A6.4-SB004-AA-A04

Information note

Removal activities under the Article 6.4 mechanism

Version 03.0

COVER NOTE

1. Procedural background

1. The Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA), by its decision 3/CMA.3 "Rules, modalities and procedures for the mechanism established by Article 6, paragraph 4, of the Paris Agreement"[1], requested the Supervisory Body of the mechanism established by Article 6, paragraph 4, of the Paris Agreement (the Supervisory Body), to elaborate and further develop, on the basis of the rules, modalities and procedures of the mechanism, recommendations on activities involving removals, including appropriate monitoring, reporting, accounting for removals and crediting periods, addressing reversals, avoidance of leakage, and avoidance of other negative environmental and social impacts, in addition to the activities referred to in chapter V of the annex (Article 6, paragraph 4, activity cycle), to be considered at its fourth session (November 2022).

2. The Supervisory Body, at its first meeting (25–28 July 2022)[2], requested the secretariat to prepare an information note providing technical information on the elements related to activities involving removals, referred to in decision 3/CMA.3, paragraph 6 (c), with respect to each type of activity, and agreed that an informal working group on removals comprising its members and alternate members as well as the secretariat staff would work prior to the second meeting of the Supervisory Body to prepare draft recommendations to be considered by the Supervisory Body at its second meeting with a view to forwarding the recommendations to CMA 4.

3. The Supervisory Body, at its second meeting (19–22 September)[3], agreed that the informal working group on removals will continue to work on the development of the information note. It requested the secretariat to launch a call for public inputs on the information note and the draft recommendations, including the in-meeting working document.

4. The Supervisory Body, at its third meeting (03–06 November)[4], took note of the high-level summary of the public inputs received in response to the calls for public input and requested the secretariat to take these inputs into account while updating the document "Information note: Activities involving removals under the Article 6.4 mechanism" for its consideration at a future meeting.

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[1] See document FCCC/PA/CMA/2021/10/Add.1 available at: https://unfccc.int/documents/460950.

[2] The meeting report of the Article 6.4 mechanism Supervisory Body first meeting (SB 001) is available at: https://unfccc.int/sites/default/files/resource/a64-sb001.pdf

[3] The meeting report of the Article 6.4 mechanism Supervisory Body second meeting (SB 002) is available at: https://unfccc.int/sites/default/files/resource/a64-sb002.pdf

[4] The meeting report of the Article 6.4 mechanism Supervisory Body third meeting (SB 003) is available at: https://unfccc.int/sites/default/files/resource/a64-sb003_0.pdf

2. Purpose

5. This information note contains the updated technical information, reflecting the public inputs provided by the stakeholders as requested by the Supervisory Body. The information note has the objective of supporting the work of the Supervisory Body for the development of recommendations on removal activities pursuant to the decision 3/CMA.3, paragraph 6 (c).

3. Key issues and proposed solutions

6. The key issues are considered from a broader perspective, and options for addressing the issues have been provided in the information note.

4. Impacts

7. This document will facilitate the Supervisory Body's consideration of the recommendations on removal activities pursuant to the decision 3/CMA.3, paragraph 6 (c).

5. Subsequent work and timelines

8. Further work will be taken up as agreed by the Supervisory Body, including the following:

   (a) Compilation or synthesis of the views to be submitted, by 15 March 2023, by Parties and admitted observer organizations as invited by the CMA at its fourth session;

   (b) Compilation or synthesis of the inputs from stakeholders to be provided in a structured public consultation process, as requested by the CMA at its fourth session;

   (c) Any other related work, including further update of this information note based on the work done under (a) and (b) above.

6. Recommendations to the Supervisory Body

9. It is recommended that the Supervisory Body take this information note into consideration while developing recommendations requested by the CMA and provide further guidance to the secretariat in this regard.

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1. Introduction

1. This note provides technical information on the elements related to activities involving removals referred to in decision 3/CMA.3, paragraph 6 (c)[1], with respect to different types of activities involving removals.

2. For brevity, the term "removal activities" has been used in this note to imply "activities involving removals".

3. Also, for reasons of brevity, the term "A6.4M-RMP" has been used to imply the "Rules, modalities and procedures for the mechanism established by Article 6, paragraph 4, of the Paris Agreement" as contained in the annex to decision 3/CMA.3.

1.1. Scope

4. In addition to the background scientific and technical information on removal activities, this note covers the following issues relating to removal activities in the context of the A6.4-RMP:

   (a) Monitoring;

   (b) Reporting;

   (c) Accounting for removals;

   (d) Crediting periods;

   (e) Addressing reversals;

   (f) Avoidance of leakage; and

   (g) Avoidance of other negative environmental and social impacts.

1.2. Sources of information

5. This note is based upon the following sources of information:

   (a) Reports of the Intergovernmental Panel on Climate Change (IPCC);

   (b) Rules, regulations, and standards of other market-based mechanisms;

   (c) Inputs provided by stakeholders in response to the public call for inputs (open from 27 September to 11 October 2022)[2]. The relevant sources referred to in the public inputs were also consulted.

   (d) Other published literature related to climate change science and policy.

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[1] Decision 3/CMA.3, paragraph 6(c) is contained in document FCCC/PA/CMA/2021/10/Add.1 available at: https://unfccc.int/sites/default/files/resource/cma2021_10a01E.pdf

[2] Submissions received in response to the call for input on activities involving removals under the Article 6.4 mechanism of the Paris Agreement are available at: https://unfccc.int/process-and-meetings/the-paris-agreement/article-64-mechanism/calls-for-input/sb002-removals-activities

6. The sources have been cited in the text as appropriate.

7. A consolidated list of sources is provided in appendix A. In the list of sources search strings have been provided for quickly navigating to the paragraph or the sentence that is relevant for the respective citation. This will be particularly helpful in the case of voluminous documents, such as IPCC reports, where finding the relevant text can take time.

2. Definitions

8. This section contains terms that are defined specifically for the scope of this information note.

2.1. Definition of removals

9. A carefully considered definition of removals and related terms has been emphasized to be of fundamental importance in some of the public inputs received. This section analyses in detail the issues and options related to defining removals and the associated terms.

10. The term removal can be used in different ways and contexts.

Removal as a process of separation

11. As an uncountable noun, removal refers to the process of separating greenhouse gases (GHGs) from the atmosphere. Atmosphere here refers to the free atmosphere where GHGs have already been uniformly mixed with the air. The capture of GHGs at or near emission sources counts as GHG avoidance, not removal. There remains some ambiguity as to how far from the emission source the capture equipment must be located to qualify as removal from the free atmosphere. One proposal is that the removal of GHGs from the atmosphere outside the direct influence of the emission sources should count as removal (P-10:b). However, it is debatable whether the construction of a carbon dioxide (CO_2) removal facility near coal-fired power plants or a methane removal facility in the middle of rice fields would qualify as removal from the free atmosphere.

Removal as a quantity removed

12. Used as a countable noun, often in the plural, 'removals' refers to the physical quantities of GHGs removed from the atmosphere. The quantities can be expressed in tonnes of the respective GHGs removed or in equivalent tonnes of CO_2 (i.e. tCO_2e) calculated on the basis of the 100-year global warming potential (GWP100) values of the respective GHGs. Tonnes of removals in the case of land-based activities are also referred to as carbon stocks, expressed commonly in units or tCO_2 or tCO_2e, but also in units of tC.

Scope of GHGs covered

13. The terms carbon dioxide removal (CDR) and greenhouse gas removal (GGR) are used to specify the scope of the gases covered.

14. The following observations can be made in this regard:

(a) According to the IPCC, there are currently no removal methods for removal of non-CO_2 GHGs that have progressed beyond conceptual discussion (R-32:a). The term GGR is no longer used by the IPCC (R-32:b). The IPCC defines "anthropogenic removals" as " withdrawal of greenhouse gases (GHGs) from the atmosphere as a result of deliberate human activities" (R-32:c);

(b) Some stakeholder submissions suggest that GHGs other than CO_2 should not be included in the definition of removals (P-28:b, P-03:b). Others suggest including all GHGs (P-16:a, P-22:a, P-14:a). There are also cases where the term GGR is used when the actual removal is limited to removal of CO_2 (R-50:a, R-16:a).

2.2. Definition of removal activities

15. For the purposes of the Article 6.4 mechanism, the definition of carbon dioxide removal (CDR) comes closest to defining removal activities. CDR is defined in three slightly different ways in the latest IPCC report (AR6 WGIII):

(a) Definition in Annex I (Glossary): “Carbon dioxide removal (CDR) Anthropogenic activities removing carbon dioxide (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 CO_2 sinks and direct air carbon dioxide capture and storage (DACCS), but excludes natural CO_2 uptake not directly caused by human activities. (R-32:e)”;

(b) Definition in the Technical Summary: “CDR refers to 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, geochemical or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities (Annex I) (R-32:f)”;

(c) Definition in Chapter 12, Cross-Chapter Box 8: “CDR refers to anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products. It includes anthropogenic enhancement of biological, geochemical or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities. Increases in land carbon sink strength due to CO_2 fertilisation or other indirect effects of human activities are not considered CDR (see Glossary) (R-32:i)”.

16. The following can be noted about the above three definitions:

(a) Compared to the definition in the Glossary, the definitions in the Technical Summary and Chapter 12 include the words "or chemical" after the word "geochemical", and remove the words referring to DACCS. Thus, these definitions provide a technology-neutral reference to chemical sinks by avoiding the term DACCS (P-13:a);

(b) The definition in Chapter 12 differs from the other two definitions in that it uses the words “includes anthropogenic” instead of the words “includes existing and potential anthropogenic” used in the other two definitions.

17. Based on the public inputs, the following observations can be made on the IPCC definition of removal activities:

(a) Some stakeholders suggest that the IPCC definition should not be changed unless there is a demonstrated need and added value (P-25:a, P-16:b). Others suggest adapting the IPCC definition to the specific needs of the mechanism (P-07; P-03);

(b) Some of the issues raised and proposed solutions are as follows:

(i) The term "durably" is not defined in terms of minimum duration (P-07). It is suggested that a minimum storage period of 200 to 300 years be included in the definition (P-07:a);

(ii) The words "storage in products" should be deleted as most products have a shorter life than the desired durability (P-07:b);

(iii) The words "net removal" should be used to convey that activity emissions should be subtracted from the removals achieved (P-07:d, P-03:a).

(c) It is worth considering whether the requirement for "net" should be specified in the definitions or elsewhere, such as in the methodologies, as "net" may imply different accounting approaches, such as the use of life-cycle assessment (LCA) emissions, embedded emissions, or only net of direct and indirect emissions.

(d) There is also the question of how many tonnes of removals would need to be subtracted for each tCO_2e of emissions resulting from the implementation of a removal activity. If an activity involving removals also results in emission reductions or avoidance, such that the net balance of the activity in terms of emissions is negative (i.e. the emissions avoided are greater than the emissions caused by the implementation of the activity), should the emissions from the activity still be deducted from the removals achieved?

(e) Avoiding the use of the word "net" in the definition itself may allow a more streamlined approach to addressing these issues in their respective places.

18. If the definition were to cover non-CO_2 GHGs, the word "storage" might not be appropriate, as in the case of methane removal, for example, it may be more appropriate to burn ("destroy") the GHGs removed. If the word "destruction" is used in the definition, "climate-neutral destruction" could be specified (P-28:a), although the emissions accounting requirements of the methodology may also cover this aspect. The IPCC no longer uses the term climate neutrality (R-32:g) because of its ambiguous meaning.

19. If the definition were to include non-CO_2 GHGs and their precursors, it would be necessary to specify the nature and extent of the precursors to be included (P-10:a), how they are physically handled, and how their mitigation value is accounted (P-07:c).

20. It has also been suggested that the words "voluntary direct anthropogenic activities" be used (P-17:a), perhaps to exclude unintentional removals and removals resulting from policy actions that could qualify as removal activities, although the words "not directly caused by human activities" in the IPCC definition already exclude unintentional removals. There is a further suggestion that policy actions should qualify as eligible removal activities if they result in quantifiable removals (P-02:a).

Removal of CO_2 from oceans

21. A further suggestion is that the definition should use the words "removal of CO_2 from the atmosphere or ocean" (P-23:a), thus allowing for removal activities that stimulate growth of macroalgae in the oceans and store it on the ocean floor, thereby accelerating the CO_2 flux from the atmosphere to the oceans. It is argued that effectively addressing the climate crisis should include addressing ocean acidification and warming. Such removal activities could shift carbon to rebalance the natural carbon reservoirs by transferring carbon from

the fast cycling reservoirs (i.e. the biosphere, the atmosphere, and the upper ocean) to the slow cycling reservoirs (i.e. the deep ocean and marine sediments).

22. Rebalancing of carbon reservoirs will also serve the broader goals of sustainable development, which include an equitable net-zero transition, socio-ecological sustainability, and the pursuit of broad economic opportunity (R-20:a, R-10:a). On the other hand, other sources maintain that macroalgae cultivation as an effective climate mitigation solution is not yet established (R-32:g, R-44:a, R-42:a)

Temporal boundary of removals

23. The time at which actual removals take place is a relevant consideration for an unambiguous definition of removal activities (P-10:c). In the broadest sense, even fossil fuels resulted from the removal of atmospheric CO_2 that occurred millions of years ago. Trees that have grown over the past few centuries store CO_2 that has been removed over that period. The biogenic waste that is burned today in an energy recovery facility was removed from the atmosphere at some point in the past, although we don't know exactly when. If a bioenergy with carbon capture and storage (BECCS) plant is powered by such biogenic waste, does it achieve removals? If the wood that was grown in country X over the last half century is pelletized and burned in a BECCS plant in country Y today, does that achieve removals?

24. If we do not impose any temporal boundary on when the removals occurred, then the above BECCS activities would count as removal activities, because the CO_2 injected into the geological storage facility was, over some period of time, removed from the open atmosphere by biological sinks. This creates a need for delineating a temporal boundary for removals to allow unambiguous attribution of removals to a particular removal activity.

25. For the purposes of the Article 6.4 mechanism, an option for clearly defining the temporal scope of removals would be to limit to removals that occur after the removal activity is registered. This would avoid the problem of old or legacy removals being counted as removals achieved by the activity. Prior consideration or prompt commencement of activities may be taken into account if so agreed under the rules of the mechanism, in which case removals occurring after notification of prior consideration would be considered removals achieved by the activity if such an activity is later successfully registered.

Ownership of removal activities

26. Since a removal activity consists of two components, separation of CO_2 from the atmospheric air and subsequent storage of the removed CO_2, the question arises how an activity participant is unambiguously identified when different actors are performing these two components.

27. For example, if a forest entrepreneur grows timber that is sold to another actor who produces engineered timber out of it thus causing prolonged storage of carbon, which actor gets the credits and if both of them get credits, in what proportion?. According to the definition, none of the two actors (and there could be many actors) by themselves achieves removals as defined.

28. In another example, deep geological storage is highly specialized operation and one such service provider can store carbon removed by a large number of actors who separate the CO_2 and ship it to the same storage service provider. Realization of actual removals

depends upon investment by both the actors. In such as case, how an activity is to be defined and how credits are to be awarded, remains an open issue.

Removals vs avoided emissions

29. Some stakeholders have argued that BECCS activities driven by biogenic waste should be considered removal activities. However, asking the question "What would be the baseline fate of the biogenic material being used in the BECCS activity?" points to different outcomes.

30. If the biogenic material would have been stored durably in the baseline (e.g. buried), then the BECCS activity achieves nothing except the emission savings resulting from displacement of the grid electricity (if the GHG balance is favourable).

31. On the other hand, if the baseline fate of the biogenic material would have been combustion without CCS, then the BECCS activity achieves emission reductions on two counts: preventing the emission of the carbon contained in the biogenic material, and displacing the emissions from the grid electricity (if the GHG balance is favourable).

32. In either case, the removal of the carbon from the atmosphere does not fall within the scope of the BECCS activity, since removal had happened before the start of the BECCS activity. Of course, a BECCS activity driven by biomass sourced from dedicated plantations or energy crops (specifically raised for the purpose of producing fuel for the power plant) generates removals. In such a case, the raising of plantation falls within the boundary of the BECCS activity and emissions associated with the cultivation of biomass will be accounted within the activity.

33. Table 1 summarizes the suggested changes to be made in the definition of removal activities provided in the Technical Summary of IPCC AR6 WGIII and the pros and cons of such changes.

Table 1. Proposed changes in the definition of removal activities provided in the Technical Summary of IPCC AR6 WGIII

Proposed change	Pros	Cons
Include non-CO_2 GHGs	- A broader scope to include potential activities from ongoing innovations under GGR.	- Removal of other GHGs is not currently anticipated at relevant scales; - It is unclear if the removal of other greenhouse gases has a comparable mitigation effect to the removal of CO_2; - IPCC recommends that, for now as well in the foreseeable future, the effects of non-CO_2 GHGs should be balanced through additional removal of CO_2 based on GWP100 equivalence.
Specify minimum duration of storage as 200 to 300 years	- Scope of what counts as removals is unambiguously defined;	- It is not clear how the number of years is to be arrived at;

Proposed change	Pros	Cons
	- Short-term removal activities are not counted as eligible removal activities.	- With this limitation, only engineering-based removal activities will qualify; - Removal activities of all durations can contribute to the mechanism goal, not just those that store carbon for 200 years or more.
Delete reference to products	- Products of shorter lifetime can be excluded from counting as durable storage.	- Products of varied lifetime can also contribute to the mechanism goal; - Products can range from biochar and other inert-carbon products to intermediate lifetime products such as timber.
Include the word "net"	- Removals are accounted as net result of implementation of the removal activity.	- Net applies to quantification and calculation of credits, not to activity itself; - There is no single method to define net for all activities and situations; this is a methodological question and includes aspects such as whether to use LCA accounting or activity accounting; - It is the accounting of removals that needs to be net of all emissions; these provisions belong to the methodologies.
Include "destruction" of GHGs	- In case of a GGR activity, destruction is relevant rather than storage (e.g. in removal of methane).	- Methane could also potentially be converted into a product.
Include "precursors"	- Leads to more comprehensive accounting of the impact of removal activities.	- There are no accepted methodologies for accounting of precursors; the science may not be settled yet; - It would add complexity without adding commensurate value.
Include removal from oceans	- The large mitigation potential of oceans can be leveraged; - Removal activities under the mechanism can contribute to rebalancing of carbon reservoirs.	- Macroalgae cultivation as an effective climate solution are not yet established.

2.3. Definition of other terms

34. The following definitions used in this document have been taken from the glossary of the IPCC reports and from the rules, modalities and procedures of Article 6.4 mechanism (RMPs) contained in annex to decision 3/CMA.3:

(a) **Carbon dioxide capture and storage (CCS)** A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. Sometimes referred to as Carbon Capture and Storage.[3]

(b) **Carbon dioxide capture and utilisation (CCU)** A process in which CO_2 is captured and then used to produce a new product. If the CO_2 is stored in a product for a climate-relevant time horizon, this is referred to as carbon dioxide capture, utilisation and storage (CCUS). Only then, and only combined with CO_2 recently removed from the atmosphere, can CCUS lead to carbon dioxide removal. CCU is sometimes referred to as Carbon dioxide capture and use.[4]

(c) **Bioenergy and carbon dioxide capture and storage (BECCS)** Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that depending on the total emissions of the BECCS supply chain, carbon dioxide (CO_2) can be removed from the atmosphere.[5]

(d) **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.[6]

(e) **"Article 6, paragraph 4, activity"** is an activity that meets the requirements of Article 16, paragraphs 4–6, these rules, modalities and procedures, and any further relevant decisions of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA).

(f) **"Article 6, paragraph 4, emission reduction" (A6.4ER)** is issued for mitigation achieved pursuant to Article 6, paragraphs 4–6, these rules, modalities and procedures, and any further relevant decisions of the CMA. It is measured in carbon dioxide equivalent and is equal to 1 tonne of carbon dioxide equivalent calculated in accordance with the methodologies and metrics assessed by the Intergovernmental Panel on Climate Change and adopted by the CMA or in other metrics adopted by the CMA pursuant to these rules, modalities and procedures.

3. Types of removal activities

35. As can be seen from the IPCC definition of removal activities, there are two main elements of a removal activity: the process of separation of CO_2 from the atmospheric air (the removal method), and the process of durably storing the removed CO_2 (the storage

[3] IPCC, 2018: Global Warming of 1.5°C, Annex I: Glossary.

[4] IPCC, 2018: Global Warming of 1.5°C, Annex I: Glossary.

[5] IPCC, 2018: Global Warming of 1.5°C, Annex I: Glossary.

[6] IPCC, 2018: Global Warming of 1.5°C, Annex I: Glossary.

method). There may be an intermediate stage of conversion (e.g. liquefaction) and transportation of CO_2 (e.g. trucking, shipping, and conveyance through pipelines). Since the transport methods are not unique to removal activities, these are not discussed further in this note.

3.1. Taxonomy of removal activities

36. The following are the broad types of removal methods (R-32:j):

(a) Biological methods: The separation of CO_2 from the atmosphere is achieved through the photosynthesis process. These methods can be further divided into:

(i) Land-based biological methods consisting of tree planting or regeneration of natural vegetation such as forests. Almost all of current removals come from this category (R-50:b);

(ii) Ocean-based biological methods including stimulating growth of macroalgae or another type of marine biomass and sinking the resulting biomass to the seabed where it is expected to last over a long period. These methods are experimental and not yet proven safe or practical and have limited feasibility of implementation at scale in view of the multilateral treaties regulating the marine environment, such as the London Protocol to the London Convention (P-12:a) and the Convention on Biological Diversity (P-12:g).

(b) Geochemical or chemical methods: These methods employ geochemical or chemical reactions to separate CO_2 from the atmospheric air. Examples include direct air capture (DAC) and enhanced weathering (EW). Most of the methods are in various stages of development and are not expected to be technologically, economically, and environmentally feasible until 2030, or even until 2050 (P-12:h). These methods theoretically have the potential to create a large and indefinitely sustained removal capacity, even if with a large share of resource use. Hence these methods are thought to be useful in the long term, when the global economy will have been decarbonized to the extent possible, but some residual GHG emissions will continue in the hard-to-abate sectors (e.g. agriculture, aviation).

37. The following are broad categories of storage methods:

(a) Storage in ecosystem carbon pools:

(i) Land-based ecosystem reservoirs such as above-ground biomass, belowground biomass, deadwood, litter, and soil-organic matter can store carbon over durations ranging from years to centuries. These reservoirs have the limitation of becoming saturated over time and thus cannot go on accumulating carbon indefinitely unless biomass is harvested at a sustained rate and transferred to other reservoirs such as long-lasting products or geological storage.

(ii) Marine ecosystem reservoirs, such as marine biomass or seabed can store carbon over durations varying from decades to centuries. However, there is considerable uncertainty about the impacts of such storage on the marine ecosystems.

(b) Storage in geological reservoirs, or storage through mineralization of CO_2 in subsurface rocks. Currently there are a few well-tested sites of deep geological storage being mainly used for storing CO_2 removed from flue gases of industrial facilities combusting fossil fuels. These storage facilities achieve carbon recycling instead of carbon removal. The same storage sites can be used by removal activities, including biological or engineering-based removal activities, for the purpose of durable storage of removals.

(c) Storage in durable products occurs when carbon removed through biological or engineering-based methods is converted to useful products and preserved over long periods of time. The products can be made either after complex conversion and transformation processes or with minimal processing. The following are some of the product types:

(i) Durable biomass products such as massive timber, engineered timber, and other structural wood used in the construction of buildings, and biochar. Typically, these products can last from decades to centuries;

(ii) Inert carbon products such as concrete, building bricks, and other products made from CO_2 removed through engineering methods. These products can typically last for centuries.

