasets to facilitate tracking of CDR deployment, e.g. on forest cover, clearing, natural disturbances, from satellite data
7. Improve international collaboration and cooperation	Paris Agreement Work Programme	• Agree common GHG reporting guidelines, metrics, GWPs • Adopt common GHG reporting formats to facilitate aggregation • Agree to sources of input for the Global Stocktake that would enable the assessment of collective progress in balancing emissions and removals and in following a 1.5°C consistent mitigation pathway
	ICAO and IMO	• Data sharing and enhanced collaboration with UNFCCC • Develop long-term vision for zero emissions in their sectors
	IPCC	• Evaluate the implications of geophysical feedbacks and other issues for emission pathways and CDR needs consistent the Paris agreement long-term temperature goal, for inclusion in assessment reports that will inform the Global Stocktake
	Climate Action Tracker & UNEP	• Expand tracking of NDCs and current policies to include CDR deployment

References

Austria and the European Commission. (2018). Submission by Austria and the European Commission on behalf of the European Union and its Member States Views on Accounting — Proposal for a Structured Summary.

CBD. (2012). UNEP/CBD/COP/DEC/XI/20 5 December 2012, Decision adopted by the Conference of the Parties to the Convention on Biological Diversity at its Eleventh Meeting, XI/20. Climate-related geoengineering. Retrieved from https://www.cbd.int/doc/decisions/cop-11/cop-11-dec-20-en.pdf

CBD. (2016). CBD/COP/DEC/XIII/14 8 December 2016, Decision adopted by the Conference of the Parties to the Convention on Biological Diversity at its Thirteenth Meeting, XIII/14. Climate-related geoengineering. Retrieved from https://www.cbd.int/doc/decisions/cop-13/cop-13-dec-14-en.pdf

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., et al. (2013). *Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Coordinating Lead Authors: Lead Authors: Contributing Authors*. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter06_FINAL.pdf

Comyn-Platt, E., Hayman, G., Huntingford, C., Chadburn, S. E., Burke, E. J., Harper, A. B., et al. (2018). Carbon budgets for 1.5 and 2 °C targets lowered by natural wetland and permafrost feedbacks. *Nature Geoscience*, 1. https://doi.org/10.1038/s41561-018-0174-9

Daioglou, V., Doelman, J. C., Stehfest, E., Müller, C., Wicke, B., Faaij, A., & van Vuuren, D. P. (2017). Greenhouse gas emission curves for advanced biofuel supply chains. *Nature Climate Change*. https://doi.org/10.1038/s41558-017-0006-8

Dixon, T., Leamon, G., Zakkour, P., & Warren, L. (2013). CCS projects as Kyoto Protocol CDM activities Selection and/or peer-review under responsibility of GHGT. *Energy Procedia*, *37*, 7596–7604. https://doi.org/10.1016/j.egypro.2013.06.704

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Grassi, G., House, J., Dentener, F., Federici, S., den Elzen, M., & Penman, J. (2017). The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, *7*(3), 220–226. https://doi.org/10.1038/nclimate3227

Grassi, G., House, J., Kurz, W. A., Cescatti, A., Houghton, R. A., Peters, G. P., et al. (2018). Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks. *Nature Climate Change*, *8*(10), 914–920. https://doi.org/10.1038/s41558-018-0283-x

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., et al. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(6), 1–6. https://doi.org/10.1073/pnas.1710465114

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., et al. (2018). A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nature Energy*, *3*(6), 515–527. https://doi.org/10.1038/s41560-018-0172-6

Herold, A., Siemons, A., & Herrmann, L. M. (2018). *Is it possible to track progress of the submitted nationally determined contributions under the Paris Agreement?* Retrieved from www.oeko.de

Houghton, R. A., Byers, B., & Nassikas, A. A. (2015). A role for tropical forests in stabilizing atmospheric CO 2. *Nature Publishing Group*, *5*. https://doi.org/10.1038/nclimate2869

IPCC. (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. I

Iversen, P., Lee, D., Rocha, M., Canaveira, P., Davis, G., Elias, P., et al. (2014). Understanding Land Use in the UNFCCC.