38. Any implementation of a removal activity will consist of a combination of removal methods and storage methods described above. Table 2 below provides some examples of such implementations.

Table 2. Examples of implementations of removal activities combining different removal methods with storage methods

Storage method	Land-based biological removal	Ocean-based biological removal	Geochemical/ chemical removal
Land-based ecosystem reservoirs	- Afforestation/ reforestation and forest restoration - Revegetation - Improved forest management - Wetland restoration	Organic matter grown in oceans is added to soils	Enhanced weathering with the sequestered atmospheric carbon stored in soils
Ocean ecosystem reservoirs	-	Stimulating macroalgae growth	-
Deep ocean storage	Biomass grown on land is sunk to the ocean floor	Stimulating macroalgae growth and sinking the biomass to seabed	DACCS activity with the removed carbon stored in seabed

Storage method	Land-based biological removal	Ocean-based biological removal	Geochemical/ chemical removal
Deep geological storage	BECCS activities driven by sustained harvest of biomass from forests or dedicated energy plantations where the removed CO_2 is injected in deep geological formations	-	DACCS activity with the removed carbon stored in deep geological formations
Sub-surface mineralization	BECCS activities driven by sustained harvest of biomass from forests or dedicated energy plantations where the removed CO_2 is mineralized in subsurface rocks	-	DACCS activity with the removed carbon stored through subsurface mineralization in rocks
Wood-based products	Biomass grown on land with the harvested wood stored in timber, engineered timber, and wooden building construction	Stimulating macroalgae growth and using the macroalgae biomass as a feedstock for bio-based products	-
Carbon products from mineralization	BECCS activities driven by sustained harvest of biomass from forests or dedicated energy plantations where the removed CO_2 is mineralized to form concrete aggregates	-	DAC activities with the removed CO_2 mineralized to form concrete aggregates

3.2. Eligibility of activity types under the A6.4 mechanism

39. Based on the public input from stakeholders, the following observations can be made on the suitability of different activity types for the Article 6.4 mechanism:

(a) Some stakeholders suggest that engineering-based methods should not be made eligible under the mechanism, citing the following reasons:

(i) Engineering-based removals are speculative, cannot be deployed at scale, and pose significant risks to human rights and the environment (P-12:b);

(ii) Most engineering-based removals depend upon the CCS as the storage technology which poses significant risks and uncertainties and serves the primary purpose of prolonging the continued use of fossil fuels (P-12:c, R-43a). In its latest report, the IPCC considers CCS among the highest-cost mitigation measures with the least potential to reduce emissions by 2030 (P-12:d);

(iii) It is estimated that direct air capture facilities are currently capturing 0.01 $MtCO_2$ per year (P-15:a), while the conventional land-based activities are removing 2,000 $MtCO_2$ per year (R-50:c);

(iv) In practice, CCS projects have repeatedly failed to meet optimistic and ambitious CO_2 capture targets set by proponents (P-12:f, R-43a), even though these were to capture carbon from point sources of emissions where CO_2 concentration is about 100 to 200 times higher than CO_2 concentration in the free atmosphere;

(v) The geological storage of CO_2 will be performed on very few jurisdictional territories, at least in the foreseeable future. It is essential that these countries and the EU be directly involved in defining these requirements (P-25:b);

(vi) BECCS is not yet deployable at a significant scale, as it faces challenges similar to fossil fuel CCS; the effectiveness of large-scale BECCS to meet Paris Agreement goals has been questioned and other pathways to mitigation have been proposed (R-30);

(vii) Deployment of BECCS will require ambitious investments and policy interventions with strong regulation and governance of bioenergy production, and such conditions may be challenging for developing countries (R-30:b);

(viii) The value of future removals expected from technologies that are uncertain in terms of their scale and roll-out is difficult to assess (R-12a);

(ix) The feasibility of most engineering-based CO_2 removal technology is highly uncertain (R-53:a);

(x) Courts have also recognized that carbon removal technologies are currently unreliable (P-12:e);

(xi) Most engineering-based removal activities do not contribute to sustainable development, are not suitable to be implemented in the developing countries and cannot contribute to reducing the global cost of mitigation. These activity types therefore do not fulfil any of the objectives of the Article 6.4 mechanism;

(xii) It has been suggested that CDR activities, other than in the context of nature-based solutions, present the risk of mitigation obstruction in the form of moral hazard. The promise of future deployment of CDR technologies, such as BECCS and DACCS, can deter or delay ambitious emission reductions while posing a (potentially false) hope that large-scale removals will solve the climate crisis in the future (R-30:c; P-15:b).

(b) Some sources suggest that only the well-established land-based activities should be made eligible under the mechanism, citing the following reasons:

(i) Work on removals under the Article 6.4 mechanism should be focused on removal methods that are low risk and with low impact on the environment and resource availability to needy populations (P-07:e);

(ii) Land-based natural climate solutions have the potential to provide 37% of cost-effective CO_2 mitigation needed through 2030, one-third of which can be delivered at or below 10 USD tCO_2, while also offering environmental co-benefits of water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience (R-24:a; R-37:a).

(c) Others suggest that all types of activities should be made potentially eligible, citing the following reasons.

(i) Comprehensive and technology-neutral scope of removal activities for compliance and voluntary carbon markets will ensure that a wide range of solutions can be scaled up (P-04:a);

(ii) While biomass-based approaches will be advantageous in specific regions and niches, engineering-based approaches such as DAC will be a critical complement to deliver adequate quantities of CDR in view of the fundamental limitations of land and water (P-05:a).

4. Quantification of mitigation value of removal activities

40. Mitigation value of a climate action can be defined in various ways with respect to different climate goals or climate policy objectives.

41. While removals cannot serve as a substitute for deep emissions reductions, these can still play multiple complementary roles in the mitigation strategies at global or national levels (R-32:h):

(a) Removals can further reduce net CO_2 or GHG emission levels in the near-term;

(b) Removals can counterbalance residual emissions from hard-to-transition sectors, such as CO_2 from industrial activities and long-distance transport (e.g., aviation, shipping), or methane and nitrous oxide from agriculture, and thus help reach net zero CO_2 or GHG emissions in the mid-term;

(c) Removals can achieve and sustain net-negative CO_2 or GHG emissions in the long-term, by deploying removal activities at levels exceeding annual residual CO_2 or GHG emissions.

4.1. Basic considerations

42. To limit the global warming so as to stay below a temperature target (e.g. 1.5 C) is the most commonly stated mitigation goal. This goal as stated says nothing about the time by when we will know that the goal has been achieved. However, in terms of practical value, reaching a warming of 1.5 C within 20 years is different from reaching the same in 50 years. The performance in the first case will be worse than that in the second. In the second case, the rate of warming is slower and therefore some unknown tipping points may have been avoided and more time may be available for adaptation of human and natural systems, and more cost-effective opportunities and technologies for decarbonization may have become available.

43. The role of removals in reducing near-term warming mentioned in paragraph 41(a) above helps delay the adverse effects of climate change by decreasing the rate of warming (R-37:b).

44. An emission pulse of CO_2 into the atmosphere causes marginal atmospheric warming over time. The time rate of marginal warming, at any point in time, is proportional to the fraction of CO_2 remaining in the atmosphere which declines over time in an exponential manner (as a sum of three exponential functions with different half-life periods). The fraction reduces to 0.38 over the first 100 years and thereafter declines slowly with ever declining rate so that a fraction of 0.20 remains even after a thousand years (R-28:a).

45. To neutralize the effect of 1 tCO_2 emission, a removal of 1 tCO_2 must happen at the same time as the occurrence of the pulse of emission and the removed CO_2 must stay outside of the atmosphere indefinitely.

46. If 'indefinitely' is understood as infinite period of time, delaying emission will have no impact. In other words, the impact of 1 tCO_2 emitted today and that of 1 tCO_2 emitted 100 years from now will be the same. Conversely, emitting 1 tCO_2 today and removing the same 20 years later could be considered an activity without any atmospheric impact. But we know that this is not so. Although the net emission over the entire period is zero, clearly some damage has been done to the atmosphere (R-26:b).

47. Because we care for the time period, or the temporal space of our relevance, delaying emissions has the effect of pushing the emission impact partly out of our temporal space (apart from helping us gain strategic or manoeuvring space). That temporal space within which we aim to address the climate crisis is our time horizon for the purpose of climate policy and climate action. A time horizon of 100 years has been widely recognized and adopted under various policy instruments, standards, and regulations relating to climate policy, including carbon accounting (see paragraphs 71ff below).

4.2. Permanent vs temporary removals

48. Within the accounting framework based on a finite time horizon, removals have the value of cancelling emissions when these are permanent and of delaying emissions when these are temporary. Note that here permanence is not about physical permanence of removals, rather permanent means that the removed carbon is stored equal to or longer than the time horizon.

49. The permanence of being chemically fixed (e.g. in rocks or in geological storage) is the physical permanence (or physical irreversibility) and does not have economic value beyond the time horizon. If we were to value carbon storage irrespective of a temporal boundary of interest, 1 tCO_2 of removal and storage through geological mineralization could be considered to deliver value that is 100 times, 1000 times or 10,000 times as much as the value of 1 tCO_2 removal stored over 100 years. This leads us to an absurd conclusion that we know is not true.

50. The value of removals, and indeed of emission reduction or any climate action, is in relation to our climate objectives and our time horizon. If our objective were to address the next ice age, we should perhaps have been setting a time horizon of 25,000 years. But given the situation we are in, a time horizon of 100 years might be more appropriate. One could, of course, argue that it should be 200 or even 300 years.

51. Some of the sources consulted suggest that, assessed on physical science basis, temporary carbon removals do not provide any reduction in atmospheric warming (R-34:a). These arguments are however countered by other sources (R-22:a, R-15:a, R-31:a,).

52. Yet others suggest that temporary carbon storage may cause temporary reduction in warming, but these do not mitigate the atmospheric concentration of CO_2 over the long term. Since carbon removed is eventually re-emitted into the atmosphere, the final effect on the total carbon budget, considered over long term, is zero. (P-24:a; P-07:f; P-27:a).

53. Others use the economic rationale and conclude that value of temporary removals can be nearly equivalent to permanent sequestration if marginal damages remain constant or if there is a backstop technology that caps the abatement cost in the future (R-25:c). Others show that based on climate economics, periodically monitored temporary removals can provide the same value as permanent removals (R-05:a).

54. Others suggest that the cooling effectiveness of negative CO_2 emissions decreases if applied at higher atmospheric CO_2 concentrations (R-56:a). This seems to imply that the maximum of the available removals capacity should be deployed now rather later from the perspective of physical effectiveness and consequently economic efficiency.

55. Another research finds that successful carbon sequestration through nature-based climate solutions can have climate benefit even in the case where the carbon storage is temporary and the stored carbon is returned to the atmosphere later this century (R-39:a). Temporary removals can also help decrease the peak warming if implemented alongside reductions in fossil fuel emissions (R-39:b).

56. In addition to the mitigation value of temporary removals in terms of slowed atmospheric warming, temporary carbon removal provides multiple other benefits. In short, deployment of temporary carbon removals:

(a) Moderates adverse impacts on biodiversity and allows ecosystems and human socioeconomic systems to adapt over a longer time;

(b) Buys time for technological developments and economic capacity to address climate mitigation more effectively, and for economic opportunities including capital turnover;

(c) Reduces risk of reaching tipping points such as release of carbon from permafrost or icesheet collapse by smoothing out the path of emissions and avoiding peaks;

(d) Reduces long-term cumulative climate impacts;

(e) Reduces costs of meeting temperature targets relative to late mitigation as a slower increase of the damage level lowers the present value of costs;

(f) Bridges the progress toward the long-term climate target through achievement of near-term benefits;

4.3. Time preference and discounting

57. Another consideration in valuing temporary removals is based on the fact that early climate action is preferable to later climate action. This is called the time rate of preference, or time discount rate, and is considered commonly in economic decision making.

58. Using a discount rate of zero implies that a mitigation activity can be postponed indefinitely without any effect on the overall objective of mitigation.

59. To appreciate this, consider three hypothetical removal activities: activity participant A removes 1 tCO_2 today and promises to store it for 500 years; activity participant B removes 5 tCO_2 today and promises to store it for 100 years; and activity participant C removes 25 tCO_2 today and promises to store it for 20 years. Which offer has more value? We can intuitively appreciate that offer C perhaps provides the best value; but how do we calculate that? In the case of the 500-year offer, our intuitive response would be “Who has seen 500 years?”, and this is a time horizon question. Between 25 tonnes for 20 years and 5 tonnes for 100 years, we tend to think that the near-term offer of 25 tonnes is more attractive as it offers more value early on and has more certainty in time. The 100 years offer is long way into the future, and there are many more uncertainties over a 100-year period than over a 20-year period. And this is the issue of time preference that is used commonly as a basis of decision making, both by economists and by policy makers as well as by private individuals.

60. Based on the above considerations, there are two parameters involved in valuation of mitigation produced by removals: time horizon and time discount rate. The first is question of relevance of valuation, and the second is a question of economics of valuation. Mitigation, or avoided climate damage, is fundamentally an economic value, otherwise we would not care for this just as we don’t care for the scientific fact that the Sun is gradually running out of hydrogen and will collapse in a few billion years, making the Earth uninhabitable.

61. Although the two parameters of time horizon and discount rate have different rationales, and both should be used in any decision making, the quantitative effect of the two can also be simulated with either of these: a time horizon with a zero discount rate and a discount rate applied over an indefinitely long time such as 1000 years can produce quantitatively similar, though not the same, results (P-18:a; P-21:a ; R-25:b). For example, using the formulation of discount rate only, a method called the social value of offsets (SVO) method yields a heuristic that 2.5 offsets each sequestering 1 tCO_2 for 50 years are equivalent to 1 tCO_2 of permanent removal (P-18:b).

62. The relationship between the effects of the two parameters can be seen from Table 3 below. The numbers in the table represent tonnes of CO_2 needed to be removed in order to produce mitigation equivalent to 1 tCO_2 of permanent removal when the removals are stored over different periods of time. Note that here ‘permanent removal’ means removals that are stored over the time horizon. Note that apart from time discounting, the non-linearity of the decay of a CO_2 pulse over time has been taken into account while calculating these factors.

Table 3. Tonnes of CO2 needed to produce mitigation equivalent to 1 tCO2 permanent removal stored over different periods of time

		Discount rate									
Time horizon (years)	Storage period (years)	0%	1.00%	1.25%	1.50%	1.75%	2.00%	2.25%	2.50%	2.75%	3.00%
100	10	13.04	7.42	6.65	6.01	**5.47**	5.02	4.63	4.3	4.02	3.77

	20	6.43	3.88	3.52	3.22	**2.96**	2.75	2.57	2.41	2.28	2.16
	50	2.44	1.75	1.65	1.56	**1.48**	1.42	1.37	1.32	1.28	1.24
	75	1.52	1.27	1.23	1.2	**1.17**	1.14	1.12	1.1	1.08	1.07
	100	1	1	1	1	1	1	1	1	1	1
500	10	68.01	10.51	8.55	7.22	6.27	5.56	5.01	4.57	4.2	3.9
	20	33.94	5.52	4.54	3.88	3.41	3.05	2.78	2.56	2.38	2.24
	50	13.49	2.54	2.15	1.9	1.72	1.59	1.48	1.41	1.34	1.29
	75	8.94	1.89	1.64	1.48	1.37	1.29	1.23	1.18	1.15	1.12
	100	6.66	1.58	1.4	1.29	1.21	1.16	1.12	1.09	1.07	1.05
1000	10	123.27	10.55	8.56	7.22	6.27	**5.56**	5.01	4.57	4.2	3.9
	20	61.63	5.54	4.54	3.88	3.41	**3.05**	2.78	2.56	2.38	2.24
	50	24.64	2.55	2.16	1.9	1.72	**1.59**	1.48	1.41	1.34	1.29
	75	16.42	1.9	1.64	1.48	1.37	**1.29**	1.23	1.18	1.15	1.12
	100	12.31	1.58	1.4	1.29	1.21	**1.16**	1.12	1.09	1.07	1.05

63. It is seen from Table 3 that using a discount rate of 1.75% with 100-year time horizon produces similar, though not the same, number of tonnes as using a discount rate of 2.0% with an indefinite time horizon.

64. Conversely, a time horizon of 100 years can be considered to be equivalent to an implicit discount rate of 3.3% applied to an indefinite time horizon (R-47:a)

65. However, explicit consideration and adoption of both the parameters would be a more rational, transparent, and scientific approach, and will result in more accurate values of the number of tonnes required to be stored at different durations (R-38:a).

66. Some sources have noted that time horizon is an important consideration independent of any discounting decision (R-23:a; R-36:a).

67. Some sources argue that discounting of physical quantities (e.g. the marginal warming or number of storms) located in the future is not justified (P-11:a). Others have argued that the discounting applies to these effects since these effects represent utility or disutility. These quantities are not something to which today's decision makers can be indifferent (R-36:b).

68. The terms time horizon, equivalence period (also called permanence period) and storage period have their precise meanings: time horizon is the span of time over which assessment is conducted, it is the relevant time space for assessment; equivalence period is the period of storage of removals such that the 1 tCO_2 of removal over this period produces mitigation value that is equal to mitigation value of 1 tCO_2 emission reduction, noting that this equivalence is not physical but an economic equivalence; storage period is the actual storage period for a given quantity of removals. The equivalence period differs

from the time horizon only if a non-zero discount is applied; with a zero rate of zero, the equivalence period is equal to the time horizon.

69. The word permanence is also used in the sense of physical/chemical irreversibility of a mass of removals. The term permanence period in this context would imply the time of storage after which the necessary chemical reactions have occurred, and the mass of removals has become irreversible. This is a completely different meaning of the term permanence period.

70. In this document and most literature consulted the term permanence period has been used to imply the equivalence period. Since the term permanence period has been more often used in literature than the term equivalence period, this document uses the term permanence period to convey the intended meaning.

4.4. Choice of time horizon

71. The time horizon of 100 years is a commonly accepted normative choice and is used in different climate policy instruments, such as follows:

    (a) Some of the carbon offset standards, in compliance as well as voluntary carbon markets, use 100 years as the permanence period for accounting and crediting of removals, notably: Canadian Greenhouse Gas Offset Credit System Regulations (N-48:a); Climate Action Reserve (R-40:a); Regulation for the California Cap on Greenhouse Gas Emissions and Market-Based Compliance Mechanisms (R-08:a); Australian Government’s Carbon Credits (Carbon Farming Initiative) Act (R-04:a).

    (b) In some GHG life cycle assessment (LCA) standards and bioenergy systems studies, a distinction is made between temporary carbon storage and permanent carbon storage based on the threshold storage period of 100 years, notably British Standards Institution's publicly available specification PAS 2050 (R-07:a); European Commission's Product Environmental Footprint (PEF) Guide (R-19:a) and ILCD Handbook General guide for Life Cycle Assessment (R-18a);

    (c) IPCC methodologies for biochar the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories use the 100-years permanence threshold (R-29:a);

    (d) Other sources listed in this note also suggest using 100-year threshold to distinguish between permanent and temporary removals (P-22:b; P-06:a; P-01:a; R-44:b; R-25:a; R-55; R-21; R-47).

72. There are others who argue that a longer time horizon such as 200 or 300 years should be used. Proponents of geological storage argue that assuming a time horizon of 100 years is not fair to removals that are physically permanent. Since geological or

geochemical storage of removals is very expensive to achieve, and provides mitigation beyond 100 years, these should be valued more.

73. However, as seen above, economic valuation means applying a non-zero discount rate which takes time value into consideration. Under this valuation, mitigation resulting from 300 years storage and 100 years storage turns out to be comparable.

74. The argument of expensive production of credits is an issue that needs perhaps to be posed elsewhere and not in the context of a market mechanism, since a market mechanism by its very nature is about leveraging low-cost mitigation opportunities and not about guaranteeing a price that is commensurate with the cost of production.

4.5. Choice of discount rate

75. A survey of climate policy literature reveals that an appropriate value of discount rate for assessment of climate action alternatives should be between 1.75% and 2.25% (P-19; R-15, R-16, R-17, R-18, R-19). Further details about choice of a discount rate are given in appendix D.

76. It might be useful to consider the practical impact of using different discount rates in quantification of mitigation value of temporary storage in real-life implementations of removal activities, as illustrated by the following examples.

Example 1. Existing compliance and voluntary carbon market mechanisms require a storage period varying from 30 years to 100 years in order to issue removal credits that are used for offsetting 1 tCO_2 of emission. When assessed under a time horizon of 100 years, the different storage periods correspond to implicit discount rates as shown in the table 4 below.

Table 4. Implicit discount rate for different storage periods under a 100-year time horizon

Required storage period (years)	Implicit discount rate under a 100-year time horizon
30	11%
40	8%
50	6.25%
60	5%
80	3.25%
100	0%

77. It is seen from table 4 (extended version not shown here) that storage periods of 92 and 88 years correspond to discount rates of 1.75% and 2.25% respectively. Thus, the standards that require storage periods of less than 92 years are issuing credits that

overestimate mitigation value assessed on a 100-yeartime horizon. Since guaranteeing or monitoring storage over a duration of 90 years is impractical, the only feasible approach to achieving this level of environmental integrity is to require multiple tonnes of removals for issuing a credit. For example, under a discount rate of 1.75%, 5.48 tCO_2 and 2.14 tCO_2 respectively should be required to earn a credit when removals are stored for 10 years and 30 years respectively.

Example 2. To assess the impact of the discount rate on real-life implementations of removal project activities, the table 5 below provides the average annual yield of credits per hectare that can be earned by medium-growth mixed-species watershed reforestation activity over a crediting period of 45 years (the maximum allowed under the A6.4 mechanism (see appendix E for the details).

Table 5. Average annual credits per hectare earned by a reforestation activity (A6.4ERs per hectare per year, averaged over the crediting period)

	Crediting period		
Discount rate	15 years	30 years	45 years
0%	0.54	1.46	2.14
1%	0.96	2.45	3.35
2%	1.43	3.50	4.51
3%	1.92	4.51	5.54
4%	2.40	5.43	6.40
5%	2.86	6.26	7.09

78. It can be seen from table 5 that use of discount rate of 2%, which falls within the range of most-recommended rates, results in 4.51 credits per hectare per year over the period of 45 years. The relevance of carbon credits in terms of financial incentive is significant if credits can be sold at a price of 20 to 50 USD (the upper limit will enable a larger number of activities than the lower one).

79. It is thus seen that not only are the discount rates between 1.75% and 2.25% justified by experts, use of these discount rates with a 100-year time horizon also results in practically feasible carbon incentives. Explicit consideration of appropriate discount rate helps make a rational choice of the equivalence period while avoiding arbitrary choices. For example, if tonne-based credits are issued at a storage period of 45 years, this corresponds to an implicit discount rate of 7% which is by far too high to be justified on sound economic rationales. Without using an assessment framework of time horizon and discount rate, we would have no way of judging whether a storage period of 45 years justified a tonne-based credit or not, and if not how much could be the extent of overcrediting or undercrediting resulting therefrom.

4.6. Short-term vs long-term removals

80. In the case of temporary removals (i.e. removals that are stored shorter than time horizon), there’s further distinction often made between short-term and long-term removals.

81. As a general term, one can speak of shorter-term removals relative to longer-term removals in a given context, but what does the term ‘short-term’ mean by itself? Just as in the case of making a distinction between temporary and permanent removals based on a threshold value of storage period, a threshold value of the storage period (e.g. 10 years) has to be agreed upon to unambiguously distinguish short-term removals from long-term removals.

82. However, there is no generally agreed threshold storage period that delineates short-term removals from long-term removals. It is also not clear on what basis, scientific or economic, can such a threshold be determined.

83. Even if such a threshold were to be agreed, e.g. by consensus, there needs to be a significance for such a threshold.

84. In general, shorter-term removals have less mitigation value than longer term removals. This is self-evident on a tone-to-tonne comparison. However, the mitigation value of 2 tCO_2 of shorter-term removals could be equal to or greater than the mitigation value of 1 tCO_2 of longer-term removals (R-49:a) depending upon the precise storage period of each.

85. In terms of science, the mitigation value of different tonnes stored over different years can simply be represented by the product of the tonnes and the years. Such a two-dimensional measure has been called tonne-year (R-011:a) and can be seen as the basic unit of mitigation produced by removals because of its proportionality with the amount of marginal atmospheric warming (i.e. Joule per tCO_2) added by emissions and reduced by removals of CO_2.

86. In the case of removals that are stored indefinitely, (e.g. fixed geochemically through mineralization), the storage period is undefined, but it is a common denominator across any two such removals, and therefore cancels out. This making a tonne-to-tonne comparison possible.

87. As far as physical science and economic science are concerned there is no unique threshold of storage period where any qualitative change, or a quantitative discontinuity, occurs in the value of temporary removals as storage period varies. The value of a 1-year removal is as valid as (though not equal to) the value of a 100-year removal. The only difference is the quantitative difference in value of the mitigation produced, which is best quantified through the reduction in atmospheric warming caused by the removals.

88. However, there may be other considerations for distinguishing between short-term and long-term removal activities such as follows:

    (a) Minimum activity periods are desirable for delivering significant co-benefits of land-based activities, such as prevention of erosion and salinization, or protection of biodiversity, which are associated with long-term restoration of vegetation cover;

    (b) Minimum (and maximum) activity periods are also relevant for the purpose of baseline setting, additionality demonstration and leakage potential in the context of a market mechanism (R-51:a,b; R-55:a-f; P-29:a).

89. These considerations of minimum period apply to the removal activities rather than to the period of storage which can in some cases be independent of the activity itself (e.g. a tree-planting activity in which the harvested biomass is used for production of biochar).

90. The duration over which removals are stored also depends upon the scale of aggregation or boundary of assessment. A series of short-term removals that are implemented sequentially, thus always storing an average amount of carbon over a longer period, can be categorized as short-term or long-term.

91. For example, if a 10-year threshold for storage period is adopted to delineate short-term removals from long-term removals, a pulpwood plantation that has a harvesting cycle of 7 years but is to be managed over a multi-rotation period of 45 years, the average stock of removals across multiple harvest cycles can be categorized as long-term storage, even though the individual rotation cycle is short.

92. The same applies to the collective impact of a large number of removal activities registered under a mechanism. If activities are registering in and dropping out constantly, at any given point of time there always is a certain amount of carbon stored that is attributable to the mechanism. This would be a case of long-term storage caused by short-term activities.

4.7. Choice of a minimum activity period

93. In view of the above considerations, it might be desirable, even required, to adopt a minimum activity period in order to exclude activities with too short periods from being eligible under the mechanism. The rationales for such a choice would be as described in paragraph 88 above.

94. A period of 10 year has been commonly adopted as the minimum period for the purpose of accounting of removals (R-55:ai; R-01:a).

95. Other sources suggest that a minimum activity period ranging from 5 to 30 years should be adopted while recognizing that many of the co-benefits are generated only by multi decade land-based removals activities (R-55:aj; N-90:i).

5. Crediting removal activities under the mechanism

96. In the case of removals that are stored in physically irreversible reservoirs (e.g. through sub-surface rock mineralization) quantified net removals can be credited on basis of 1 credit per tCO_2. The storage period is indefinite and hence common across all tonnes of such removals.

97. In case of removals that are stored in leaky reservoirs, such as the ecosystem carbon pools or durable wood carbon products, the storage by its very nature is temporary and hence crediting methods have to take this aspect into account.

98. Different approaches to crediting temporary removals as described in the sub-sections below.

5.1. Temporary crediting

99. Under this method special types of credits are issued which are of temporary nature and expire after a certain period from the date of their retirement (i.e. deployment for the purpose of offsetting). These credits do not offset emissions; these offset delays in achieving emission reductions, that is, temporary exceedance of emissions compared to the permitted limits (the caps). These credits are issued on the basis of tonnes of removals

but the storage period of these tonnes must at least be equal to the number of years by which the exceedance of the emissions occurs. This is best illustrated through an example.

Example. An entity X is subject to emission cap of 100 tCO_2 during each 5-year accounting period. At the end of the first accounting period, the entity's emissions are found to be 110 tCO_2 which exceed the allowance by 10 tCO_2. The entity has the option of buying 10 temporary credits from a removal activity. These removals must have been stored at least for a period of 5 years. At the end of the second accounting period, the entity's emissions are found to be 100 tCO_2, which meet the allowance over the second accounting period, but do not make up the shortfall of the previous accounting period. The entity must buy another 10 temporary credits to cover the exceedance during the second accounting period. During the third accounting period, the entity's emissions amount to 90 tCO_2. Thus, the temporary exceedance of targets has been covered now with permanent emission reductions and the entity is free from any further obligation to buy temporary credits. For the removal activity, there remains the possibility of getting further temporary credits as long as the same removals continue to be stored.

100. This arrangement is similar to the temporary certified emission reductions (tCERs) that are used under the clean development mechanism (CDM). There are some important differences:

(a) In tCERs quantification, the actual storage period is not taken into account. If 100 tCO_2 of removals were to be achieved, irrespective of whether these were stored over 5 years or 10 years, the number of credits issued would be the same. From the atmospheric value perspective, the period of storage matters as much as the number of tonnes. Thus, the environmental integrity is not the same across the different tCERs;

(b) The tCERs issued were not allowed to be carried forward across emission accounting periods. This restriction diminished the market value of the credits since these could only be used within a narrow window of time.

5.2. Tonne-year crediting

101. As discussed in the previous section, the quantification of credits earned by a removal activity is carried out on the basis of an agreed permanence period and the actual storage period of each tonne of removal.

102. In terms of issuance of the credits, however, the following two institutional design solutions can be considered:

5.2.1. Ex-post tonne-year crediting

103. Under this method, credits are issued on the basis of the permanence period, the verified tonnes and the verified storage of these tonnes. Since the tonnes as well as the storage have been verified, ex-post crediting eliminates the need for continued monitoring, reversal risk management, liability agreement and its enforcement. On the other hand, fewer credits get issued early in the crediting period. In the case of land-based removal activities, however, the annual rate of crediting accelerates over time since both the number of tonnes and the associated storage period increase with time (see figure E.1(b) in appendix E).

Example. A verification occurs in year 5 of an activity having a crediting period of 15 years. Number of credits is calculated based on the verified tonnes and the verified storage period applicable to each tonne, which results in 150 credits. Potentially each tonne could have been stored over a different period and this is accounted for. As long as the removal stocks are stored over the coming years, annual issuance of credits is possible, since for a given number of tonnes, the years increase with time. If the crediting period is successfully renewed, the annual credits stream can continue to flow. Whenever additional tonnes are verified, the rate of annual credits will increase accordingly.

5.2.2. Advance tonne-year crediting

104. Under this method, credits are issued on the basis of the permanence period, the verified tonnes and a nominal (assumed) storage period such as the period up to the end of the crediting period. Since the credits are issued in expectation of achieving a certain storage period, there remains a need for continued monitoring, reversal risk management, liability agreement and its enforcement until the expected storage period has been verified. The advantage of this method is that more credits get issued early in the crediting period.

Example. A verification occurs in year 5 of an activity having a crediting period of 15 years. Number of credits is calculated based on the verified tonnes and a nominal storage period of 10 years, which results in 280 credits. If the crediting period is successfully renewed, the credits can be re-calculated, for the same tonnes, based on a nominal storage period of 25 years. The difference between the re-calculated number of credits and the previously issued credits is issued upon successful renewal. Whenever additional tonnes are verified, the number of credits can be recalculated, and the difference issued accordingly.

105. This crediting methods brings forward in time the availability of credits. However, it requires the activity participants, and potentially the host Party, to enter into contractual arrangements to ensure the continued storage of the verified tonnes of removals until the end of the expected storage period. The mechanisms for enforcing the contractual arrangements and managing the risks of reversals can include pooled buffer of credits, pooled buffer of credits backed up by host Party guarantee, or pooled buffer of credits backed up by commercial insurance. The details of possible contractual arrangements for addressing reversals are described in appendix G.

5.3. Tonne-based crediting

106. Under this method, credits are issued equal to the verified tonnes of removals in expectation of achieving the storage period equal to the permanence period. Under this method ex-post crediting is not feasible since the credits issued at the end of the storage period would get issued too far the future. Only advance crediting is feasible under this method. This method has the advantage of getting a large number of credits upfront. However, since the credits are issued in expectation of achieving a certain storage period, there remains a need for continued monitoring, reversal risk management, liability agreement and its enforcement until the expected storage period has been verified. The mechanisms for enforcing the contractual arrangements and managing the risks of reversals can include pooled buffer of credits, pooled buffer of credits backed up by host Party guarantee, or pooled buffer of credits backed up by commercial insurance. The details of possible contractual arrangements for addressing reversals are described in appendix G.

Example. A verification occurs in year 5 of an activity having a crediting period of 15 years. Number of credits is calculated to be equal to the verified tonnes which results in 12,500 credits. The storage of these tonnes will be periodically monitored until the year 105 (assuming a permanence period of 100 years). Activity participants can get additional tonnes verified when they wish. The monitoring liability at each issuance will extend 100 years beyond the date of issuance. If the crediting period is renewed twice, and issuance happens in year 45,then these tonnes will be periodically verified until year 145. The details of the contractual arrangements for addressing reversals are described in appendix G.

107. Table 6 summarizes the characteristics of the different crediting methods discussed above.

Table 6. Crediting methods and their characteristics

Characteristics	Temporary crediting	Ex-post tonne-year crediting	Advance tonne-year crediting	Tonne-based crediting
The basis of credits (the measured/verified quantity)	Verified tonnes of removals and verified storage	Verified tonnes of removals and verified storage	Verified tonnes of removals	Verified tonnes of removals
Calculation of credits from the basis	Number of credits is equal to the number of verified tonnes.	Number of credits is equal to the verified tonnes multiplied by the respective crediting factors for the verified storage period of the tonnes.	Number of credits is equal to the verified tonnes multiplied by the crediting factors for expected storage up to the end-of-the crediting period.	Number of credits is equal to the verified tonnes.
Credits are issued after actual mitigation	Yes	Yes	No. Storage remains to be verified.	No. Storage remains to be verified.
Mitigation period remains within the crediting period	Yes	Yes	Yes	No. Mitigation produced after the end of the crediting period is also credited.
Credits correspond to their net present value	Yes	Yes	No. Future credits are brought forward at today’s value.	No. Future credits are brought forward at today’s value.
Activity participants are free from post-issuance liability	Yes	Yes	No. A liability agreement must be entered into.	No. A liability agreement must be entered into.

Characteristics	**Temporary crediting**	**Ex-post tonne-year crediting**	**Advance tonne-year crediting**	**Tonne-based crediting**
Buyers are free from cancellation risks	Yes. Buyers know the expiry date of the credits at the time of purchase.	Yes. Credits don't carry any reversal risk.	No. If reversal occurs and is not compensated, credits can get cancelled.	No. If reversal occurs and is not compensated, credits can get cancelled.
Other pros	The credits allow the users to gain time for either procuring permanent credits or reducing their emissions by the next commitment period.	– Because of flexibility and simplicity, a broad range of activities can be enlisted; – Credits can be issued annually with simplified monitoring ("the no-decrease" monitoring report). – Environmental integrity is guaranteed.	– More credits are issued upfront than in the case of ex-post tonne-year crediting.	– More credits are issued upfront than in any other crediting method.
Other cons	The credits are not fungible with A6.4ERs and cannot be traded in market generally. These can only be used by countries or entities to cover their shortfall in achieving emission targets in a particular accounting period.	– Fewer credits get issued earlier on.	– Requires the activity participants, and potentially host Parties, to enter into contractual arrangements to ensure the continued storage of the removals until the end of the crediting period; – Activity participants face unknown opportunity costs related to future land use and market developments; – Buyers are not free from cancellation risks and uncertainties; – Uncompensated reversals can adversely affect the	– Requires the activity participants, and potentially host Parties, to enter into contractual arrangements to ensure the continued storage of the removals until 100 years after the date of issuance; – Activity participants face unknown opportunity costs related to future land use and market developments; – Buyers are not free from cancellation risks and uncertainties. – Uncompensated reversals can adversely affect the

Characteristics	Temporary crediting	Ex-post tonne-year crediting	Advance tonne-year crediting	Tonne-based crediting
			environmental integrity of the credits.	environmental integrity of the credits.

5.4. Concerns raised about use of tonne-year accounting

109. From the preceding analysis it appears that tonne-year accounting, including tonne-year crediting, has several advantages over other methods of accounting and crediting. However, some of the inputs received from stakeholders have questioned the method of tonne-year accounting whereas others have recommended the use of tonne-year accounting. Yet others have suggested that further consultation should be conducted on this issue before deciding about the use of tonne-year accounting.

110. Table 7 and table 8 summarize the arguments and responses relating use of tonne-year accounting methods.

Table 7. Arguments against use of tonne-year accounting and their response

Arguments against use of tonne-year accounting	Response to the arguments
(1) Temporary storage of carbon cannot provide the same benefits as emission reductions and therefore cannot be used to offset CO_2 emissions for the following reasons: a. The consequences of CO_2 emissions beyond an arbitrary time horizon are ignored which makes the approach physically inconsistent with the Paris Agreement's goal of temperature stabilization (P-11:e, P-24b, P-11:b; P-29:d); b. Tonne-year accounting approach is not compatible with the reality of a limited remaining global carbon budget. From a carbon budget perspective storing carbon for 1 year makes no difference whatsoever (R-55:y; P-07:f; P-11:c; R-55:ac); c. Temporarily storing carbon reduces the cumulative amount of energy trapped by the Earth's atmosphere, but that does not make it identical to either avoiding emissions or permanently storing CO_2 (R-11:a; P-07:g); d. Creating this equivalence will open the door to creative accounting in carbon markets (P-07:h); e. Tonne-year approach is myopic because all the benefits will accrue in the short term while the costs will materialize in the long term (R-55:aa); f. Actors will benefit financially today (from not having to reduce the tonne that is being offset, and from selling a carbon credit and society will	(1) Most of these objections relate to temporary carbon storage in general and not to the specific case of tonne-year accounting. For example, argument (a) notes that the consequences of CO_2 emissions beyond an arbitrary time horizon are ignored. In a tonne-based accounting method applying a fixed permanence period, the consequences beyond the adopted permanence period are also ignored. (2) The following responses to the arguments can be found in other sources: a. Use of a time horizon provides a framework to quantify the value of climate-relevant policies and actions. It is not just the physical effects that matter but their economic impact in a given policy context should guide decision making. Temporary removals are a strategic tool that can be leveraged to navigate the path to the goal of CO_2 stabilization while minimizing the damages and risks along the way. The benefits generally agreed to be accruing from temporary removals are listed under paragraph 56; b. Temporary removals help staying within the carbon budget longer, even if these don't help indefinitely postpone the event of using up the budget. The assertion that "storing carbon for 1 year makes no difference whatsoever" is not logical, as can be seen from the following scenario: An entity emits on 1 tCO_2 on 1 January every year and removes on 1 tCO_2 on 31 December of the year for ever. Will they have no effect on the atmosphere whatsoever? Evidently their activity will have as much impact the atmosphere as 1 tCO_2 of permanent emission; c. The question, in unambiguous terms, is this: Can N tCO_2 of removals stored for 10 years produce the benefit to counteract the impact of 1 tCO_2 emission? The answer evidently is yes. Only the number N needs to be determined on some scientific and economic basis. That is what tonne-year is accounting does; d. On the contrary, the explicit approach of tonne-year accounting based on science and economics helps keep away from creative accounting such as assuming that 1 tCO_2 of 30-year or 40-year removals can offset 1 tCO_2 of emissions. When assessed under the tonne-year method with rational choice of parameters, one

benefit from lower climate impacts today. It is society in the future that will suffer from increased climate impacts. (R-55:ab).	concludes that any fixed storage shorter than 80 to 100 years does not have the required environmental integrity to justify offsetting of emissions (see paragraph 77); e. Taking out a financial loan can appear to be myopic: consumption in the short term is preferred in lieu of repayment liabilities in the long term. Yet financial loan is not a zero-sum game, it has a value: it helps navigate an urgency. By the logic suggested, all form of financing would be myopic; but we know that that is not the case; f. It is not about enjoying benefits; it is about taking urgent action to save a house from collapsing so that future generations can still have the house intact or at least minimally damaged. Present generation should recruit all means available, even temporary removals, to safely navigate the path so that a relatively safer planet can be handed over to the future generations.
(2) Equivalence of removals to emission reductions is based on arbitrary choices: a. The tonne-year concept measures climate impacts over a predetermined time horizon, the choice of which remains largely a policy decision rather than a scientific one (R-52:b); b. The arguments for choosing a time horizon are conceptually flawed. Suggesting that the time horizon could be linked to expectations about how long it will take to decarbonize the global economy is far too simplistic. If we expect the world to decarbonize by 2060, it does not follow that we no longer need to be concerned about reversals of stored carbon after that date (P-24:c); c. Tonne-year method rests on enormous assumptions about the atmospheric lifetime of carbon dioxide (R-55:v); d. Conversion rate is highly sensitive to policy choices: Validity of tonne-year approach is highly	(3) The equivalences are based on scientific and economic principles: a. Relevant policies choices have to be made in any decision-making context except the most trivial ones. A fixed period temporary removal such as 30-year or 50-year removals under tonne-based accounting also assumes a predetermined horizon that is normatively adopted; b. It is not that we are not concerned about emissions after 2060; it is that emission reduction after 2060 will cost less than today. Secondly, the reversals will not happen all together after 2060, rather there will be a statistical distribution of activities that will gradually trail off as carbon price declines. Many of the land-use changes will get locked in economically and will never be reversed; c. The CO_2 diffusion model (the Bern-CC model) has been in use for a very long time by now. Different versions of the Bern-CC model only lead to a marginal change in the equivalence period or in the intermediate conversion rates. IPCC has been using these models for all of it's the IAM assessments. Secondly, the model does not make a key difference since if we don't know how removals decay, we also don't know how emissions decay. d. The Lashoff method is widely used approach to equivalence time calculation. The parameter choices of time horizon and discount rate are objectively determined on the considerations of policy relevance and economic valuation of alternatives. There

dependent upon the specific assessment method and assumptions therein (e.g., equivalence timeframes, discount rates, asymptotic decay of CO_2, etc.). These concerns are not trivial, as recent work shows choice of these variables can affect crediting outcomes vary as much as 10-fold5 (P-29b).	is no ambiguity or leeway beyond the choice of these parameters. As indicated in paragraph 77, the equivalence time comes out to be between 80 and 100 years. This does not support the observation that there could be 10-fold difference in outcomes.
(3) Tonne-year accounting incentivizes short-term storage: a. Under tonne-year accounting the payments per tonne would in decline over time, reducing the incentive to avoid reversals (P-24:h); b. Tonne-year approaches inherently fail to internalize maintenance costs since reservoir owners can essentially “walk away” from a mitigation activity at any time, without any penalty for ensuing reversals (P-24:j); c. The generation of a significant amount of credits on large areas during a period of one or two years after which the reservoirs are destroyed, we would propose that tonne-year credits can only be issued after a minimum period of five years (R-55:a-g);	(3) Tonne-year accounting does not require short-term activities; it allows flexibility in the duration of activities. Adopting tonne-year accounting or tonne-year crediting does not preclude the prescription of a minimum activity period. a. Reversals cannot occur under tonne-year crediting if ex-post (i.e. incremental) crediting is followed. Where credits are issued in advance (i.e.in expectation of a nominal storage period), number of credits issued per unit time grow over time because the two variables, tonnes and years, grow together in most tree planting activities. Because of this the activity participants have a strong incentive to continue the activity. See figure E.1(b) in appendix E; b. Where advance tonne-year crediting happens, the activity participants have to enter into contractual agreements for liability compensation liability of reversals and also contribute to the buffer. In the case of ex-post (i.e. incremental) tonne-year crediting, reversals cannot occur because credits are issued only for the storage period that has been verified; c. Generation of a significant amount of credits on large areas during a period of one or two years is not possible where credits are issued on ex-post basis, since in two years no significant tonnes of removals can be achieved and the number of credits would be a small fraction those tonnes. Where ex-ante issuance happens, the activity participants have to enter into contractual agreements for liability of compensation for reversals and also contribute to the buffer. Nevertheless, it is also possible to enforce a minimum period of time before ex-ante credits can be issued.
(4) Using tonne-year accounting will lead to too many credits: Under tonne-year accounting there is a risk that a large number of temporary credits could suddenly enter the market, lowering prices for existing	(4) There is certainly no justification to suggest that using tonne-year accounting will lead to too many credits in the market. On the contrary, the main concern commonly expressed about the use of tonne-year accounting is that there will be too few credits to incentivize sufficient number of activities. (R-35:b ; R-54:a). Tonne-year accounting based on 80 to 100-year permanence period and ex-post crediting has the highest stringent

developers who have committed to traditional long-term commitments (R-51:f; R-55:ag).	environmental integrity. Since there is trade-off between stringency of environmental integrity and number of credits produced, the logical expectation would be to have fewer credits issued. On the other hand, it is in the tonne-based accounting method that leads to a huge number of credits (R-49:b).
(5) Alternative discount-based methods are better suited: We are very sceptical of the tonne-year approach which generates equivalence of permanent and temporary emissions reductions in a manner that ignores a) the latest climate science; b) the welfare economic aspects of the problem of temporary reductions; c) the risks associated with temporary projects. In the attached paper we provide offer a useful alternative that solves these shortcomings. While it could be said that our approach introduces controversial issues concerning discount rates, the previous contributions which focus on the physical measures of carbon make implicit discounting assumptions and assumptions about damages (P-18:c).	(5) The alternative proposed called SVO is based on temporary carbon valuation based on discounting only without using a finite time horizon. As noted in paragraph 61, indefinite time horizon can be assumed if non-zero discount is used, and still quantitively similar valuation of temporary carbon can be arrived at. According to this alternative proposal based on the social cost of carbon, 125-tonne-years is considered equivalent to 1 tonne of emission reduction. Quantitively it is similar to the tonne-year method based on 100-year time horizon and zero discount rate which requires a conversion rate between 134 and 100 tonnes to a credit as the storage period increases. On practical application, the outcomes are comparable. However, this proposal incorporates uncertainties in additionality and leakage into the model used, which under the Article 6.4 mechanism will be addressed separately and explicitly based on activity design and the methodology applied.
(6) The alternative method of tonne-based accounting is better: a. Rather than coming up with overly sophisticated discounting techniques (tonne-year or tonne-based crediting options), we believe that buffers have worked well in other programs and initiatives dealing with permanence of removals (P-02:b); b. The tonne-based crediting approach in that context would be more straightforward where credits issued are equal to the tonnes of verified removals. It is more in line with the current practices in the voluntary markets (P-20:d); c. The alternative tonne-based methods are not premised on the idea of equating arbitrarily short	(6) The basis of the observation that tonne-based crediting has performed well is not clear. If fungible credits are issued on the basis of storage period of 30 or 40 years, the environmental integrity is not certainly the same as when the credits are issued on the basis of a storage period of 80 to 100 years. In the case of mechanisms issuing tonne-based credits based on a 100-year permanence period, there remains considerable uncertainty about the reality of these credits since their future is fraught with so many uncertainties (see below). There already is wide criticism of the existing voluntary carbon market mechanisms, including those using a 100-year permanence period, questioning the environmental value of the credits generated (B-05, B-19, R-49). Under Article 6.4 mechanism, however, if tonne-based crediting is to be followed, the following scenario emerges: Assuming a permanence period of 80 to 100 years and a maximum crediting period length of 45 years (which is already decided under the RMPs), the period over which liabilities for compensation of reversals will have to be enforced will be from 125 to 145 years. Over such a long period, the credibility and robustness of

carbon storage periods with permanent mitigation. Instead, credits are issued only if there are credible guarantees to compensate for reversals if they occur at any point during the permanence period (P-24:i).	environmental integrity of the credits faces numerous challenges for the following reasons: (i) In an international setting, entities may be unwilling or unable to enter into contractual obligations for such long durations; (ii) Entities, including activity participants, emitting entities that retire credits, and the regulating governance institutions, may not last that long; in such a case, the atmosphere will be left stranded; (iii) Buffers may be ineffective against intentional reversals, which are inherently difficult to model at a system level; (iv) The intentional reversal penalties, if used, would implicitly recognize that real-world factors may induce project attrition during the 145-year monitoring period, raising questions about the validity of baselines and increasing landowners' costs of participation; (v) Predicting the growth and timber harvests over a 100-year period is highly uncertain, compromising the robustness of the baseline; (vi) It is difficult to distinguish between a project that would have happened without the offset program from one that is motivated; (vii) Commercial insurance is not well-suited to cover against these intentional actions, and a system-wide buffer could put the entire system at risk if the prevalence of intentional reversals is high relative to the size of the buffer; In a sovereign jurisdiction it is easier to enforce long-term contracts since institutional stability is guaranteed through succession laws. In an international setting it is not clear how inter-generational contracts can be enforced and under which laws. A feasible option would be to issue partial incremental credits at certain interval e.g. every 5 or 10 years. That is already a version of tonne-year accounting.