Krug, J. H. A. (2018). Accounting of GHG emissions and removals from forest management: a long road from Kyoto to Paris. *Carbon Balance and Management*, *13*(1), 1. https://doi.org/10.1186/s13021-017-0089-6

Lenzi, D., Lamb, W. F., Hilaire, J., Kowarsch, M., & Minx, J. C. (2018). Don't deploy negative emissions technologies without ethical analysis. *Nature*, *561*(7723), 303–305. https://doi.org/10.1038/d41586-018-06695-5

Lomax, G., Lenton, T. M., Adeosun, A., & Workman, M. (2015). Investing in negative emissions. *Nature Climate Change*, *5*(6), 498–500. https://doi.org/10.1038/nclimate2627

Mace, M. J. (2016). Mitigation Commitments Under the Paris Agreement and the Way Forward. *Climate Law*, *6*, 21–39. https://doi.org/10.1163/18786561-00601002

Metz, B., Davidson, O., de Coninck, H., Loos, M., & Meyer, L. (2005). *IPCC Special Report on Carbon Dioxide Capture and Storage*.

Ming, T., & Richter, R. De. (2016). Fighting global warming by greenhouse gas removal : destroying atmospheric nitrous oxide thanks to synergies between two breakthrough technologies. *Environ Sci Pollut Res*, 6119–6138. https://doi.org/10.1007/s11356-016-6103-9

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., et al. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 063001. https://doi.org/10.1088/1748-9326/aabf9b

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., et al. (2018a). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, *13*(6), 063003. https://doi.org/10.1088/1748-9326/aabff4

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., et al. (2018b). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, *13*(6), 063003. https://doi.org/10.1088/1748-9326/aabff4

Ogle, S. M., Domke, G., Kurz, W. A., Rocha, M. T., Huffman, T., Swan, A., et al. (2018). Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. *Carbon Balance and Management*, *13*(1). https://doi.org/10.1186/s13021-018-0095-3

Peters, G. P., & Geden, O. (2017). Catalysing a political shift from low to negative carbon. *Nature Climate Change*. https://doi.org/10.1038/nclimate3369

Pongratz, J., Reick, C. H., Houghton, R. A., & House, J. I. (2014). Terminology as a key uncertainty in net land use and land cover change carbon flux estimates. *Earth Syst. Dynam*, *5*, 177–195. https://doi.org/10.5194/esd-5-177-2014

Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., et al. (2018). Global Carbon Budget 2017. *Earth Syst. Sci. Data*, *10*, 405–448. https://doi.org/10.5194/essd-10-405-2018

Rogelj, J., Fricko, O., Meinshausen, M., Krey, V., Zilliacus, J. J. J., & Riahi, K. (2017). Understanding the origin of Paris Agreement emission uncertainties. *Nature Communications*, *8*, 15748. https://doi.org/10.1038/ncomms15748

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5°C. *Nature Climate Change*, *8*(4), 325–332. https://doi.org/10.1038/s41558-018-0091-3

Schleussner, C. F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E. M., et al. (2016, September 25). Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*. https://doi.org/10.1038/nclimate3096

Shue, H. (2018). Climate Surprises: Risk Transfers, Negative Emissions, and the Pivotal Generation. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3165064

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global*

Change Biology, *22*(3), 1315–1324. https://doi.org/10.1111/gcb.13178

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., et al. (2014). Chapter 11 Agriculture , Forestry and Other Land Use (AFOLU). In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, et al. (Eds.), *Climate Change 2014: Mitigation of Climate Change.* Cambridge Univ Press.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., et al. (2015). Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, (December). https://doi.org/10.1038/nclimate2870

South Africa. (2018). Submission by South Africa to the Ad Hoc Working Group on the Paris Agreement and Subsidiary Body for Scientific and Technological Advice on Accounting across Articles 4, 6 and 13 of the Paris Agreement. Retrieved from http://www4.unfccc.int/sites/SubmissionPortal/Documents/201809011649—180830 SA SUBMISSION ON MTM ACCOUNTING DRAFT 4 220818 — final version1 (3) correct version.pdf

The Royal Society and Royal Academy of Engineering. (2018). *Greenhouse gas removal*. Retrieved from https://www.raeng.org.uk/publications/reports/greenhouse-gas-removal

Wallquist, L., Seigo, S. L., Visschers, V. H. M., & Siegrist, M. (2012). Public acceptance of CCS system elements: A conjoint measurement. *International Journal of Greenhouse Gas Control*, *6*(6), 77–83. https://doi.org/10.1016/j.ijggc.2011.11.008

Wohland, J., Witthaut, D., & Schleussner, C.-F. (2018). Negative Emission Potential of Direct Air Capture Powered by Renewable Excess Electricity in Europe. *Earth's Future*. https://doi.org/10.1029/2018EF000954