Table 8. Arguments for use of tonne-year accounting and its framing

Advantages of using tonne-year accounting	Conditions and limitations
Tonne-year accounting provides the following advantages: a. Avoids the risk of carbon credits that are issued before verifying their storage period (P-21:b); b. Credits the climate benefit that has already occurred on an annual basis, and therefore is irreversible (R-55:p); c. Allows flexibility in activities and thus broadens potential participation of stakeholders (P-21:b); d. Pays for climate action occurring today, rather than paying for carbon removal decades from now (P-21:b); e. Adds transparency to credits of varying durations and time horizons that are observed across different standards and different activities under a given standard; (R-55:t); f. Avoids the need for locking up land in specific land uses for prolonged periods thus creating particularly valuable flexibility for small-holders (R-14:a); g. Avoids long-term liabilities as a means of justifying credit that is given in advance (i.e. before required storage period is verified); h. Allows credits to be awarded as the project goes along, rather than waiting until the end of the project or crediting in advance with open liabilities (R-21:a);	No sources contradict the benefits of tonne-year accounting listed in the first column. However, see table 6 for objections raised about use of tonne-year accounting, including the scientific validity of the value of temporary carbon storage. Regarding the details and design of tonne-year credit system the following views are found in the sources: (i) Only ex-post crediting should be used (R-35:a); (ii) Minimum storage period should be made mandatory; suggested minimum period ranges from 5 years to 30 years; (iii) Interpolation of conversion ratio should be based on cumulative radiative forcing rather than on a linear proportionality of the storage period; (iv) Time horizon of 100 years should be used without applying discounting; this implies a permanence period of 100 years. However, others suggest that a conversion ratio of 50:1 would be more pragmatic and economically viable. Elsewhere it is suggested that the issue of economic viability should not be addressed by weakening environmental integrity of offsets (R-49:c). Instead, this should be addressed from the credit price perspective. If price of credits is too low for certain activity types, that means the carbon market is not yet ready to leverage these types of activities. (v) Appropriate consideration should be made for implication of tonne-year accounting for baseline, additionality, and leakage provisions in the respective methodologies. Others suggest that further details should be provided, and further public consultation should be held on tonne-year accounting before making a decision to adopt this approach: (P:51:c; P-29:g): (i) Policy choices such as time horizon, discount rate, calculation models (linear vs radiative forcing based) and minimum storage period should be decided carefully; (ii) Compatibility of tonne-year crediting with NDC accounting and corresponding adjustments should be considered (P-13:b, P-20:c);

Advantages of using tonne-year accounting	Conditions and limitations
i. Provides a means of avoiding sovereignty concerns in countries hosting the projects**.**	(iii) Review, comment, and ‘road’ testing should be conducted before prescribing tonne-year accounting as an approved method under article 6.4 (P-29:c); (iv) Practical implementation details such as how to apply this approach over multiple verifications where each subsequent verification extends the permanence period of the achieved carbon stocks, should be worked out (P-20:b).

6. Methodological issues related to land-based removal activities

111. Land-based activities currently provide most of the removals and are expected to be the main driver of removal in the near-term (i.e. to 2030) and possibly even until 2050.

112. Table 9 lists examples of common implementations of land-based removal activities currently practiced. The categorization of the implementations is based on two facets: the biophysical characteristics of the vegetation and the underlying dominant management objective types. It should be noted that a conservation activity can also result in some economic products, and a production activity can also provide environmental and conservation services, but the main goal of an activity differs from its co-benefits.

Table 9. Categorization with examples of land-based removal activities

Activity type based on the biophysical characteristics of vegetation	Activity type by dominant management objective: Conservation	Activity type by dominant management objective: Production
Afforestation/reforestation	– Reforestation of watersheds – Restoration of protected/ designated forests – Restoration of biodiversity areas/protected areas	– Timber plantations – Pulpwood plantations – Horticultural plantations – Energy plantations
Revegetation	– Sand dune stabilization – Reclamation of saline/alkaline soils – Revegetation of watersheds	– Energy plantations (perennial non-tree vegetation) – Cultivation of perennial crops – Cultivation of medicinal plants
Tree planting	– Urban forestry – Agroforestry – Shelterbelts	– Agrisilvipastoral systems – Fuelwood woodlots – Small timber woodlots
Improved forest management	– Restocking native species by planting – Assisted natural regeneration	– Rotation age management – Reduced impact logging – Cleaning/pruning/ thinning treatments
Wetland management	– Rewetting wetlands – Restoring mangrove habits	-
Soil organic carbon enhancement	– Conservation tillage – Fallows	– Soil productivity improvement

113. The sections that follow provide information on the different issues listed under paragraph 4 to be addressed under land-based activities. The activity types based on engineering methods are addressed in section 7.

6.1. Monitoring

114. The monitoring of all removal activities is based on the quantification of carbon stocks.

115. In the case of land-based removal activities, the quantification of carbon stocks is carried out through a ‘carbon stock inventory’ based on sampling, field measurements and regression models. Remotely sensed data may be used in combination with the data from field measurements for cost-effective monitoring.

6.1.1. Quantification of carbon stocks

116. In the case of land-based activities, methods based on the IPCC Guidelines exist for the measurement and estimation of carbon stocks in all terrestrial carbon pools[11]. Estimates at successive points in time are used for calculating changes in the carbon stocks. The methods may vary in complexity, precision, accuracy and cost. Different methods are appropriate for different carbon pools at different temporal and spatial scales.

117. The most commonly used carbon stock quantification methods employ measurements conducted on vegetation (e.g. trees and shrubs) in field sample plots, in conjunction with biomass-allometry models that allow for the conversion of measured quantities into biomass.

118. It is possible to use remotely sensed data in combination with field measurements to reduce the number of required sample plots and thus reduce the cost of monitoring.[12]

119. The use of conservative default factors should be allowed to provide flexibility for activities that do not seek to measure some carbon pools due to cost considerations.

120. As a further cost-saving measure, it is also possible for activities to exclude certain carbon pools from accounting where such exclusion results in conservative outcomes.

121. It is possible that different methods of carbon stocks inventorying will be required for carbon pools other than in-situ carbon stocks (e.g. the carbon pool of long-lasting wood products achieved under the activity).

122. The accuracy of measurements can be ensured by laying out in advance the specifications of data collection methods, such as relevant sampling methods, calibration of the equipment, validation of the models, and specifications for the use of remote-sensing data.

123. Estimations should include the associated uncertainties, and the uncertainties should remain within the prescribed limits. In the event of uncertainties exceeding the prescribed limits, the estimates should be adjusted to make these conservative in cases where the activity participants do not wish to additional measurements for cost reasons.

124. The use of digital tools can be leveraged for improving accuracy and reducing the cost of monitoring and avoiding data-related errors.

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[11] IPCC GPG-LULUCF, IPCC 2006 with 2019 enhancement, IPCC KP-Supplement, IPCC Wetland Supplement

[12] See, for example, section 8.1.2 of the CDM methodological tool AR-TOOL14: Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities.

6.1.2. Frequency of monitoring

125. The efficient frequency of monitoring depends upon the rate of accumulation of the carbon stocks to justify the cost of monitoring. There needs to be a sufficient accumulation of carbon stocks before the initial verification of the carbon stocks achieved by an activity is carried out.

126. As will be seen later, the timing for the first verification and the frequency of the subsequent verifications, as well as the maximum permissible period between successive mandatory verifications, will depend upon the type of storage, the crediting method used and the arrangements used for addressing reversals. In some cases, periodic monitoring may be a requirement even after the end of the crediting period (e.g. for ensuring that no reversals occur until the end of a specified period).

6.2. Reporting

127. Verified monitoring reports form the basis of the issuance of credits.

128. Monitoring reports summarize the monitoring outcomes. Monitoring reports are transmitted to a designated operational entity (DOE) which verifies the correctness of the monitoring results.

129. Verified monitoring reports form the basis of the issuance of credits.

130. Reports should be submitted soon enough after the quantification of the achieved carbon stocks to allow the DOE to visit the site and conduct sample checks as needed.

131. Monitoring report may either be required to contain all the relevant data, or if such data is too voluminous, to contain a summary of such data. In any case, the full data set should be made available to the verifier at the time of verification, except for the confidential data, if any.

132. Apart from the data related to carbon inventory, the reporting should include the records of events and incidents, such as fire, pest outbreak, harvests, leaks and seepage, that might have affected the carbon stocks in the intervening period.

133. Simplified monitoring and reporting is possible under certain circumstances, for example when the purpose of reporting is to ensure the continued storage of the carbon stocks for reasons of permanence; it cannot be used to seek the issuance of additional credits.[13]

134. Reporting should be required to include information on how the environmental and socioeconomic impacts were assessed and addressed.[14]

135. Reporting should be required to include information on how the activity contributes to the sustainable development in the host Party.[15]

[13] See, for example, section 6.4 Demonstration of “no-decrease” in the CDM AR-TOOL14 “Estimation of carbon stocks and change in carbon stocks of trees and shrubs in A/R CDM project activities”.

[14] See, A6.4M-RMP, paragraph 24(x).

[15] See, A6.4M-RMP, paragraph 24(xi).

6.3. Accounting of removals

136. Net removals achieved by a removal activity are equal to the total removals achieved by the activity minus the baseline removals, minus activity emissions, minus leakage emissions.

137. As activity emissions and leakage emissions are permanent and cannot be directly deducted from tonnes of removals, these need to be deducted on a tonne-year basis from the accumulated tonne-years of the activity. For example, if 1 tCO_2 emission occurred during a monitoring period, then 100 tonne-years should be deducted from the generated tonne-years. In absence of tonne-years, it would be impossible to do this accounting.

138. Accounting burden for both emissions and emissions can be reduced by avoiding the need to account for emissions that are merely theoretical possibility and cannot be anything but insignificant (P-20). Instead of specifying a quantitative threshold for defining insignificant emission, the emission sources can be allowed to be excluded from accounting on this ground. This is in addition to exclusion of the sources where the GHG balance is likely to be in favour of the atmosphere (the conservative exclusion of carbon pools). However, where no monitoring cost is involved and a conservative estimate can be made of emissions, such emissions should not be excluded but instead accounted as conservative estimated value.

6.3.1. Baselines

139. Baselines are the reference scenario against which a change in carbon stocks and removals is measured.

140. There are three types of business-as-usual (BAU) scenarios possible (see Figure 1):

(a) Significant carbon stocks exist in the BAU scenario and the carbon stocks are growing. Both the initial carbon stocks and the BAU removals are non-zero in this case;

(b) Significant carbon stocks exist in the BAU scenario, but the carbon stocks are declining over time. The initial carbon stocks are non-zero, but the BAU removals are zero in this case;

(c) No significant carbon stocks exist in the BAU scenario. Both the initial carbon stocks and the BAU removals are zero in this case.

6.3.1.1. Determining the baseline scenario

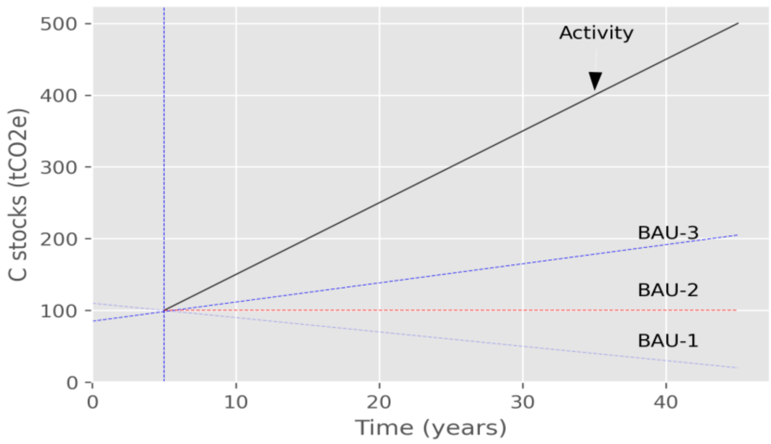
141. According to the “Rules, modalities and procedures for the mechanism established by Article 6, paragraph 4, of the Paris Agreement” (RMP) agreed by decision 3/CMA.3, activities under the mechanism shall require the application of one of the following approaches to setting the baseline:

(a) A performance-based approach, taking into account the best available technologies that represent an economically feasible and environmentally sound course of action, where appropriate;

(b) An ambitious benchmark approach where the baseline is set at least at the average emission level of the best performing comparable activities providing similar outputs and services in a defined scope in similar social, economic, environmental and technological circumstances;

(c) An approach based on existing actual or historical emissions, adjusted downwards to ensure alignment with paragraph 33 of the annex to decision 3/CMA.3.

Figure 1. Types of business-as-usual scenarios in a removal activity



142. Baseline-setting rules shall recognize that a host Party may determine a more ambitious level at its discretion.

143. Baseline scenarios shall be consistent with the applicable legal and regulatory requirements.

144. Baselines could be set at a national, regional or activity level. National or regional baselines are also known as standardized baselines, and presumably these would be developed from analyses of national and/or regional trends and practices and could be based on a combination of measurements of control scenarios, models and published datasets.

145. The activity-specific setting of baselines can address the specificities of the carbon stocks as well as any other local conditions and is thus likely to yield a more accurate prediction of changes in carbon stocks.

146. Baselines developed by activity participants also pose a risk that the participants would choose scenarios that maximize their perceived benefits.

147. Within a crediting period, baselines could be set to be fixed or to be updated periodically. In the case of a renewable crediting period, baselines are assessed at the beginning of each renewal and updated if appropriate.

6.3.1.2. Quantification of baselines

148. Baselines are quantified ex ante and these estimates remain valid throughout the crediting period. Quantified baselines are based on the quantified projection of the growth or the decline of the carbon stocks over time. Methods for estimating the baselines could be the same quantification methods that are used for the purpose of monitoring (see 4.1.1 above) or simplified conservative default-based methods, particularly where baseline carbon stocks are relatively small (e.g. less than 10 per cent of the carbon stocks expected to be

achieved under the activity).[16]

149. Where the carbon stocks are growing under BAU, the baseline is often quantified as the projection of the growth. Whether the projection is linear or non-linear would depend upon the availability of data and the specific attributes of the activity. Both types of projections need to be subject to the principle of conservativeness in terms of assumption and data uncertainties.

150. However, where significant removals are likely to occur under the baseline scenario, the baselines can also be estimated by using control areas where the baseline activities are expected to be continued.

151. The projections should take into consideration trends and events that are likely to affect the carbon stocks (e.g. changes in legislation, changes in market prices, changes in environmental awareness).

152. Where GHG emissions occur in the baseline of the activity and the implementation of the activity leads to reduction in those emissions, the emission reductions should not be accounted as credits. However, any increase in the GHG emissions, relative to the baseline, caused by the implementation of the removal activity, should be deducted from the achieved removals.

6.3.1.3. Periodic re-validation of the baseline

153. The baseline is set at the time of the validation and registration of the activity and is re-assessed at the time of the renewal of the crediting period

6.3.2. Accounting boundaries

154. Accounting of net removals achieved by an activity are affected by the boundaries defined in terms of the physical boundaries (e.g. carbon pools, equipment and materials, sources of emissions related to the activity) and the greenhouse gases (GHGs) considered.

155. The choice of the carbon pools and the GHGs to be considered can be optionally simplified by allowing activities to exclude some of these if such exclusion results in a conservative outcome.

156. Comprehensive accounting of activity emissions requires use of life-cycle assessment (LCA) approach where appropriate (P-25; P-07; P-16; P-22; P-14; P-05). Accounting burden can be reduced by using known standardized emission factors of products used (e.g. the LCA emissions associated with production of a tonne of a particular type of fertilizer might be known) (P-16). Further, if a piece of equipment or machinery is exclusively acquired for implementation of the activity (e.g. a tractor), then the LCA emissions including embodied emissions should be included. If the equipment was already in use in the baseline, then this cancels out and thus need to be accounted.

[16] Baselines for some of the land-based removal activities are not as large as in emission reduction (ER) projects. In an ER project, e.g. a renewable energy activity, more than 90% of emissions could be in the baseline; in an A/R project, baseline typically has less than 10% as much carbon stocks as are expected to be achieved by the activity. An uncertainty of 10% in the baseline estimation actually corresponds to 1% uncertainty in the estimation of credits. Exceptions to this pattern are improved forest management and soil carbon sequestration activities, wherein the baseline stocks could be comparable to the activity stocks.

157. Accounting of emission reductions caused by the activity need to be separately accounted and not be converted to tonne-years and added to the activity tonne-years. This can be an important case when for example in wetland restoration, the amount of emissions reduced can be significant, even more than the removals achieved through sequestration. On the other hand, smaller emission reductions, such as those of degrading baseline vegetation in a reforestation activity can simply be ignored as conservative choice.

6.3.3. Additionality

158. A removal activity is required to demonstrate that changes in the removals associated with it are additional to the removals that would occur in the baseline.

6.3.3.1. Types of additionality

159. Financial additionality implies that the removal activity or its outcome would not have been realized without the revenue from the carbon credits.

160. Regulatory additionality implies that the mandatory requirements such as law, regulations, industry standards and/or enforced policies would on their own cause the implementation of the activity in the absence of its registration under the mechanism.

161. Common practice additionality implies that the activity goes beyond what is commonly practiced in similar socioeconomic, ecological, and technological environments, which is a proxy of the most economically attractive of the activities that do not face barriers.

162. Performance additionality implies that the activity represents GHG removals that exceed the average emission performance of the peer activities in the industry or the sector and match the best performing comparable activities providing similar outputs and services in a defined scope in similar social, economic, environmental and technological circumstances.

6.3.3.2. Demonstration of additionality

163. The fact that the baseline has been determined independently of the activity automatically satisfies the requirement of additionality specified under paragraph 158 above, since the net removals are to be estimated relative to the removals occurring in the baseline.

164. Financial additionality is demonstrated by carrying out a financial analysis showing that the activity is not financially viable without the carbon revenues.

165. Under most existing carbon market standards, including the clean development mechanism (CDM), financial additionality is not a mandatory requirement for removal activities, but an optional add-on test.

166. A removal activity can be economically attractive but still be additional because it faces non-financial barriers that prevent it from being realized in the absence of being registered under the mechanism, and the mechanism contributes in removing these barriers.

167. In this case, barrier analysis is carried out to demonstrate that the existence of specified barriers would effectively prevent the activity from being implemented without the added support from the mechanism. The types of barriers included could be adverse ecological conditions, the non-availability or high cost of investment capital, inadequate infrastructure, lack of capacity, cultural barriers, institutional barriers, local barriers, organizational barriers, prevailing practice barriers, property rights barriers, social barriers, technological barriers and barriers linked to tradition. For the barrier analysis to be

credible, the activity participants have to demonstrate how the mechanism will contribute to overcoming the barriers.

168. Automatic additionality may be applied using approved positive lists based on certain criteria implying that removal activities are unlikely to be implemented in absence of the mechanism where such criteria are met.[17]

169. Regulatory additionality, common practice additionality and performance additionality are demonstrated by providing justification, supported by data and analysis where appropriate, as to why and how the removal activity passes these additionality tests.

6.3.4. Double counting

170. Activity validation should take into account the possibility of double-counting, double issuance and double-claiming in the context of the different international collaboration instruments, mechanisms and registries.

171. Double issuance occurs if more than one unit is issued for the same removals, either under the same mechanism or under two or more different mechanisms.

172. Double use occurs when the same issued unit is used twice (e.g. sold twice if the inter-registry tracking is not fully secured).

173. Double claiming occurs if the same removals are counted twice by both the buyer and the seller.

174. There could be two principal methods to avoid double-counting:

    (a) Registry-level integrity checking and transaction processing, as well as linking of registries;

    (b) The host Party may be required to provide necessary affirmations, at the time of authorization letter is issued, that rules out the possibility of double-counting of any type.

175. More specifically, a Party to the Paris Agreement that intends to host an Article 6.4 land-based removal activities in an area covered by an activity under jurisdictional approaches to enhance forest carbon stocks shall specify in its approval and authorization letter of the activity that it agrees to the implementation of the Article 6.4 land-based removal activity in the area and shall demonstrate that:

    (a) Where the host country conducts monitoring across the jurisdiction, the purpose is to ensure that project leakage and any reversals within the jurisdiction are accounted for and that environmental integrity is maintained at the jurisdictional level, but no credit is issued at the jurisdictional level, although a baseline can be set at the jurisdictional level;

    (b) The activity area credited under the activity under jurisdictional approaches to enhance forest carbon stocks is non-activity area for the Article 6.4 land-based removal activities. There is no overlap between the activity area credited under the activity under jurisdictional approaches to enhance forest carbon stocks and the

[17] See, for example, A/R CDM standardized baseline AR-ASB0001 "Afforestation and reforestation project activities in Namibia" which provides for automatic additionality. Available at https://bit.ly/3KOpCM8

activity area credited as Article 6.4 land-based removal activities and therefore, no double counting or double claim is taking place

176. Providing the accurate geolocation of a removal activity in the activity design document should be made mandatory.

177. Furthermore, to avoid double-counting the concept of "*nested accounting*" – where emissions are accounted for at one level of analysis (e.g., a specific improved forest management (IFM) project) and are factored into emissions at a higher level of analysis (e.g., a Party or group of Parties) – has been proposed. The nested accounting approach collects data at the smallest unit of analysis (i.e., the project) within nested jurisdictions and then rolls up into higher aggregation levels such as national inventories and submitted to international frameworks. To address the issue of assigning the emissions to the correct jurisdiction the nested accounting data shall be spatially referenced at the source through geotagging and timestamping. [18]

178. However further analysis on relationship between activities under the approaches to enhance forest carbon stocks and removal activities under 6.4 mechanism would be required to fully address any potential issues, including the relationship with the requirements under Article 5 of the Paris Agreement.

6.4. Crediting period

179. The crediting period for a removal activity is the period during which the activity is eligible to be issued credits.

180. The RMP contained in the annex of decision 3/CMA.3 requires that a crediting period in respect of activities involving removals shall not be more than 15 years (renewable maximum twice).

181. The host party may require that any shorter crediting period be applied for activities hosted within its jurisdiction.

182. The crediting period of a removal activity may be renewed in accordance with relevant requirements if the host Party has approved such renewal, following a technical assessment by a DOE to determine necessary updates to the baseline, and the ex-ante estimates of emission reductions.

183. The end of the crediting period of a removal activity is not necessarily the end of the obligations of the activity proponents to continue periodic monitoring of the carbon stocks against which credits were issued until such carbon stocks have been held out of the atmosphere for a period equal to that for which credits were issued.

184. Activities that created carbon debt in earlier phase and then recover this in the following years (e.g. re-wetting of wetlands) should not be eligible if this recovery cannot be ensured within the crediting period. It should be noted that each tCO_2 of emission will require a deduction of N tonne-years from the achieved tonne-years, where N is the permanence period in years.

[18] M. Schletz, A. Hsu, B. Mapes and M. Wainstein. "*Nested Climate Accounting for Our Atmospheric Commons—Digital Technologies for Trusted Interoperability Across Fragmented Systems*" POLICY BRIEF article. Available at https://bit.ly/3xrFNcS

185. This also applies to a situation where, for example, soil organic carbon (SOC) cannot be claimed on the basis of default transition factors of IPCC if the crediting period is shorter than the time required for transition (e.g. 20 years). However, SOC gains demonstrated through measurement-based monitoring may be included in removals.

6.5. Addressing reversal

186. Reversal of removals occurs when the verified tonnes against which credits have been issued are released back into the atmosphere before the end of the required storage period for which credits were issued. The causes of reversal can be common natural hazards (unintentional reversal) or a decision of the activity participants (intentional reversal).

187. Not all fluctuations in carbon stocks within the boundary of a removal activity lead to a reversal. Fluctuations in carbon stocks, whether due to natural hazards or intentional actions, that do not decrease the carbon stocks below the minimum level required by the issued credits do not qualify as reversals.

188. Two methods can be employed for addressing reversals:

(a) Use of ex-post crediting: under this method credits are issued based on verified storage period. Hence it would be impossible to emit the tonnes of removals before the required storage period since the required storage period has already been verified.

(b) Use of pooled buffer of credits backed by a liability agreement guaranteeing compensation of reversals: this method is used when credits are issued on the basis of verified tonnes and an expected storage period specified in a contractual agreement. Details of such arrangements are provided in appendix G.

6.6. Avoidance of leakage

189. “Leakage” is defined as the indirect increase in GHG emissions occurring outside the activity boundary and attributable to the activity. Leakage can be caused by various factors.

6.6.1. Leakage caused by shifting of baseline activities

190. If implementation of a removal activity prevents any activities occurring in the baseline scenario, the latter are likely to be shifted somewhere else. The emissions caused by the shifted activities in excess of the emissions caused in their original location would be accounted as leakage emissions.

191. For removal activities implemented in lands that have no competing use, this type of leakage is unlikely to occur.

192. This type of leakage can be addressed through the design of the removal activity such that the baseline level of services continues to be provided within the removal activity. For example, in cases of fuelwood collection and livestock grazing activities occurring in the baseline, the demand for these services may be initially met through the staggered closure of areas over the years and finally by allowing local communities to collect fuelwood and fodder from the reforested areas under managed access.

193. If a solution by appropriate activity design is not possible, or only partially possible, leakage may be estimated by collecting monitoring data on the baseline activities (e.g. how many households no longer collect their fuelwood from the area). The receiving lands of the shifted activities may be identified, and a conservative estimate of carbon stocks lost due to the shifted activity may be made. The net removals achieved by the removal activity are then reduced by the amount of carbon stocks estimated to have been lost as a result of the shifted activities.

6.6.2. Leakage caused by market effects

194. Market leakage is caused by the shift in the supply and demand equilibrium of a product. If the removal activity decreases or increases the supply of a marketable products, the market prices of the products may be driven up or down. The extent of the price changes will depend upon the size of the removal activity relative to the size of the reachable market. Higher prices may cause the product to be sourced from other lands that might be carrying higher carbon stocks per unit area than the activity lands. Lower prices may induce other producers of the same or similar product to shift to different activities that could possibly generate higher levels of emissions.

195. Since market leakage is indirect and diffuse, its effects cannot be isolated and directly measured. A possible solution is to use leakage adjustment factors based on the circumstantial probability and the relative size of the removal activity.

6.7. Avoidance of other negative environmental and social impacts

196. The implementation of land-based removal activities can have effects on other environmental and social objectives. The side effects can be either positive co-benefits or negative side-effects.

197. The impacts, risks and co-benefits of removal activity deployment for ecosystems, biodiversity and people will be highly variable depending on the type of activity, the site-specific context, the implementation and the scale.

198. This section describes the negative environmental and social impacts and their avoidance.

6.7.1. Impacts on land, biodiversity, and water

199. Afforestation, reforestation, forest restoration and improved forest management can have negative impacts on the biodiversity if these activities result in the replacement of native species with exotic species.

200. Large-scale afforestation and reforestation can lead to competition for land, thereby adversely affecting biodiversity conservation and food production.

201. Activities of agroforestry and enhanced of soil organic carbon can affect crop productivity adversely if not planned carefully and synergistically.

202. In general, any land-based removal activity implemented outside of the context of sustainable development (i.e. an activity with the sole objective of maximizing removed carbon) is likely to lead to adverse environmental and social impacts.

203. A removal activity that is designed to be implemented in the context of other activities delivering economic or ecological services, where removals are realized as co-benefits

rather than the main benefit, is less likely to lead to adverse environmental and social impacts.

204. For example, a removal activity including a BECCS power plant that is driven by the sole objective of maximizing carbon stocks achieved can lead to competition for land and drive out other higher priority needs such as food security and fuelwood for cooking. Such an activity may also compete for land that is supporting biodiversity conservation. On the other hand, a BECCS-supported removal activity that is driven by the objective of unblocking the saturation of bio-sequestration sink in a vegetation system that provides economic or ecological services is complementary and synergistic with the underlying goal of meeting human needs or providing ecological services, and is thus less likely to cause adverse environmental and social impacts.

6.7.2. Impacts on food security and local livelihoods

205. Negative social impacts can result if removal activities are implemented on land for which communities have alternative priorities, such as agricultural production, and if communities are not effectively engaged in all phases of activity design and implementation.

206. This negative impact can be reduced by ensuring that the removal activity is consistent with long-term regional land-use plans and that community development priorities are effectively incorporated during activity design, development and implementation.

207. Afforestation or production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse impacts on local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is not clearly defined.

208. Adverse impacts are less likely occur if free, prior and informed consent has been obtained from the relevant stakeholder groups before the activity is registered and stakeholder consultations are systematically followed.

209. Assessments of social and environmental impacts should be a requirement for the registration of a removal activity.

210. The scope of the assessments must cover human welfare and the conservation of biodiversity and other natural resources.

211. Periodic community consultations over the duration of the crediting period may be appropriate if applicable to the nature of the activities being undertaken.

212. Feedback and dispute resolution mechanisms to address matters related to adverse environmental and social impacts may be set up, allowing for feedback from employees, the local communities and relevant regional or national authorities.

213. Feedback and dispute resolution mechanisms should be easily accessible to the public and sufficiently advertised.

7. Methodological issues related to engineering-based removal activities

214. This section provides information on removal activities that are based on engineering approaches and technologies. Since there is no experience with the implementation of

these types of removal activities under existing market mechanisms, the information appearing below is based on the IPCC reports and other published scientific literature.

215. The following types of engineering-based removal activities are considered:

(a) Direct air carbon capture and storage (DACCS);

(b) Enhanced rock weathering (EW);

(c) Ocean alkalinization (OA);

(d) Ocean fertilization (OF).

216. Summary description of each of these activity types is provided in appendix H.

217. IPCC guidance on quantifying removals is available for land-based biological CDR methods (IPCC, 2006 and 2019), but it has yet to be developed for other CDR methods. Challenges with the development of estimation algorithms, data collection and attribution between sectors and countries will need to be overcome. Trusted methodologies for measurement, reporting and verification, which is required to enable private sector participation, will need to address the permanence, leakage and saturation challenges associated with land and ocean-based biological methods.

218. International governance considerations include global technology transfer around CDR implementation options; land-use change that could affect food production and land conditions and cause conflict around land tenure and access; and efforts to create sustainable and just supply chains for CDR, such as resources used for BECCS, EW and/or OA.

219. International governance would be particularly important for methods posing transboundary risks, especially for ocean-based methods. Specific regulations have so far only been developed in the context of the London Protocol, an international treaty that explicitly regulates OF and allows Parties to govern other marine CDR methods like ocean alkalinity enhancement.

220. The activities of enhanced rock weathering and the activities related to the oceans do not have any known method of monitoring, apart from the fact that there is considerable uncertainty about their environmental and social impacts. These types of activities are therefore not addressed under the sections that follow.

7.1. Monitoring

221. The monitoring of all removal activities is based on the quantification of carbon stocks.

222. In engineering-based removal activities, the quantities of carbon stocks are known through physical measurements such as the total mass of CO_2.

223. The monitoring of removal activities using geological formations for storage should be carried out in accordance the relevant provisions contained in the annex to decision 10/CMP.7 “Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities”.

224. For removal activities that have multi-Party boundaries (e.g. in a BECCS activity where wood is grown in Party A, pellets are made in Party B and are transported to Party C where

electricity is produced, and the separated through CCS is sent to Party D for storage in geological storage, these complexities will need to be addressed.

7.1.1. Frequency of monitoring

225. The frequency of monitoring will depend upon the rate of accumulation of the carbon stocks to justify the cost of monitoring. There needs to be a sufficient accumulation of carbon stocks before the initial verification of the carbon stocks achieved by an activity.

226. As will be seen later, the timing or the first verification and the frequency of the subsequent verifications, as well as the length of time over which mandatory periodical verification is required, will also depend upon the type of storage, and options used for addressing reversals.

227. Periodic monitoring will be a requirement even after the end of the crediting period (e.g. for ensuring that no reversals through seepage occur until the end of a specified period).

7.2. Reporting

228. Verified monitoring reports form the basis of the issuance of credits.

229. Monitoring reports summarize the monitoring outcomes. Monitoring reports are transmitted to a DOE, which verifies the correctness of the monitoring results.

230. Verified monitoring reports form the basis of the issuance of credits.

231. Reporting must happen soon enough after the end of the monitoring operations in order to allow the DOE to visit the site and conduct sample checks on the measurement carried out during the monitoring operations.

232. Monitoring report may either be required to contain all the relevant data, or if such data is too voluminous, to contain a summary of such data. In any case, the full data set should be made available to the DOE at the time of verification, except for the confidential data, if any.

233. Apart from the data on carbon stocks achieved and stored in the geological formations, the reporting should include the records of events and incidents, such as seepage from already stored and verified carbon stocks in the intervening period.

234. Simplified reporting is possible under certain circumstances, for example when the purpose of reporting is to ensure the continued storage of the carbon stocks for reasons of permanence; it should not be used to seek the issuance of additional credits.

235. Reporting should be required to include information on how the environmental and socioeconomic impacts were assessed and addressed.[19]

236. Reporting should be required to include information on how the activity contributes to the sustainable development in the host Party.[20]

[19] See, A6.4M-RMP, paragraph 24(x).

[20] See, A6.4M-RMP, paragraph 24(xi).

7.3. Accounting of removals

237. Net removals achieved by a removal activity are equal to the total carbon stocks achieved by the activity minus the baseline carbon stocks, minus emissions attributable to the implementation of the activity, minus leakage emissions.

238. For removal activities that have multi-Party boundaries (e.g. in a BECCS activity where wood is grown in Party A, pellets are made in Party B and are transported to Party C where electricity is produced, and the separated through CCS is sent to Party D for storage in geological storage, these complexities will need to be addressed.

239. Since current format of national GHG inventories does not provide space for accounting engineering-based removals, the CMA/COP with the aid of the IPCC will have to address this issue (P-22).

7.3.1. Baselines

240. Baselines are the reference scenario against which a change in carbon stocks and removals is measured.

241. In the case of engineering methods of removal, the baseline is zero in the case of a new facility.

242. If the capacity of an existing unit is increased, the baseline removals would be equal to the removals that occurred prior to the activity.

7.3.1.1. Periodic re-validation of the baseline

243. The baseline is set at the time of the validation and registration of the activity and is re-assessed at the time of the renewal of the crediting period.

7.3.2. Activity boundaries

244. Accounting of net removals achieved by an activity are affected by the boundaries defined in terms of the physical boundaries (e.g. the plant, equipment and materials, sources of emissions related to the activity), and in the case of geological storage of achieved carbon stocks, meet the requirements contained in the annex to decision the annex to decision 10/CMP.7 “Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities”.

7.3.3. Additionality

245. A removal activity is required to demonstrate that changes in the removals associated with it are additional to the removals that would occur in the baseline.

246. If an activity uses the removed carbon dioxide for economically useful products, financial additionality also needs to be demonstrated.

247. Regulatory additionality should be demonstrated by proving that that the activity would not be realized in the absence of its registration under the mechanism because of the mandatory requirements such as law, regulations, industry standards and/or enforced policies.

7.3.4. Double counting

248. Activity validation should take into account the possibility of double-counting, double issuance and double-claiming in the context of the different international collaboration instruments, mechanisms and registries.

249. Double issuance occurs if more than one unit is issued for the same removals, either under the same mechanism or under two or more different mechanisms.

250. Double use occurs when the same issued unit is used twice (e.g. sold twice if the inter-registry tracking is not fully secured).

251. Double claiming occurs if the same removals are counted twice by both the buyer and the seller.

252. There could be two principal methods to avoid double-counting:

    (a) Registry-level integrity checking and transaction processing, as well as linking of registries;

    (b) The host Party may be required to provide necessary affirmations, at the time of authorization letter is issued, that rules out the possibility of double-counting of any type.

253. Providing the accurate geolocation of a removal activity in the activity design document should be made mandatory.

7.4. Crediting period

254. The crediting period for a removal activity is the period during which the activity is eligible to be issued credits.

255. The RMP contained in the annex of decision 3/CMA.3 requires that a crediting period in respect of activities involving removals shall not be more than 15 years (renewable maximum twice).

256. The host party may require that any shorter crediting period be applied for activities hosted within its jurisdiction.

257. The crediting period of a removal activity may be renewed in accordance with relevant requirements if the host Party has approved such renewal, following a technical assessment by a DOE to determine necessary updates to the baseline, and the ex-ante estimates of emission reductions.

258. The end of the crediting period of a removal activity is not necessarily the end of the obligations of the activity proponents to continue periodic monitoring of the carbon stocks against which credits were issued until such carbon stocks have been held out of the atmosphere for a period equal to that for which the credits were issued..

7.5. Addressing reversal

259. Reversal of removals occurs when the verified tonnes against which credits have been issued are released back into the atmosphere before the end of the required storage period for which credits were issued. The causes of reversal can be common natural

hazards (unintentional reversal) or a decision of the activity participants (intentional reversal).

260. Not all fluctuations in carbon stocks within the boundary of a removal activity lead to a reversal. Fluctuations in carbon stocks, whether due to natural hazards or intentional actions, that do not decrease the carbon stocks below the minimum level required by the issued credits do not qualify as reversals.

261. Two methods can be employed for addressing reversals:

(a) Use of ex-post crediting: under this method credits are issued based on verified storage period. Hence it would be impossible to emit the tonnes of removals before the required storage period since the required storage period has already been verified;

(b) Use of pooled buffer of credits backed by a liability agreement guaranteeing compensation of reversals: this method is used when credits are issued on the basis of verified tonnes and an expected storage period specified in a contractual agreement. Details of such arrangements are provided in appendix G.

7.6. Avoidance of leakage

262. Leakage is defined as the indirect decrease or increase in carbon stocks occurring outside the activity boundary.

7.6.1. Leakage caused by resource competition

263. If implementation of an engineering-based removal activity uses resources (e.g. energy, water, PV panels, windmills) that in the baseline scenario would have been used by some other activity, the latter will likely be shifted to some other resource (e.g. take recourse to less clean energy). The emissions caused by the resource shifted should be accounted as leakage.

264. This type of leakage can be addressed through the design of the removal activity such that the activity uses only the resources that have no competing use.

265. If a solution by appropriate activity design is not possible, or only partially possible, leakage may be estimated by collecting monitoring data on the baseline activities (e.g. how much resource shift has taken place). A conservative estimate of consequent emissions may be made. The net removals achieved by the removal activity are then reduced by the amount of emissions estimated to have been caused by the resource shift.

7.6.2. Leakage caused by market effects

266. Market leakage is caused by the shift in the supply and demand equilibrium of resources such as energy and water. If the removal activity decreases the availability of energy or water by competing for the resources, the market prices of the resources may be driven up or down. The extent of the price changes will depend upon the size of the resources used by the activity relative to the amount of resources available in the reachable market. Higher prices may cause the resources (e.g. energy, water) to be derived from more emitting sources and technologies.

267. Since market leakage is indirect and diffuse, its effects cannot be isolated and directly measured. A possible solution is to use leakage adjustment factors based on the circumstantial probability and the relative size of the removal activity.

7.6.3. Addressing seepage in geological storage

268. Seepage of carbon stocks in geological storage should be addressed in accordance with relevant provisions contained in the annex to decision 10/CMP.7 “Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities”.

7.7. Avoidance of other negative environmental and social impacts

269. The implementation of removal activities can have effects on other environmental and social objectives. The side effects can be either positive co-benefits or negative side-effects.

270. The impacts, risks and co-benefits of removal activity deployment for ecosystems, biodiversity and people will be highly variable depending on the type of activity, the site-specific context, the implementation and the scale.

271. This section deals with the negative environmental and social impacts and their avoidance in relation to engineering-based removal activities.

7.7.1. Impacts on land, biodiversity and water

272. Large-scale engineering-based removal activities, such as DACCS, can lead to competition for resources such as clean energy and water. This may affect energy security and access to water in the areas in immediate vicinity of the activity site.

273. If waste products of the activity such as used chemicals and effluent water are not handled safely, these can cause toxicity and other harm to the land, biodiversity, and water resources.

7.7.2. Impacts on food security and local livelihoods

274. Negative social impacts can result if removal activities implemented compete for resources used by local vulnerable populations.

275. This negative impact can be reduced by ensuring that the removal activity is appropriately sited and uses resources that do no have opportunity cost.

276. Assessments of social and environmental impacts should be a requirement for the registration of a removal activity.

277. The scope of the assessments must cover human welfare and the conservation of biodiversity, water and other natural resources.

278. Feedback and dispute resolution mechanisms to address matters related to adverse environmental social impacts may be set up, allowing for feedback from employees, the local communities and relevant regional or national authorities.

279. Feedback and dispute resolution mechanisms should be easily accessible to the public and sufficiently advertised.

Appendix A: List of sources

The following table contains the list of sources used in this information note. There are two types of sources: public inputs received from stakeholders (P-series) and other references including the IPCC reports and published papers (R-series).

Table A.1. List of sources

Source ID	Source with search strings
P-01	Aircapture. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/40Dfv4v a:100 years
P-02	ALLCOT. Call for input 2022 - Activities involving removals under the Article 6.4 https://bit.ly/3xbZcxS a:passing a law a:passing a law, b:worked well
P-03	Bellona. Call for input 2022 - Activities involving removals under the Article 6.4 https://bit.ly/3Xl8hPz a: balance of a removal process, b:only focus on a:balance of a removal process, b:only focus on, c:land and geological
P-04	Carbon Business Council. Activities involving removals under the Article 6.4 https://bit.ly/3x5DD27 a: range of solutions a:range of solutions, b:two distinct
P-05	Carbon Engineering. Activities involving removals under the Article 6.4 https://bit.ly/3YCZzNZ a: fundamental limitations a:fundamental limitations
P-06	Carbon Finance Labs. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/3HI8yq5 a:activity over a 100-year
P-07	Carbon Market Watch (2021). Respecting the laws of physics. Principles for carbon dioxide removal accounting http://bitly.ws/zHsJ a:new proposed Option, b:majority of all products, c:unclear what, d:in a net removal, e:sb to focus, f:budget perspective, g:a quantitative manner. h:creative accounting
P-08	Carbon Market Watch (May 2022). Carbon Market Watch recommendations to Article 6 negotiators on removals https://bit.ly/3lDBpo8 a:offsetting or to meet
P-09	Carbon Market Watch (Sept. 2022). Carbon Market Watch inputs on grievances, methodologies, and removals prior to the Article 6.4 Supervisory Body 2nd meeting https://bit.ly/3IbwlyY a:fungible
P-10	Carbon Recycling - Activities involving removals under the Article 6.4 https://bit.ly/3IgnITE a:consider defining, b: influence of the sources, c: recentness of the carbon a:consider defining, b:influence of the sources, c:recentness of the carbon
P-11	CarbonPlan. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/3RMVcNV a:undermines, b:inconsistent with the Paris, c:on cumulative emissions, d:are used to justify, e:ignore the climate, f:employ discounting , g:recently reached
P-12	Center for International Environmental Law - Activities involving removals under the Article 6.4 https://bit.ly/3ljtzjA a:present significant risks, b:are speculative, c:serves to prolong, d:highest-cost mitigation, e:courts have, f:capture targets set, g:has engaged with a:present significant risks, b:are speculative, c:serves to prolong, d:highest-cost mitigation, e:courts have, f:capture targets set, g:has engaged with, h:do not exist, i:on their own
P-13	Clean Air Task Force. Call for input 2022 - Activities involving removals under the Article 6.4 https://bit.ly/3JVyAsH a:technology-neutral a:technology-neutral, b:greater clarity
P-14	Climeworks. Call for input 2022 - Activities involving removals under the Article 6.4 https://bit.ly/40CC4Gp a:more inclusive a:more inclusive
P-15	DAC Coalition. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/3RKAs9E a:0.01 mt, b:risk of detracting

Source ID	Source with search strings
P-16	Evident C-capsule. Activities involving removals under the Article 6.4 https://bit.ly/3lh4aa6 a:replaced with GHG, b:why a departure a:replaced with GHG, b:why a departure
P-17	Global CCS Institute. Activities involving removals under the Article 6.4 https://bit.ly/3x5deRV a: voluntary direct a:voluntary direct
P-18	Groom, B. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/3lh7DWa a:equivalent to 1 ton, b:offsets each, c:sceptical
P-19	International Emissions Trading Associatio. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/40GSsG8 a:limited adoption, b:been rejected, c:further public
P-20	MDB Article 6 Working Group. MDB Working Group comments on the annotated agenda of the third meeting of the Supervisory Body A6.4-SB003-AA-A03 Draft recommendation: Removal activities under the Article 6.4 mechanism (couldn't find on the website for submissions) a:details on the factors, b:practical implementation, c:corresponding adjustments, d:current practices
P-21	Natural Capital Exchange. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/3DRubTW a:for early action, b:numerous benefits
P-22	Perspectives GmbH. Call for input 2022 - Activities involving removals under the Article 6.4 https://bit.ly/3DSjYXr a:all greenhouse gases a:all greenhouse gases, b:period of 100 years
P-23	Running Tide. Activities involving removals under the Article 6.4 https://bit.ly/40yUYy5 a:atmosphere or ocean a:atmosphere or ocean
P-24	Stockholm Environment Institute. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/3Ys9kP2 a:fails to, b:ignores any effects, c:to be concerned, d:a problematic, e:context of reversible, f:far enough, g:future generations, h:decline over time, i:are not premised, j:at any time
P-25	Stockholm-Exergi. Activities involving removals under the Article 6.4 https://bit.ly/3Ia9zsk a:why that is necessary b:involved in defining a:why that is necessary, b:involved in defining
P-26	The Nature Conservancy (2022) Recommendations to the Article 6.4 Supervisory Body on activities involving removals https://bit.ly/3HTVmzF a:all options a:all options
P-27	Verdane. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/3x4BoMw a:carbon budget
P-28	Wetlands International. Activities involving removals under the Article 6.4 https://bit.ly/3YC8lMe a: climate-neutral, b:instead of GGR a:climate-neutral, b:instead of ggr
P-29	Winrock-ACR & ART. Call for input 2022 - activities involving removals under the Article 6.4 Mechanism of the Paris Agreement https://bit.ly/3K9v0vp a:absence of a minimum, b:highly dependent, c:further review, d:promote permanence, e:opinion was, f:shows choice, g:further public
R-01	Achieving NRT Permanence. (n.d.) Nori. https://nori.com/achieving-permanence a:carbon retention term
R-02	Allen M.R., Friedlingstein P. (2022) Net Zero: Science, Origins, and Implications. Annual Review of Environment and Resources. Vol. 47:849-887 https://bit.ly/40mmOgN a:compensating for fossil
R-03	Amanullah, Professor. (2019). Measuring and modelling soil carbon stocks and stock changes in livestock production systems A scoping analysis for the Livestock Environmental Assessment and Performance (LEAP) Partnership work stream on soil carbon stock changes. https://bit.ly/3YAUaGW a:and carbon storage
R-04	Australian Government (2022). Carbon Credits (Carbon Farming Initiative) Act 2011 https://bit.ly/3KgF2KX a:100-year permanence
R-05	Balmford A. et al. (2023). The value of impermanent carbon credits. Cambridge Open engage. https://bit.ly/3KsGbzj a:many impermanent credits

Source ID	Source with search strings
R-06	Baral, A., Malins, C. (2014). Comprehensive Carbon Accounting for Identification of Sustainable Biomass Feedstocks.The International Council on Clean Transportation https://bit.ly/3Yku4Iy a:savings in earlier years
R-07	British Standards Institution (2011). The Guide to PAS 2050:2011. How to carbon footprint your products, identify hotspots and reduce emissions in your supply chain. UK. https://bit.ly/3jOLZrV a:100 year time
R-08	California Air Resources Board (CARB) (2019). Unofficial electronic version of the Regulation for the California Cap on Greenhouse Gas Emissions and Market-Based Compliance Mechanisms https://bit.ly/3EjrMBu a:at least 100 years
R-09	Canada Gazette (2022.06.08) Canadian Greenhouse Gas Offset Credit System Regulations: SOR/2022-111. Part II, Volume 156, Number 12 https://bit.ly/3wQfTim a:at least 100 years
R-10	Carbon Market Watch (2021), Respecting the laws of physics. Principles for carbon dioxide removal accounting. https://bit.ly/3lmQSsR a:back into the slow
R-11	Carbonplan. (2022.01.31) Unpacking ton-year accounting. https://bit.ly/3wNAmo7 a:identical to either
R-12	Carton, W., Lund, J. F. & Dooley, K. (o. D.). Undoing Equivalence: Rethinking Carbon Accounting for Just Carbon Removal. https://www.frontiersin.org/articles/10.3389/fclim.2021.664130/full a:are hypothetical, b:distinguish between removals, c:a sectoral basis, d:fungible
R-13	Carvalho, M., Meneses, M., et al. (2022). Offset approaches in existing compliance mechanisms Adding value and upholding environmental integrity?. German Environment Agency. https://bit.ly/3jJx7uW a:nbs to be eligible
R-14	CIFOR (2000) Capturing the value of forest carbon for local livelihoods: opportunities under the clean development mechanisms of the Kyoto protocol https://bit.ly/3HuR4xy a:flexibility is particularly
R-15	Dornburg, V., Marland, G. (2008). Temporary storage of carbon in the biosphere does have value for climate change mitigation: a response to the paper by Miko Kirschbaum. Mitig Adapt Strateg Glob Change 13, 211-217 https://bit.ly/3HQ3Oi7 a:is an artifact
R-16	Element Energy, E4tech and Cambridge Econometrics for the UK Department for Business, Energy and Industrial Strategy (BEIS). (2022). Policy Mechanisms for First of a Kind Direct Air Carbon Capture and Storage (DACCS) and other Engineered Greenhouse Gas Removals. https://bit.ly/3XyrUUN a:primarily CO_2
R-17	European Biochar Industry Consortium (2022)-Position Paper-Certification of carbon removals EU rules https://bit.ly/416Dn0u a:separation of sink
R-18	European Commission - Joint Research Centre - Institute for Environment and Sustainability (2010). International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition. Luxembourg. Publications Office of the European Union https://bit.ly/3Yy3R99 a:longer than 100 years
R-19	European Commission - Joint Research Centre Institute for Environment and Sustainability (2012). Product Environmental Footprint (PEF) Guide. https://bit.ly/3DTgN1r a:100 year period
R-20	Fankhauser, S., Smith, S.M., Allen, M. et al. The meaning of net zero and how to get it right. Nat. Clim. Chang. 12, 21 (2022). https://doi.org/10.1038/s41558-021-01245-w a:broader sustainable
R-21	Fearnside, P.M. Why a 100-Year Time Horizon should be used for Global Warming Mitigation Calculations. Mitigation and Adaptation Strategies for Global Change 7, 19-30 (2002). https://bit.ly/3DS8uTP a:has advantages, b:on day one, c:sovereignty concerns
R-22	Fearnside, P.M.(2008). On the value of temporary carbon: A comment on Kirschbaum. Mitigation and Adaptation Stategies for Global Change https://bit.ly/3lqNay4 a:given equal weight
R-23	Galik CS, Baker JS, Daigneault A and Latta G (2022) Crediting temporary forest carbon: Retrospective and empirical perspectives on accounting options. Front. For. Glob. Change 5:933020. doi: 10.3389/ffgc.2022.933020 https://bit.ly/3YyKi0i a:independent of any

Source ID	Source with search strings
R-24	Griscom B. W., Adams J. (2017) Natural climate solutions. PNAS https://bit.ly/3JDXBZb a:cost-effective climate mitigation, b:largely a, c:not outweigh
R-25	Herzog, H., Caldeira, K. & Reilly, J. (2003). An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage. Climatic Change 59, 293-310. https://bit.ly/3x7UYaK a:is permanent, b:valuing temporary storage, c:nearly equivalent to
R-26	IPCC (2000). IPCC Special Report on Land use, Land-use Change and Forestry https://bit.ly/2KimF9e a:two-dimensional, b:there clearly has, c:reduce the uncertainty
R-27	IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. https://bit.ly/3REXEpU a:may no longer
R-28	IPCC (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report https://bit.ly/3HXNc9E a:based on the revised
R-29	IPCC (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories http://bitly.ws/zHAH a:a permanence time frame
R-30	IPCC (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems https://www.ipcc.ch/srccl/ a:not yet deployable, b:ambitious investments, c:promise of future cdr
R-31	IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report http://bitly.ws/zHiW a:cooling or avoided warming
R-32	IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report http://bitly.ws/zHzZ a:progressed beyond conceptual, b:are known as CDR, c:deliberate human activities, d:refers to anthropogenic activities removing, e:(CDR) Anthropogenic, f:geochemical or chemical CO_2, g:climate neutrality is not used, g:unknown how long, h:levels in the near-term, i:the main cdr methods, j:categorised based on removal
R-33	ISO (2022). Net Zero Guidelines: International Workshop Agreement https://bit.ly/3xJZcFY a:exclusively use
R-34	Kirschbaum, M.U.F. (2006) Temporary Carbon Sequestration Cannot Prevent Climate Change. Mitig Adapt Strat Glob Change 11, 1151-1164 https://bit.ly/3kSrYAP a:outcome is that
R-35	Locatelli, B., Pedroni, L. (2004). Accounting methods for carbon credits: Impacts on the minimum area of forestry projects under the Clean Development Mechanism. Climate Policy. 4. 193-204. https://bit.ly/3jI6OoY a:awarded ex post, b:credits very slowly
R-36	Lueddeckens, S., Saling, P., Guenther, E (2022). Discounting and life cycle assessment: a distorting measure in assessments, a reasonable instrument for decisions. Int. J. Environ. Sci. Technol. 19, 2961-2972 https://bit.ly/3YoELtJ a:are not equivalent, b:even without the
R-37	Mackey, B., & Prentice, I. et al. (2013). Untangling the confusion around land carbon science and climate change mitigation policy. https://go.nature.com/3Xgmg9m a:the right kinds, b:slow the rate
R-38	Marshall L and Kelly A (2010) The Time Value of Carbon and Carbon Storage: Clarifying the terms and the policy implications of the debate. World Resources Institute https://bit.ly/3HvWCb0 a:to select two
R-39	Matthews, H.D., Zickfeld, K., Dickau, M. et al. (2022) Temporary nature-based carbon removal can lower peak warming in a well-below 2°C scenario. Commun Earth Environ 3, 65 https://go.nature.com/3HGuwKh a:even in, b:the peak temperature increase
R-40	Mexico Forest Protocol. (2022). Climate Action Reserve. https://bit.ly/3DSLeoo a:make a 100-year, b:with the minimum
R-41	Murray, B.C., Galik, C.S.; Mitchell, St. (2012). Alternative approaches to addressing the risk of non-permanence in afforestation and reforestation projects under the clean development mechanism (English). Washington, D.C.: World Bank Group. https://bit.ly/3DQZWwf a:lack of economic viability

Source ID	Source with search strings
R-42	Ricart, A. et al. Environmental Research Letters. (2022, August 12). Sinking seaweed in the deep ocean for carbon neutrality is ahead of science and beyond the ethics. https://bit.ly/3ImRR50 a:unintended environmental
R-43	Robertson, B. et al.(2022) The Carbon Capture Crux: Lessons Learned. Institute for Energy Economics and Financial Analysis (IEEFA) https://bit.ly/3KcWqQP a:extrapolated in
R-44	Rose, D.J.; Hemery, L.G. (2023).Methods for Measuring Carbon Dioxide Uptake and Permanence: Review and Implications for Macroalgae Aquaculture. J. Mar. Sci.Eng https://bit.ly/3DUL001 a:wishful thinking, b:typically defined as
R-45	Ruseva T. et al. Additionality and permanence standards in California's Forest Offset Protocol: A review of project and program level implications, Journal of Environmental Management, Volume 198, Part 1, 2017, Pages 277-288 https://bit.ly/3I7eDOb a:harvests over, b:opportunity costs related
R-46	Salinas, Z. et al. (2011). BioCarbon fund experience : insights from afforestation and reforestation clean development mechanism projects (English). Washington, D.C. : World Bank Group. https://bit.ly/3Xdzt2P a:not fungible
R-47	Sarofim M. C. et al. (2018) A quantitative approach to evaluating the GWP timescale through implicit discount rates. Earth Syst. Dynam., 9, 1013â€“1024 https://bit.ly/3l5x9h1 a:calculating an equivalent
R-48	Sierra, C.A. et al. (2021). The climate benefit of carbon sequestration. Biogeosciences, 18, 1029-1048 https://bit.ly/3YBSgG7 a:resemble our
R-49	Smith, J. (2019). California Compliance Offsets: Problematic Protocols and Buyer Behavior. Mossavar-Rahmani Center for Business & Government Weil Hall Harvard Kennedy School www.hks.harvard.edu/mrcbg. https://bit.ly/3jIT0um a:ratio that captures, b:and wow, c:no reason to avoid
R-50	Smith, M., Geden, O., et al (2023). The State of Carbon Dioxide Removal - 1st Edition https://bit.ly/3YBTSzU a:to include potential removal, b:primarily via, c:currently occurring on
R-51	The Integrity Council for the Voluntary Carbon Markets. Public consultation on its draft Core Carbon Principles, Assessment Framework and Assessment Procedure. https://bit.ly/40ulMPP a:require a minimum, b:has to be a minimum, c:excessively long, d:credited truly, e:arbitrary minimum, f:flood, g:a minimum storage, h:should me a minimum, i:term is 5-10
R-52	The Oxford Institute for Energy Studies (2022) The Evolution of Carbon Markets and Their Role in Climate Mitigation and Sustainable Development https://bit.ly/3RwBC8p a:not always accurately
R-53	UNFCCC. (2022, September 20). Structured expert dialogue on the second periodic review ofÂ the long-term global goal under the Convention (2020-2022) Synthesis report by the co-facilitators of the structured expert dialogue. https://bit.ly/3jUFcNo a:feasibility of most
R-54	VCS (2022). Additional Background Information on Tonne-Year Accounting https://bit.ly/3DQtOca a:small volume
R-55	VCS V4 Public Consultation Summary of Comments: Q2 2022. Verified Carbon Standard. https://bit.ly/3JOUyxC a:is paired with careful, b:would support a minimum, c:issued after a minimum, d:credible minimum, e:mandate a minimum, f:required to use the minimum, g:a minimum period, h:simplicity in accounting , i:sacrifices accuracy, j:accurate representation, k:happen ex-post, l:flat and linear, m:discounting prohibited, n:that substantiates, o:rate depends, p:strongly support, q:should not be applied, r:explicitly prohibited, s:supportive of tonne-year, t:no concerns, u:low volumes, v:enormous assumptions, w:beneficial flexibility, x:assumes that balancing, y:limited remaining, z:will create, aa:is myopic, ab:financially today, ac:on cumulative emissions, ad:that the short-term, ae:from optionality, af:more warming, ag:gigantic flow, ah:clear differentiation, ai:urgent action, aj:minimum acceptable

Source ID	Source with search strings
R-56	Zickfeld, K., MacDougall, H. & Matthews, H. (o. D.). On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions. https://iopscience.iop.org/article/10.1088/1748-9326/11/5/055006 a:effectiveness of negative

Appendix B: Equivalence of cumulative radiative forcing

1. To analyse the equivalence between emission reductions and removals, a hypothetical example is used below for the purpose of illustration, in which a pulse emission is balanced by a removal over an assumed time horizon of 100 years as an example.

Equivalence without discounting

2. A pulse emission of 1 tCO_2 into the atmosphere results in a marginal change in the atmospheric concentration of carbon dioxide and causes a marginal radiative forcing. The amount of pulse CO_2 remaining in the atmosphere declines over time as the CO_2 is absorbed into the ocean, the biosphere and other terrestrial sinks. Figure B.1(a) shows the decay profile of such a pulse.[1] The decay continues beyond the time horizon, but the portion beyond the time horizon is not taken into account.[2]

3. Figure B.1(b) shows a removal of 1 tCO_2 that occurs at the same time as the emission pulse. As long as that removal is in effect, and is not reversed, the net change in the atmospheric CO_2 concentration is zero and hence the marginal cumulative radiative forcing is zero. If the removal is reversed before the end of the time horizon, for example in year 60, then the area under the decay curve of the new pulse emission represents the atmospheric damage (i.e. the cumulative radiative forcing) caused by this reversal.

4. Calculation of the areas under the two curves Figure B.1(a) and Figure B.1(b) shows that at the end of the time horizon, marginal cumulative radiative forcing caused in the baseline scenario corresponds to 48.14 tonne-years whereas marginal cumulative radiative forcing caused in the removal activity scenario corresponds to 23.96 tonne-years. The removal activity, which consists of removing 1 tCO_2 in year 0 and re-emitting 1 tCO_2 in year 60, effectively reduces the marginal cumulative radiative forcing by 50.22%. The removal activity is thus equivalent to a permanent emission reduction of 0.5022 tCO_2.

5. The factor, such as 0.5022 in this case, has been termed the crediting factor in this note, since multiplying the net carbon stocks achieved and held continuously out of the atmosphere for a definite period (henceforth termed the storage period) by this factor gives the number of credits achieved by the removal activity.

6. From the above, it becomes clear that a 1 tCO_2 of removal can be equated to 1 tCO_2 emission only if the removed carbon stock is held out of the atmosphere for the period of the time horizon, i.e. until 100 years. Thus, in absence of discounting, the permanence period of removals is equal to the length of the time horizon.

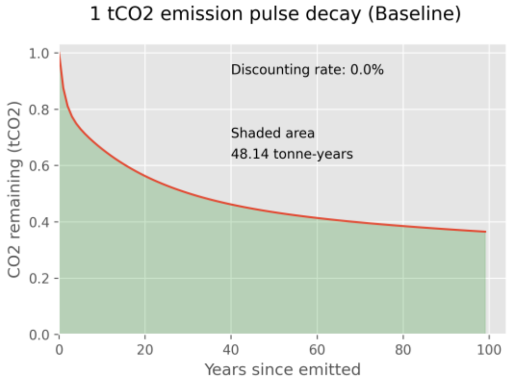
7. However, considering that the marginal cumulative radiative forcing is equal to the product of the tonnes of CO_2 removed and the number of years over which the removed carbon stocks are held out of the atmosphere, the permanent mitigation value equal to 1 tCO_2 can be achieved within 60 years if the amount of the removal is 1/0.5022 or 1.99 tCO_2 instead

[1] The curve in the diagram is generated from the Bern2.5CC model with the coefficients provided in the Fourth Assessment Report of the IPCC (IPCC-AR4-WG-I). The area under the of tonne-year curve is therefore 48.14 tonne-years which differs from 46 tonne-years as reported in the IPCC-SR-LULUCF.

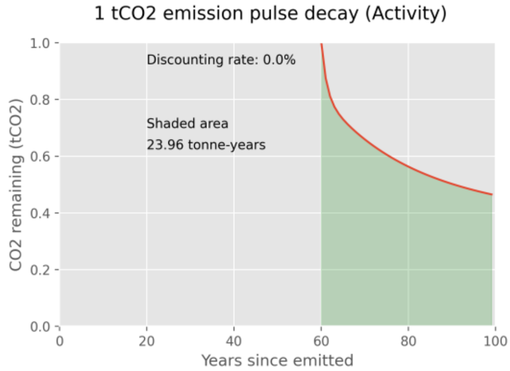
[2] The time horizon defines the temporal boundary for the purpose of accounting of radiative forcing and its mitigation.

of 1 tCO_2. In other words, removal of 1.99 tCO_2 with a storage period of 60 years results in mitigation equal to 1 tCO_2.

Figure B.1. Effect of 1 tCO_2 emission in year 0 compared to 1 tCO_2 removal followed by reversal in year 60, assuming a time horizon of 100 years and no discounting



(a) Carbon dioxide remaining in the atmosphere following a pulse emission of 1 tCO_2 in year 0 of the time horizon. The area under the curve is 48.14 tonne-years. The area is proportionate to the marginal cumulative radiative forcing.



(b) Carbon dioxide remaining in the atmosphere following a pulse emission of 1 tCO_2 in year 60 of the time horizon. The area under the curve is 23.96 tonne-years.

Equivalence with discounting

8. If discounting is used, current mitigation is valued more than the future mitigation. In the same way, current damage (cost) is valued more than the future damage.

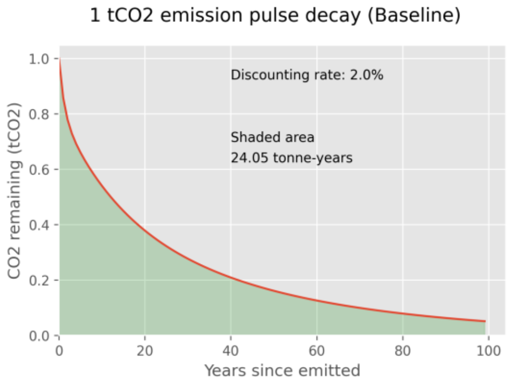
9. Applying a discount rate of 2% results in the tonne-years achieved by a 1 tCO_2 removal in year 0 followed by a 1 tCO_2 reversal in year 60 as shown in Figure B.2.

10. Calculation of the areas under the two curves Figures B.2(a) and B.2(b) shows that at the end of the time horizon, marginal cumulative radiative forcing caused in the baseline scenario corresponds to 24.05 present tonne-years whereas marginal cumulative radiative forcing caused in the activity scenario corresponds to 5.31 present tonne-years. It should be noted that the future tonne-years have been discounted to the present tonne-years. The removal activity, which consists of removing 1 tCO_2 in year 0 and re-emitting 1 tCO_2 in year 60, effectively reduces the marginal cumulative radiative forcing by 77.91%. The removal activity is thus equivalent to permanent emission reduction of 0.7791 tCO_2.

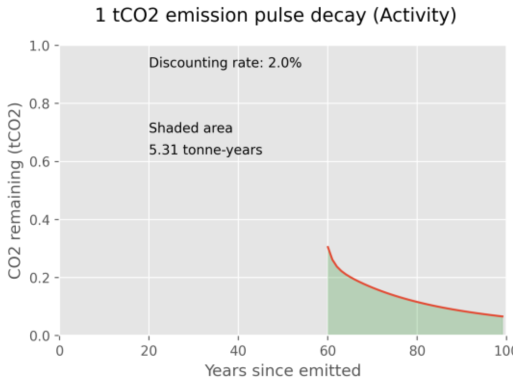
11. Using different discount rates with different storage periods results in the curves shown in Figure B.2(c).

12. It is noted that as discounting rate increases, less amount of initial removal is required to achieve 1 tCO_2 of mitigation over a given storage period. Similarly, as storage period increases, the crediting factor asymptotically approaches 1.0 at a storage period equal to the time horizon.

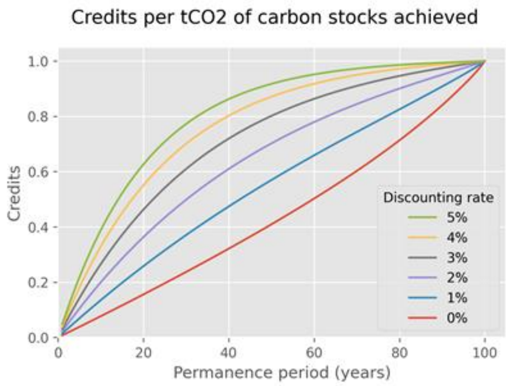
Figure B2. Effect of 1 tCO_2 emission in year 0 compared to 1 tCO_2 removal followed by reversal in year 60, assuming a time horizon of 100 years and a discounting rate of 2 percent.



(a) Marginal cumulative forcing caused by a pulse emission of 1 tCO_2 in year 0 of the time horizon. The area under the curve is 24.05 present tonne-years.



(b) The present value of marginal cumulative forcing caused carbon dioxide remaining in the atmosphere following a pulse emission of 1 tCO_2 in year 60 of the time horizon. The area under the curve is 5.31 present tonne-years.



(c) Crediting factor curves for removal of 1 tCO_2 with different storage periods and discount rates.

13. Table B.1 provides the crediting factors at different storage periods and discount rates, assuming a time horizon of 100 years.

Table B.1. Crediting factors at different storage periods and discount rates[3]

Storage period (years)	0%	1%	2%	3%	4%	5%
1	**0.007574**	**0.01402**	**0.0217**	**0.030134**	**0.038929**	**0.04783**
2	0.015168	0.027912	0.042979	0.059392	0.076361	0.093383
3	0.022782	0.041677	0.063847	0.087801	0.112355	0.136767
4	0.030415	0.055316	0.084311	0.115385	0.146966	0.178086
5	0.038069	0.068832	0.104379	0.142169	0.180247	0.217438
6	0.045743	0.082224	0.124059	0.168175	0.212249	0.254916
7	0.053437	0.095495	0.143359	0.193426	0.243021	0.290611
8	0.061152	0.108646	0.162287	0.217944	0.272611	0.324606
9	0.068888	0.121679	0.180849	0.241752	0.301065	0.356983
10	0.076646	0.134594	0.199053	0.264868	0.328425	0.387819
11	0.084425	0.147392	0.216906	0.287314	0.354735	0.417187
12	0.092226	0.160076	0.234415	0.30911	0.380033	0.445157
13	0.100049	0.172646	0.251587	0.330273	0.404361	0.471796
14	0.107894	0.185104	0.268428	0.350823	0.427753	0.497167
15	0.115762	0.197451	0.284946	0.370778	0.450248	0.52133
16	0.123653	0.209689	0.301146	0.390154	0.471879	0.544344
17	0.131568	0.221817	0.317034	0.408969	0.492679	0.566262
18	0.139506	0.233839	0.332618	0.427239	0.512681	0.587137
19	0.147468	0.245755	0.347903	0.444981	0.531915	0.607019
20	0.155455	0.257566	0.362894	0.462209	0.55041	0.625955
21	0.163467	0.269273	0.377599	0.478938	0.568196	0.643989
22	0.171503	0.280879	0.392022	0.495183	0.585299	0.661166
23	0.179566	0.292383	0.40617	0.510959	0.601747	0.677525
24	0.187654	0.303788	0.420047	0.526279	0.617563	0.693106
25	0.195769	0.315094	0.43366	0.541156	0.632772	0.707946
26	0.203911	0.326303	0.447013	0.555603	0.647398	0.72208
27	0.21208	0.337416	0.460112	0.569633	0.661463	0.735542
28	0.220278	0.348434	0.472962	0.583258	0.674989	0.748363
29	0.228504	0.359358	0.485568	0.59649	0.687997	0.760575

[3] These factors are calculated using the Bern2.5CC model with the coefficients provided in the Fourth Assessment Report of the IPCC (IPCC-AR4-WG-I). The factors were independently calculated earlier in other published literature, i.e. Murray B. C. et al "Alternative approaches to addressing the risk of non-permanence in A/R projects under the CDM" (see a brief extract of crediting factors, without discounting, in Table 1 in Chapter 1 of the publication). Available at https://bit.ly/3xg3OUj

Storage period (years)	0%	1%	2%	3%	4%	5%
1	**0.007574**	**0.01402**	**0.0217**	**0.030134**	**0.038929**	**0.04783**
30	0.236759	0.370191	0.497934	0.609341	0.700506	0.772206
31	0.245044	0.380932	0.510067	0.621821	0.712536	0.783284
32	0.253359	0.391583	0.521969	0.633942	0.724105	0.793835
33	0.261705	0.402145	0.533647	0.645714	0.735231	0.803885
34	0.270083	0.412621	0.545105	0.657147	0.745931	0.813457
35	0.278493	0.42301	0.556347	0.668252	0.756221	0.822574
36	0.286936	0.433314	0.567378	0.679037	0.766118	0.831258
37	0.295412	0.443534	0.578201	0.689513	0.775636	0.839529
38	0.303924	0.453673	0.588823	0.699688	0.78479	0.847408
39	0.312471	0.46373	0.599245	0.709572	0.793594	0.854912
40	0.321054	0.473707	0.609473	0.719173	0.802062	0.86206
41	0.329675	0.483606	0.619511	0.728499	0.810206	0.868869
42	0.338334	0.493427	0.629363	0.737558	0.81804	0.875354
43	0.347032	0.503173	0.639033	0.746359	0.825575	0.881532
44	0.355771	0.512844	0.648524	0.754909	0.832822	0.887416
45	0.364551	0.522442	0.65784	0.763215	0.839793	0.893022

14. The following observations can be made from Table B.1:

    (a) The crediting factor of 1 cannot be achieved with a storage period that is less than the time horizon;

    (b) At a discount rate of 3%, a post-10-year reversal results in credit factor of 0.26487. In other words, with a storage period of 10 years, every 3.78 tCO_2 of the achieved carbon stocks can result in a single credit;

    (c) At a storage period of 60 years and a discount rate of 3%, 0.86307 credits can be issued for each tCO_2 of the achieved carbon stocks. To achieve 1 credit, 1/0.86307 or 1.159 tCO_2 needs to be achieved with a storage period of 60 years.

15. It is to be noted that adopting a different time horizon will result in a different set of crediting factors.

16. The permanence period (i.e. the time horizon) is distinct from the activity period. The activity period can be shorter for the underlying economic reasons or to fit in with a shorter crediting period.

17. The ‘permanence’ of mitigation achieved by removal activities is defined by permanence period (i.e. the time horizon), and not by the activity period.

18. Each credit produced by the removal activities has the same mitigation value, i.e. it corresponds to the same amount of decrease in cumulative forcing, since the impact of the activity is assessed over the full period of the time horizon.

Appendix C: Time horizon and its choice

1. All climate action is underpinned by policy objectives and goals to be achieved over a finite period of time. In terms of policy relevance, therefore, the equivalence of mitigation services produced by avoided emissions and achieved by removals could be assessed only within the framework of a finite time horizon.

2. A time-horizon-based approach has been used to compare the climate-change impacts of emissions of different GHGs that have different residence times in the atmosphere as well as different radiative forcing per molecule. Global warming potentials (GWPs) are calculated by integrating the total radiative forcing of an emissions pulse over a 100-year time horizon. The relative GWPs are calculated as the ratio of the cumulative radiative forcing caused by 1 tonne of a given GHG to that caused by 1 tonne of CO_2.

3. A commonly adopted climate-relevant time horizon is 100 years as is seen in the following:

   (a) In IPCC 2019 refinements to 2006 Guidelines, biochar methodology uses 100 years as the basis for permanence;

   (b) British Standards: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (PAS 2050) uses the same approach for carbon storage (release) as for delayed emissions and uses 100 years as assessment period;

   (c) Life Cycle Impact Assessment in the European context (ILCD handbook) recommends a time horizon of 100 years;

   (d) Forestry-related offset protocols of some existing mechanisms such as Climate Action Reserve (CAR), Regional Greenhouse Gas Initiative (RGGI), California Air Resources Board (CARB) require, monitoring, verification and reporting for a period of 100 years from credit issuance;

   (e) Other private organizations such as the Carbon Sink Registry of Carbon Standards International uses 100 year time horizon to qualify permanence of removals (see https://bit.ly/3Mkm2KQ).

4. Choosing a time horizon is a normative judgement rather than the expression of a scientific consensus or physical reality.

5. Selecting a shorter time horizon implies earlier climate action is more relevant to policy objective. If one assumes that the global economy will be decarbonized by year 2100, then a time horizon of 75 years (i.e. from 2025 to 2100) would be appropriate since any post-decarbonization mitigation action will not have value.

Appendix D: Discount rate and its choice

1. Discounting is the mechanism by which a value for time is translated into economic decision making. Mitigation value (which correlates with damages avoided) generated early on is worth more than the mitigation value generated late in the future. As a result, it is efficient to discount the future mitigation value to its net present worth using the social discount rate relevant to climate policy.

2. Various climate policy assessments have recommended the discount rates variously, such as 1.4% (Stern 2007), 2.0% (Cline 1992) and 4.3% (Nordhaus 2007).[1]

3. Another study finds that the mean recommended discount rate relevant to climate policy is 2.27%, with a range from 0 to 10%. Under this study, more than three-quarters of the expert economists surveyed were comfortable with the median discount rate of 2%, and over 90% of them found a discount rate in the range of 1 to 3% acceptable.[2] The same team of authors have since surveyed expert philosophers. For this group, the mean responses are almost identical at 2.27%. Over 90% are comfortable with a discount rate of 2%.[3]

4. Some of the common arguments seen in the economic literature relating to climate policy discounting are summarized below:[4]

   (a) The social cost of carbon—the cost to society of an additional ton of CO_2 emissions—is a crucial measure of the desirable intensity of climate policy. The models economists use to calculate it, however, are highly sensitive to the choice of discount rate, which measures our concern for the well-being of future generations. Different economists favour different values, and this leads to radically different policy prescriptions.

   (b) Projects, including those involving climate change, should be evaluated by discounting the costs and benefits at the market rate of return, properly adjusted for uncertainty and for the inherent value of the environment.

   (c) Discounting, however, should be seen only as a method for choosing projects, not as a method for determining our ethical obligations to the future.

   (d) The Ramsey discounting equation can then be written as $r = \eta g + \delta$. where r is the discount rate, η is the elasticity of marginal utility of consumption, g is the growth rate of consumption, and δ is the pure rate of time preference.

   (e) Most economists think that discount rates should be positive both because people are impatient (positive rate of pure time preference) and because people will have higher income on average in the future (and hence lower marginal benefits from

[1] Goulder L. H. and Williams R. C. The choice of discount rate for climate change policy evaluation (2012) Available at https://stanford.io/3Reu4G1

[2] Drupp, M. et al. Discounting disentangled (2018). Available at https://bit.ly/3yW7N9u

[3] Drupp, M. et al. Philosophers and Economists Can Agree on the Intergenerational Discount Rate and Climate Policy Paths (2022) Available at https://bit.ly/3D9jhrB

[4] The summary largely follows this paper: Weisbach, D. and Sunstein C.R. Climate Change and Discounting the Future: A Guide for the Perplexed. Available at https://bit.ly/3cQzubJ

additional consumption). Experience of the past several hundred years is consistent with this expectation.

(f) Discounting plays a central role in determining whether to recommend policies that rapidly reduce greenhouse gas emissions or that take a more gradual approach to reducing emissions.

5. While selecting a discount rate for valuing the mitigation contributed by removal activities, the following considerations may be kept in view:

(a) Adopting a higher discount rate (e.g. 3%) values earlier mitigation more than later mitigation (i.e. a sense of urgency for climate action). A 0% discount implies that it does not matter whether 1 tCO_2 is mitigated today or any time in the future. Discounting at non-zero rates implies that mitigation taking place now, or in the near future, is more valuable than the mitigation taking place far in the future.

(b) Adopting a higher discount rate (e.g. 3%) accords the removal activities a more significant place in the mitigation strategy, along with the emission reduction activities;

(c) Both short-term and long-term removal activities have mitigation value when the value is calculated on the basis of the equivalence of the marginal cumulative radiative forcing.[5] However, small-scale and short-term activities can be incentivized with a higher discount rate (e.g. 3%).[6] This choice broadens the mechanism participation base in terms of the variety of removal activities involving different sizes, types, durations and actors.[7]

[5] While two activities A (1000 tonnes held over 10 years) and B (1000 tonnes held over 10 years) produce slightly less mitigation than activity C (1000 tonnes held over 20 years), the mitigation value of A and B combined is exactly equal to twice the mitigation value of A. Thus a large number of short-term and small-size activities can be as effective as, or more effective than, a few long-term and large-size removal activities.

[6] Participation by small and micro businesses in the mechanism is to be encouraged. See, A6.4-RMP, paragraph 5(g).

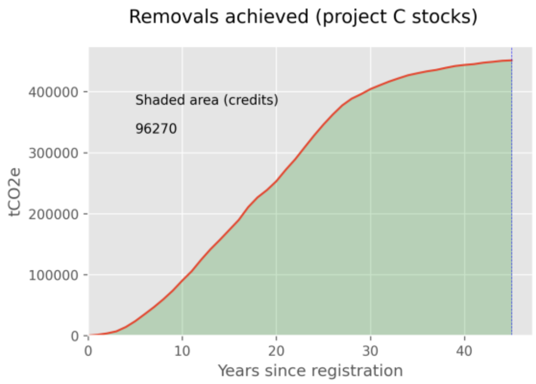
[7] A higher carbon price also incentivizes small-size activities participation in the mechanism. For example, with a carbon price of USD 100 per tCO2, some small-holders in the low-income countries may get motivated to participate in the mechanism even with crediting at a 0% discount rate.

Appendix E: Tonne-year crediting: an illustrative example

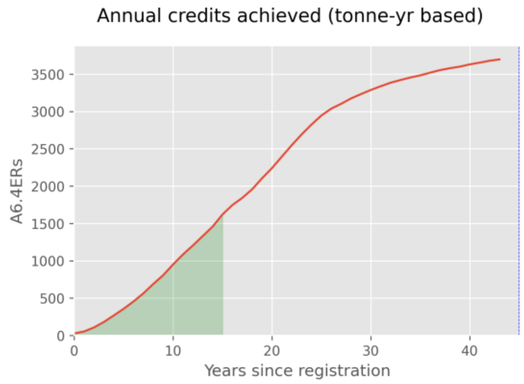
1. The example removal activity consists of reforestation in a watershed with a total area of 1,150 hectares (ha) and a plantable area of 1,000 ha. The activity area of 1,000 ha is planted in parts, covering 200, 200, 350 and 250 ha during years 1, 3, 4 and 5, respectively. Local species are used, and the local communities are allowed to extract 5 tonnes/ha of biomass starting from year 15. Two incidents of fire and pests are simulated to occur in years 12 and 21, with biomass losses of 10,000 and 5,000 tonnes, respectively. The mortality of plants is assumed during first 5 years and the thinning of the plantation at years 7 and 11 are also assumed. The tree species used have a growth profile such that the plantation biomass reaches saturation (or rather an equilibrium with the biomass extraction rate) at year 35. A crediting period of 45 years is assumed.

2. As seen in Figure E.1(a), total carbon stocks in the watershed become saturated at about 451,000 tCO_2. By the end of the crediting period, a total of 96,270 credits are achieved. Major portion of credits are issued in the second half of the crediting period.

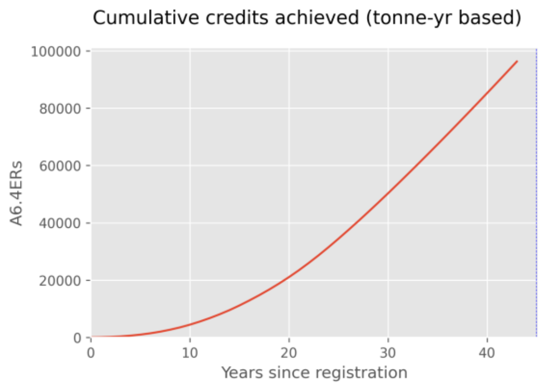
Figure E.1. Removal activity consisting of tropical watershed reforestation with mixed stands of local species (tonne-year accounting)



(a) Evolution of carbon stocks in the in-situ carbon pools



(b) Number of credits achieved per year (e.g. in and around year 20, approx. 4,000 credits are earned per year). Total credits achieved up to a year are represented by the green area under the curve.



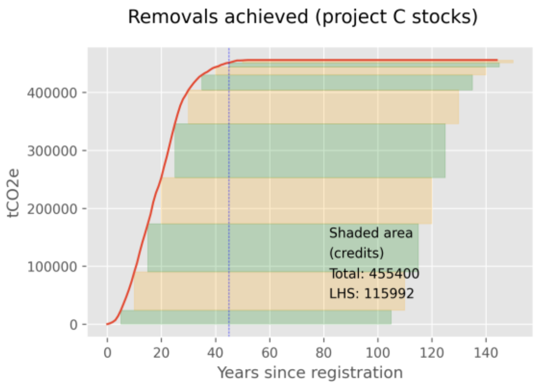
(c) Cumulative number of credits achieved. By the end of the crediting period (year 45) 96,270 credits are achieved.

Appendix F: Tonne-based crediting: an illustrative example

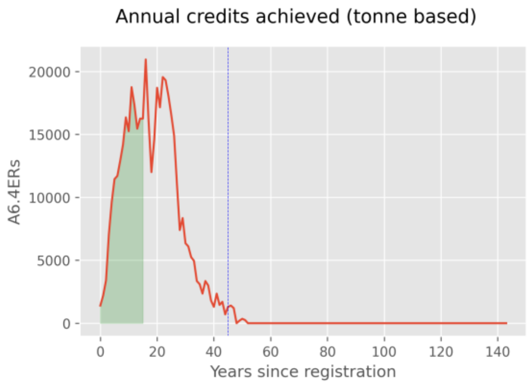
1. The same reforestation activity described in appendix E is credited by using the tonne-based crediting. As tonnes are verified at periodical intervals (5 years in this example, but could be at any interval), credits equal to the number of verified tonnes are issued. This is under the condition that the carbon stocks against which credits have been issued will be preserved for the full permanence period, that is, for 100 years from the date of issuance.

2. Figure F.1 shows the carbon stocks and the credits resulting from tonne-based crediting under the same example of watershed reforestation described in appendix E.

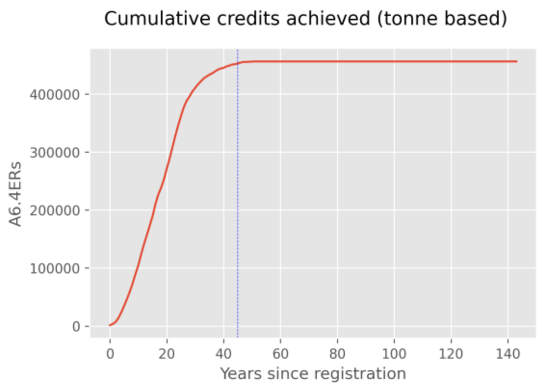
Figure F.1. Removal activity consisting of tropical watershed reforestation with mixed stands of local species (tonne-based crediting)



(a) Evolution of carbon stocks in the in-situ carbon pools.



(b) Number of credits achieved per year (e.g. in and around year 20, about 15,000 credits are earned per year). Total credits achieved by a year are represented by the shaded area under the curve.



(c) Cumulative number of credits achieved. By the end of the crediting period (year 45), 455,400 credits are achieved.

3. The horizontal shaded rectangular areas represent the credits resulting from verifications at the five-year interval. The figure shows that the carbon stocks related to credits issued

in later years will have to be periodically verified for a longer period beyond the crediting period (i.e. up to year 145 from the start of the activity).

4. Mitigation value produced during the years beyond the end of the crediting period is also included in the shaded area. This results in a total of 455,400 credits, which is more than four times the credits issued under tonne-year crediting.

5. It can be seen that under this approach the majority of credits are issued in the first half of the crediting period.

Appendix G: Risk mitigation and compensation mechanism

1. A mechanism for risk mitigation and compensation will be required for addressing the reversal of carbon stocks after the carbon stocks have been verified and credited under the advance tonne-year crediting and the tonne-based crediting method.

2. A mandatory post-issuance monitoring report will be required at a fixed interval in order to observe any reversals.

3. A mandatory post-issuance monitoring report will also be required whenever an event occurs that could potentially result in a reversal of carbon stocks. Such an event could be a forest fire, a pest outbreak and/or an intentional or planned human activity affecting the carbon stocks.

4. If a required monitoring report is not received within prescribed time, it would be assumed that full reversals occurred, and the reversal compensation procedure would be triggered.

5. A risk mitigation and compensation mechanism could be based on one of the options described below.

Permanence buffer backed up by host Party guarantee

6. The permanence buffer backed up by a host Party guarantee works as follows:

   (a) Under this option, a percentage of credits to be issued to a removal activity is set aside into a buffer pool of credits at the time of issuance. In the event of a reversal, an equivalent number of credits from the buffer pool are used to replace the credits affected by the reversal;

   (b) A pooled buffer implies a sharing of risk by the activities that have subscribed to and keep contributing to the buffer. However, at any given time, the buffer may or may not have enough resilience to absorb simultaneous reversals from several activities. If the buffer is exhausted before compensating all the reversals, the liability needs to be taken over by the host Party. The fate of the credits issued and the consequences for the holders of the credits (in the event that these have been sold) would also need to be addressed;

   (c) As the buffer pool at a given time will be made of credits that have different ‘maturity’ (different storage periods since the verification of the corresponding carbon stocks, possibly none of these having completed the permanence period), the credits that will be selected to compensate a particular reversal will need to be decided (a stack-based or queue-based order);

   (d) An individual activity-level buffer implies that an activity, in the event of a reversal, can only have recourse to their own buffered credits. Any reversal beyond the size of the buffer may not be compensated. Particular difficulty arises when the activity participants decide to abandon the activity. For example, removal activity X is issued 100 credits in year 5, of which 70 are held by the activity participants and 30 are held in the buffer. In year 10, the activity participants no longer want to continue the activity and reverse all the carbons stocks. At this time, the 30 credits held in the buffer have also been invalidated. They have no compensatory value since the carbon stocks underlying these credits have been reversed;

(e) A guarantee by the host Party or an entity designated by it could assume the liability for intentional reversals and the portion of unintentional reversals exceeding the capacity of the permanence buffer pool. The buffer might be required to be segmented by the host Party countries, since activities hosted in one Party may report more reversals than another. Host Party a guarantee could also be required in the early phase of the mechanism until the buffer pool of credits is built up to a sufficient level of resilience. How a host Party compensates the reversals will need to be decided by them: whether to use public funds to buy A6.4ERs from market, or to charge a financial contribution from all registering activities to constitute a fund for purchase of A6.4ERs to be used for meeting the liability, or some other mechanism might be required.

(f) The percentage of credits to be contributed by a removal activity to the permanence buffer could be determined on the basis of the risk rating of the activity. This percentage could be either fixed ex ante at the time of registration of the activity or re-assessed ex post at the time of verification, as the risk profile of the activity could change over time;

(g) The credits accumulated in the permanence buffer could be retained permanently, or they could be returned to the activity participants once all the credits issued to a removal activity have fulfilled the permanence requirement. Retaining credits would increase the resilience of the permanence buffer. Another option could be to return the credits to those activities that did not experience any reversals and did not have recourse to the permanence buffer. This option would incentivize good risk management by activity participants.

Commercial insurance

7. The option of commercial insurance can work as follows:

(a) Under this option, the activity participants would buy insurance from a third-party insurer against the potential reversal of credited removals. The insurer would provide a guarantee to the Supervisory Body on behalf of the activity participants to compensate for any reversals of verified carbon removals. This would be similar to the commercial third-party liability insurance plans, since the Party injured in the case of reversals would be the atmosphere (i.e. the mechanism regulator, on its behalf) and not the activity participants who are free to abandon the activity at any time;

(b) The viability of such an insurance would depend upon the insurability in terms of the potential size of losses, the ability to quantify the risks, and the corresponding risk premiums that would be built into the insurance costs.

Menu of options

8. The availability of multiple options, including a combination of the options specified above, would allow activity participants to select the option that would best suit the needs and circumstances of their activity.

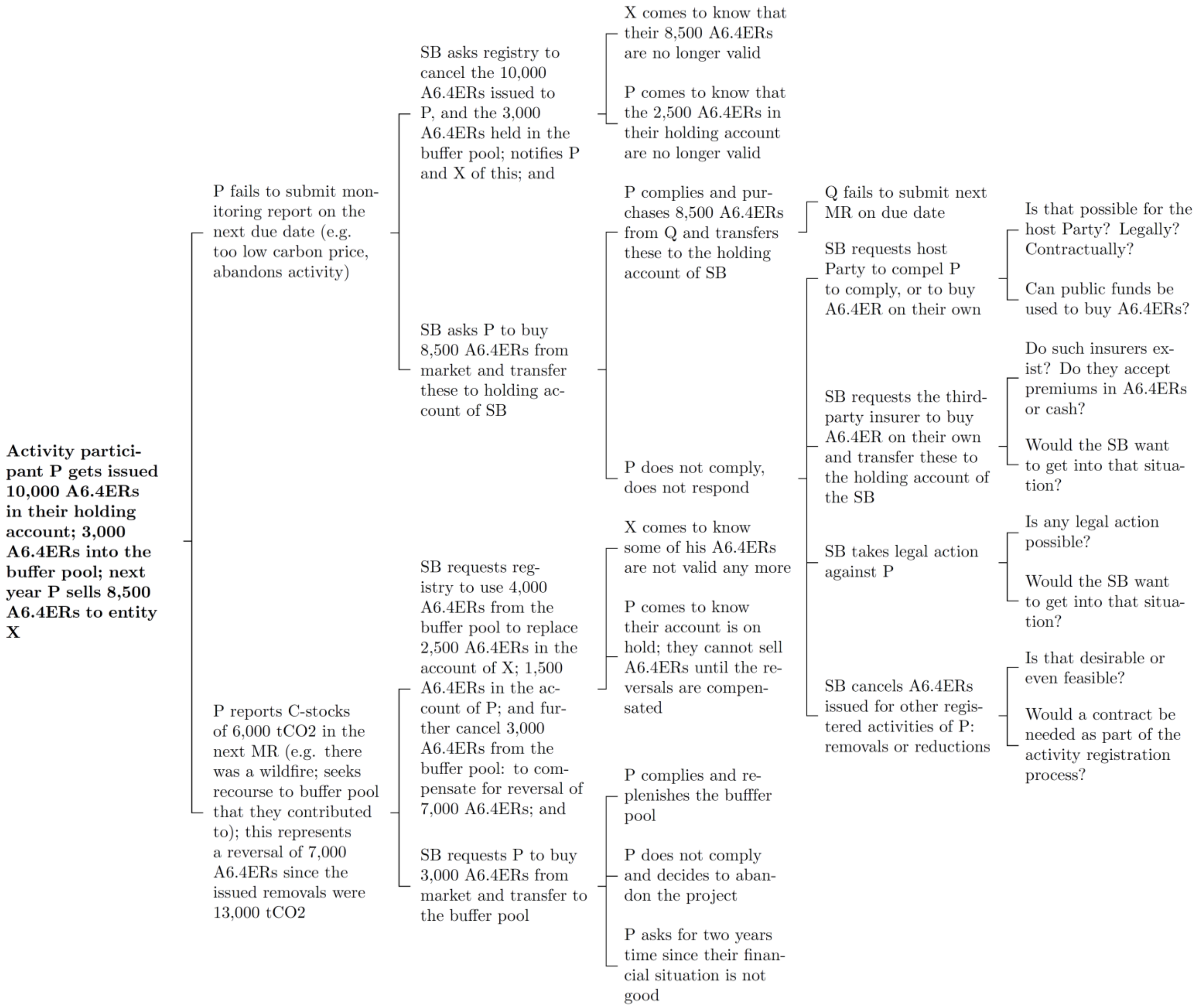
Reliability

9. The performance or adequacy of risk management arrangements should be assessed by considering how well these arrangements can address the worst case scenarios.

10. Figure F1 shows an example of chain of events that may or may not be fully addressed by the arrangements of pooled buffer backed up by a host Party guarantee, depending upon the options and choices available to host Parties under the domestic socio-legal environment.

11. There also remain other open enforceability issues such as: e.g. what to do in case of non-payment of risk premium to the insurer; the level of assurance that host countries will have the financial means to compensate for eventual reversals; what if there is no availability of commercial insurance in the host Party for this type of activities.

Figure F1. Possible issues that can arise in risk management and compensation: a hypothetical event tree (abbr. used SB: Supervisory Body)



Appendix H: Land-based removal activity supported by long-term storage of removals

Removal activity with BECCS

1. As an illustration of how BECCS can increase the removal potential of a given area of land, consider the simulation example of reforestation described in appendix E with some modification. An area of 1,000 ha is afforested using relatively fast-growing species with a 15-year rotation and a sustained yield design. To ensure a constant flow of biomass to drive the energy system, the area is planted in 15 stands, each staggered by one year in its planting. After 15 years, the mature stand is harvested every year and the biomass is used for energy purposes with the carbon dioxide resulting from its combustion being captured and stored in a geological formation. It is assumed that the carbon capture and storage (CCS) component has 80 per cent efficiency in capturing and storing the carbon contained in the biomass combusted.

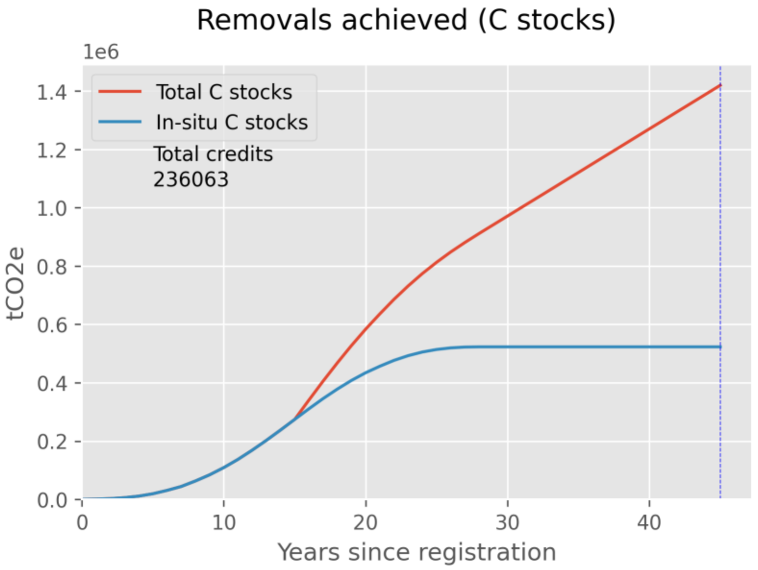
2. The resulting carbon stocks and the removal credits generated from the activity are shown in Figure H.1. Credits are estimated based on tonne-year crediting (no discounting).

3. Figure H.1 shows that total carbon stocks of 1.4 million tCO_2 ($MtCO_2$) are achieved over the crediting period of 45 years. The in-situ carbon stocks become saturated by year 25, but the continued removal of biomass opens up a biosequestration stream and the carbon is transferred from the atmosphere to geological storage through the CCS component, while the in-situ component (the growing stock or the capital stock) remains constant.

4. By the end of the crediting period, a total of 236,063 credits are achieved (compared to 96,270 credits in the case of watershed reforestation).

5. The emissions associated with the establishment of the plantations and the energy consumed to drive the CCS system as well emissions associated with transportation are not included in this simulation. If significant, these will have to be deducted from the credits shown in the example.

Figure H.1. Removal activity consisting of afforestation with fast-growing species with biomass feeding into bioenergy with carbon capture and storage (tonne-year crediting). The plot shows evolution of carbon stocks in the in-situ carbon pools and in geological storage.



Removal activity with storage in durable products

6. As an illustration of how long-lasting HWP can increase the removal potential of a given area of land, consider the reforestation simulation example in appendix E with some modification. An area of 1,000 ha is afforested using relatively fast-growing species with a 15-year rotation and a sustained yield design. To ensure a sustained yield of wood products, the area is planted in 15 stands, each staggered by one year in planting. After 15 years, the mature stand is harvested every year, and the wood products resulting from the harvest are used for their economic value. It is assumed that the annual harvest yields four different types of wood products with their fractional weights as follows: saw wood 0.30; veneer wood 0.20; paper 0.30; and fuelwood and fodder: 0.20. Of these, the last type (fuelwood and fodder) is not a long-lasting product, and the carbon stocks contained in this fraction of biomass are assumed to be emitted instantaneously. For the remaining three fractions (saw wood, veneer wood and paper), the IPCC default half-lives of 35 years, 30 years and 2 years, respectively, are assumed.

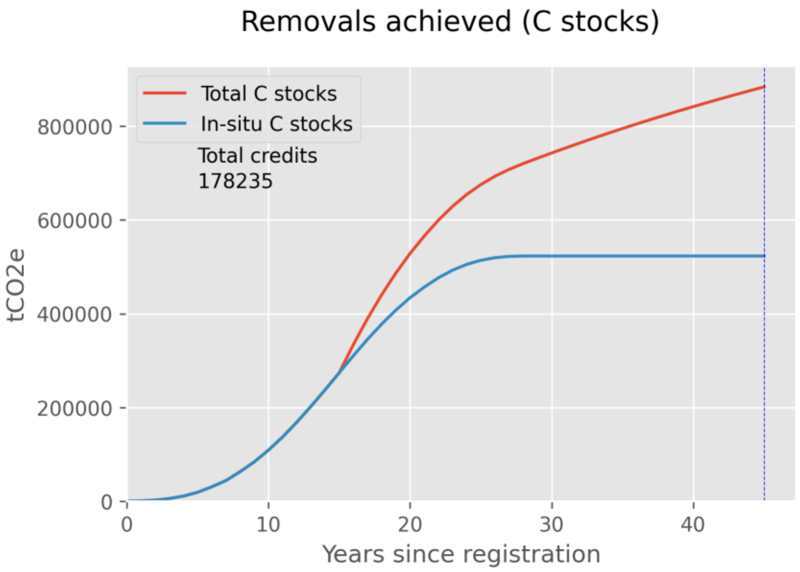
7. The resulting carbon stocks and the removal credits generated from the activity are shown in Figure H.2. Credits are estimated based on tonne-year crediting (no discounting).

8. Figure H.2 shows that total carbon stocks of 850,000 tCO_2 are achieved over the crediting period of 45 years. The in-situ carbon stocks become saturated by year 25, but the continued removal of biomass opens up the biosequestration stream and the carbon is transferred from the atmosphere to the pool of wood products.

9. By the end of the crediting period, a total of 178,235 credits are achieved (compared to 96,270 credits in the case of watershed reforestation and 236,063 credits in the case of afforestation with BECCS).

10. The emissions associated with the establishment of the plantations and the energy consumed to drive the CCS system as well as emissions associated with transportation are not included in the simulation. If significant, these will have to be deducted from the credits shown in the example.

Figure H.2. Removal activity consisting of afforestation with fast-growing species with sustained harvesting of long-lasting wood products (tonne-year crediting).



Appendix I: Summary descriptions of engineering-based removal activities

1. Direct air carbon capture and storage

1. Direct air carbon capture and storage (DACCS) captures CO_2 from ambient air through chemical processes and subsequently stores captured CO_2 in geological formations. While the theoretical potential for DACCS is mainly limited by the availability of safe and accessible geological storage, the CO_2 concentration in ambient air is 100–300 times lower than that at thermal power plants, thus requiring more energy than flue gas CO_2 capture. The literature on metrics related to DACCS (energy use, water use, cost, etc.) has low agreement. Cost estimates range from USD 20 to 1,000 per t CO_2. Given the technology's early stage of development and few demonstrations, deploying the technology at scale is still a considerable challenge, though both optimistic and pessimistic outlooks exist.

2. DACCS shares the same transport and storage components as conventional CCS, but it is distinct in its capture part. The duration of storage is an important consideration; geological reservoirs or mineralization result in the safe storage of carbon for more than 1,000 years.

3. An alternative approach is direct air carbon capture and utilization (DACCU), in which the captured CO_2 is used in making useful products. The duration of the removal through DACCU varies with the lifetime of respective products, ranging from weeks to months for synthetic fuels to centuries or more for building materials (e.g. concrete cured using mineral carbonation).

4. The efficiency and environmental impacts of DACCS and DACCU options depend on the carbon intensity of the energy input (electricity and heat) and other life-cycle assessment considerations. Another key consideration is the net carbon CO_2 removal of DACCS over its life cycle. It has been reported in some research findings that that the life-cycle net emissions of DACCS systems can be negative, even for existing supply chains and some current energy mixes.

5. **Status** There are some demonstration projects by start-up companies and academic researchers. They are developing various types of direct air capture (DAC) technologies, including using aqueous potassium solvents with calcium carbonation and solid sorbents heat regeneration. These projects are supported mostly by private investments and grants and sometimes serve utilization niche markets (e.g. CO_2 for beverages, greenhouses, enhanced oil recovery).

6. **Potentials** There is no specific study on the potential of DACCS, but the literature has assumed that the technical potential of DACCS is virtually unlimited provided that high energy requirements could be met since DACCS encounters fewer non-cost constraints than any other CDR method. It has been reported that, when focusing only on the Maghreb region, there is an optimistic removal potential of 150 gigatonnes of carbon dioxide (Gt CO_2) at less than USD 61 per t CO_2 by 2050. Other research suggests a potential of 0.5–5 Gt CO_2 per year by 2050 because of environmental side effects and limits to underground storage.

7. **Risks and impacts** DACCS requires a considerable amount of energy and, depending on the type of technology, high amounts of water and make-up sorbents; however, its land footprint is small compared to other CDR methods. However, depending on the source of energy for DACCS (e.g. renewables versus nuclear), it could also require a significant land footprint. The theoretical minimum energy requirement for separating CO_2 gas from the air is about 0.5 gigajoules (GJ) per t CO_2. Other research reports the estimates of energy requirements for the current technologies as approx. 4–10 GJ per t CO_2, with heat accounting for about 80 per cent and electricity about 20 per cent. At a 10 Gt CO_2/yr^{-1} sequestration scale, this would translate into 40–100 exajoules (EJ)/yr^{-1} of energy consumption, which can be contrasted with the current primary energy supply of approx. 600 EJ/yr^{-1}.

8. **Co-benefits** It has been proposed that solid sorbent-based DAC plants could use excess renewable power (at times of low or even negative prices), even though such an operation would add additional costs. Installations would need to be designed for intermittent operations (i.e. at low load factors), which would negatively affect capital and operation costs. Solid sorbent DAC designs can potentially remove more water from the ambient air than needed for regeneration, thereby delivering surplus water that would contribute to Sustainable Development Goal (SDG) 6 (Clean water and sanitation) in arid regions.

9. **Trade-offs and spill over effects** Liquid solvent DACCS systems need substantial amounts of water, although much less than BECCS systems. Although the high energy demand of DACCS could negatively affect SDG 7 (Affordable and clean energy) through potential competition or positively through learning effects, its impact has not been thoroughly assessed yet.

2. Enhanced rock weathering

10. Enhanced rock weathering (EW) involves the mining of rocks containing minerals that naturally absorb CO_2 from the atmosphere over geological timescales (as they become exposed to the atmosphere through geological weathering), the comminution of these rocks to increase the surface area, and the spreading of these crushed rocks on soils so that they react with atmospheric CO_2. Construction waste and waste materials from mining can also be used as a source material for EW. Silicate rocks (such as basalt), which contain minerals rich in calcium and magnesium and lack metal ions such as nickel and chromium, are the most suitable for EW; they reduce soil solution acidity during dissolution and promote the chemical transformation of CO_2 to bicarbonate ions.

11. **Status** EW has been demonstrated in the laboratory and in small scale field trials, but has yet to be demonstrated at scale. The chemical reactions are well understood, but the behaviour of the crushed rocks in the field and potential co-benefits and adverse-side effects of EW are uncertain. Small scale laboratory experiments have calculated weathering rates that are orders of magnitude slower than the theoretical limit for mass transfer-controlled forsterite and basalt dissolution. Uncertainty surrounding silicate mineral dissolution rates in soils, the fate of the released products, the extent of legacy reserves of mining by-products that might be exploited, the location and availability of rock extraction sites, and the impact on ecosystems remain poorly quantified and require further research to better understand feasibility.

12. **Costs** Costs are closely related to the source of the rock, the technology used for rock grinding, and material transport. Due to differences in the methods and assumptions between studies, literature ranges are highly uncertain and range from

USD 15–40/t CO_2^{-1} to USD 3,460/tCO_2^{-1}. One study suggested a cost range of USD 50–200/tCO_2^{-1} for a removal potential of 2–4 Gt CO_2/yr^{-1} from 2050.

13. **Potentials** There is limited evidence and low agreement on the mitigation potential of EW. The highest reported regional sequestration potential, 88.1 Gt CO_2 yr^{-1}, is reported for the spreading of pulverized rock over a very large land area in the tropics, a region considered promising given the higher temperatures and greater rainfall. Considering cropland areas only, the potential carbon removal is estimated to be 95 Gt CO_2/yr^{-1} for dunite and 4.9 Gt CO_2/yr^{-1} for basalt. In another study, lower potentials were estimated at 3.7 Gt CO2 yr^{-1} by 2100, but with mean annual removals an order of magnitude less at 0.2 Gt CO_2 eq yr^{-1}.

14. **Risks and impacts** Mining of rocks for EW will have local impacts and carries risks similar to that associated with the mining of mineral construction aggregates, with the possible additional risk of greater dust generation from fine comminution and land application. In addition to direct habitat destruction and increased traffic to access mining sites, there could be adverse impacts on local water quality.

15. **Co-benefits** EW can improve plant growth by pH modification and increased mineral supply and can enhance soil carbon sequestration in some soils. Through these actions, it can contribute to SDGs 2 (Zero hunger), 15 (Life on land) (by reducing land demand for croplands), 13 (Climate action) (through CDR), 14 (Life below water) (by ameliorating ocean acidification) and 6 (Clean water and sanitation). There are potential benefits in poverty reduction through the employment of local workers in mining.

16. **Trade-offs and spillover effects** Air quality could be adversely affected by the spreading of rock dust, though this can be partly ameliorated via water spraying. As noted above, any significant expansion of the mining industry would require careful assessment to avoid possible detrimental effects on biodiversity. The processing of an additional 10 billion tonnes of rock would require up to 3,000 terawatt-hours, which could represent approximately 0.1–6 percent of global electricity in 2100. The emissions associated with this additional energy generation may reduce the net CO_2 removal by up to 30 per cent with present day average grid emissions, but this efficiency loss would decrease with low-carbon power.

3. Ocean alkalinization

17. CDR, through ocean alkalinity enhancement or artificial ocean alkalinization (OA), can be based on the dissolution of natural alkaline minerals that are added directly to the ocean or coastal environments; the dissolution of such minerals upstream from the ocean, the addition of synthetic alkaline materials directly to the ocean or upstream; and the electrochemical processing of seawater. These processes result in the chemical transformation of CO_2 and its sequestration as bicarbonate and carbonate ions in the ocean. Imbalances between the input and removal fluxes of alkalinity can result in changes in global oceanic alkalinity and therefore the capacity of the ocean to store carbon. Such alkalinity-induced changes in the partitioning of carbon between the atmosphere and the ocean are thought to play an important role in controlling climate change in timescales of 1,000 years and longer.

18. **Status** OA has been demonstrated by a small number of laboratory experiments.

19. **Costs** Techno-economic assessments of ocean alkalinity enhancement largely focus on quantifying overall energy and carbon balances. Cost ranges are USD 40–260/tCO_2^{-1}.

Considering the life-cycle carbon and energy balances for various OA options, adding lime (or other reactive calcium or magnesium oxide/hydroxides) to the ocean would cost USD 64–260/tCO_2^{-1}.

20. **Potentials** The ocean theoretically has the capacity to store thousands of Gt CO_2 (cumulatively) without exceeding pre-industrial levels of carbonate saturation if the impacts were distributed evenly across the surface ocean. The potential of increasing ocean alkalinity may be constrained by (i) the limited capability to extract, process and trigger chemical reactions; (ii) the demand for co-benefits; and/or (iii) the need to minimize impacts around the points of addition. Important challenges with respect to the detailed quantification of CO_2 sequestration efficiency include nonstoichiometric dissolution, reversed weathering and potential pore water saturation in the case of adding minerals to shallow coastal environments. Some researchers suggest storage potentials of 1–100 Gt CO_2/yr^{-1}.

21. **Risks and impacts** For OA, the marine biological impacts are largely unknown. Ecological and biogeochemical consequences of OA largely depend on the minerals used. When natural minerals such as olivine are used, the release of additional silicon and iron could have fertilizing effects. In addition to perturbations to marine ecosystems via the reorganization of community structure, the potentially adverse effects of OA that should be studied include the release of toxic trace metals from some deposited minerals.

22. **Co-benefits** The intentional addition of alkalinity to the oceans through OA would decrease the risk to ocean ecosystems caused by the CO_2-induced impact of ocean acidification on marine biota and the global carbon cycle. OA could be jointly implemented with EW, spreading the finely crushed rock in the ocean rather than land. Regional alkalinization could be effective in protecting coral reefs against acidification. Coastal OA could be part of a broader strategy for the geochemical management of the coastal zone, safeguarding specific coastal ecosystems from the adverse impact of ocean acidification.

23. **Trade-offs and spillover effects** There has been very little research on biological effects of alkalinity addition. The very few studies that have explored the impact of elevated alkalinity on ocean ecosystems have largely been limited to single species experiments and a constrained field study quantifying the net calcification response of a coral reef flat to alkalinity enhancement. The addition rate would have to be great enough to overcome the mixing of the local seawater with the ambient environment, but not sufficient to detrimentally impact ecosystems. More research is required to assess locations in which this may be feasible, and how such a scheme may operate. The environmental impact of the large-scale release of natural dissolution products into the coastal environment will strongly depend on the scale of olivine application, the characteristics of the coastal water body (e.g. residence time) and the particular biota present (e.g. coral reefs will react differently compared with seagrasses). Model simulations suggest that the termination of OA implemented on a massive scale under a high CO_2 emission scenario might pose high risks to biological systems sensitive to rapid environmental changes because it would cause a sharp increase in ocean acidification.

4. Ocean fertilization

24. Ocean fertilization (OF) is based on the idea that increasing nutrient availability would stimulate the uptake of CO_2 through phytoplankton photosynthesis producing organic matter, some of which would be exported into the deep ocean, sequestering carbon. In areas of the ocean where macronutrients (nitrogen, phosphorus) are available in sufficient quantities, the growth of phytoplankton is limited by the lack of trace elements such as

iron. Thus, OF CDR can utilize two implementation options to increase the productivity of phytoplankton: macronutrient enrichment and micronutrient enrichment. Iron fertilization is the best studied OF option to date, but knowledge so far is still inadequate to predict global ecological and biogeochemical consequences.

25. **Status** OF options may appear technologically feasible, and the enhancement of photosynthesis and CO_2 uptake from surface waters is confirmed by a number of field experiments conducted in different areas of the ocean, but there is scientific uncertainty about the proportion of newly formed organic carbon that is transferred to deep ocean and the longevity of storage. The efficiency of OF also depends on the region and experimental conditions, especially in relation to the availability of other nutrients, light and temperature. In the case of macronutrients, very large quantities are needed, and the proposed scaling of this technique has been viewed as unrealistic.

26. **Costs** OF costs depend on nutrient production and its delivery to the application area. The costs range from USD 2/tCO_2^{-1} for fertilization with iron to USD 457/tCO_2^{-1} for nitrate. The median of OF cost estimates (USD 230/tCO_2^{-1}) indicates low cost-effectiveness, albeit the uncertainties are large.

27. **Potentials** Estimates indicate potentially achievable net sequestration rates of 1–3 Gt CO_2/yr^{-1} for iron fertilization, translating into cumulative CDR of 100–300 Gt CO_2 by 2100, whereas OF with macronutrients has a theoretical potential of 5.5 Gt CO_2/yr^{-1}. Modelling studies show a maximum effect on atmospheric CO_2 of 15–45 parts per million by volume in 2100.

28. **Risks and impacts** Several of the mesoscale iron enrichment experiments have seen the emergence of potentially toxic species of diatoms. There is also evidence of increased concentrations of other GHGs such as methane and nitrous oxide during the subsurface decomposition of the sinking particles from iron-stimulated blooms. Impacts on marine biology and food web structure are not well known. OF at larger scales could cause changes in nutrient distributions or anoxia in subsurface water. Other potential risks are perturbation to marine ecosystems via the reorganization of community structure, enhanced deep ocean acidification and effects on the human food supply.

29. **Co-benefits** The co-benefits of OF include a potential increase in fish biomass through enhanced biological production and reduced ocean acidification in the short term in the upper ocean.

30. **Trade-offs and spillover effects** Potential drawbacks include subsurface ocean acidification and deoxygenation; altered regional meridional nutrient supply and fundamental alteration of food webs; and increased production of nitrous oxide and methane. OF is considered to have negative consequences for eight SDGs and a combination of both positive and negative consequences for seven SDGs.

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