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Policy Paper

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Abstract: Nature-based solutions and global climate protection

Nature-based Solutions (NbS) build synergies between biodiversity conservation and societal challenges such as climate change. This paper derives a **working definition of NbS** based on an **evaluation of existing definitions**, in particular the IUCN (2016) definition. It comprises the key elements of the existing definitions that we believe to be important to inform the scope of this study. It critically assesses the global mitigation potential of NbS in relevant studies for forests, croplands, grasslands, terrestrial and coastal wetlands as well as settlements. Recommendations for international climate policy are derived. The study finds that it is likely that NbS potentials provided by scientific literature overestimate the realistic potential of NbS for climate change mitigation. This is due to a lack of integrated studies, overly optimistic assumptions on land availability as well as the quality of available information. Furthermore, the influence of measures on GHG fluxes, uncertainties related to carbon fluxes and quantification methodologies as well as climate impacts are not taken into account. The majority of studies evaluating the mitigation potential of NbS focus on the technical mitigation potential. General ecological constraints such as existing threats to ecosystems, and biodiversity impacts, land use conflicts and other social, cultural and political barriers as well as the risk of non-permanence further limit mitigation potentials. The success of NbS to mitigate climate change and deliver ecological and social co-benefits will very much depend on eliminating direct and indirect pressures on ecosystems caused by current patterns of production and consumption. Nevertheless, the uncertainties related to the quantification of mitigation effects of NbS should not be used as an argument against their implementation. Neither should they be used as an excuse to delay ambitious mitigation action to reduce emissions. In the UNFCCC negotiation process, information on NbS in biennial transparency reports may serve as a basis for technical discussion to improve methodologies and indicators to assess how NbS contribute to achieving NDCs and to make further financial support available. In implementing activities under Article 6 of the Paris Agreement, the specific risks related to NbS must be taken into account. In the development of processes or support schemes to foster NbS, social and environmental safeguards need to be put in place. Coherence with work under other international policy frameworks such as the other Rio Conventions is required to foster synergies.

Kurzbeschreibung: Naturbasierte Lösungen und globaler Klimaschutz

Naturbasierte Lösungen (NbS) schaffen Synergien zwischen dem Schutz der Biodiversität und gesellschaftlichen Herausforderungen wie dem Klimawandel. In diesem Papier wird eine Arbeitsdefinition von NbS abgeleitet, die sich auf andere bestehende Definitionen, insbesondere auf die Definition der IUCN (2016) stützt. Sie enthält zentrale Elemente der bestehenden Definitionen, die für den Rahmen dieser Studie wichtig sind. Das globale Minderungspotenzial von NbS in relevanten Studien für Wälder, Ackerland, Grünland, terrestrische und küstennahe Feuchtgebiete sowie Siedlungen wird kritisch analysiert und es werden Empfehlungen für die internationale Klimapolitik abgeleitet. Die Studie kommt zu dem Ergebnis, dass die in der wissenschaftlichen Literatur angegebenen Potenziale das realistische Potenzial von NbS für den Klimaschutz wahrscheinlich überschätzen. Dies ist auf das Fehlen integrierter Studien, zu optimistische Annahmen zur Flächenverfügbarkeit und die Qualität der verfügbaren Informationen zurückzuführen. Außerdem werden der Einfluss von Maßnahmen auf Treibhausgasflüsse, Unsicherheiten in Bezug auf Kohlenstoffflüsse und Quantifizierungsmethoden sowie Klimawandelauswirkungen nicht berücksichtigt. Die Mehrzahl der Studien, die das Minderungspotenzial von NbS untersuchen, konzentriert sich auf das technische Minderungspotenzial. Allgemeine ökologische Einschränkungen wie bestehende Bedrohungen für Ökosysteme, Auswirkungen auf die Biodiversität, Landnutzungskonflikte und andere soziale, kulturelle und politische Hindernisse sowie das Risiko der Nicht-Permanenz von

Minderungserfolgen schränken die Minderungspotenziale weiter ein. Der Beitrag von NbS bei der Bekämpfung des Klimawandels und der Erzielung ökologischer und sozialer Co-Benefits wird in hohem Maße davon abhängen, ob die direkten und indirekten Belastungen der Ökosysteme aufgrund der vorherrschenden Produktions- und Konsummuster beseitigt werden. Dennoch sollten die Unsicherheiten in Bezug auf die Quantifizierung der Minderungseffekte von NbS nicht als Argument gegen ihre Umsetzung verwendet werden. Sie sollten auch nicht als Vorwand dienen, um ehrgeizige Minderungsmaßnahmen zur Reduzierung von Emissionen zu verzögern. Im Rahmen des UNFCCC-Verhandlungsprozesses können die Informationen über NbS in den zweijährlichen Transparenzberichten als Grundlage für technische Diskussionen dienen, um Methoden und Indikatoren von NbS im Kontext der NDCs weiterzuentwickeln, und um finanzielle Unterstützung bereitzustellen. Bei der Umsetzung von Aktivitäten unter Artikel 6 des Übereinkommens von Paris müssen die spezifischen Risiken im Zusammenhang mit NbS berücksichtigt werden. Bei der Entwicklung von Verfahren oder Unterstützungsregelungen zur Förderung von NbS müssen soziale und ökologische Schutzmaßnahmen eingeführt werden. Zur Förderung von Synergien ist eine Kohärenz mit der Arbeit im Rahmen anderer internationaler politischer Rahmenwerke wie den anderen Rio-Konventionen erforderlich.

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List of abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
BECCS	Bioenergy with Carbon Capture & Storage
C	Carbon
CBD	Convention on Biological Diversity
CDM	Clean Development Mechanism
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
COP	Conference of the Parties
FAO	Food and Agriculture Organisation
GHG	Greenhouse gas
Ha	hectar
IPCC	Intergovernmental Panel on Climate Change
ITMO	Internationally transferred mitigation outcomes
IUCN	International Union for Conservation of Nature
JI	Joint Implementation
K	Potassium
KJWA	Koronivia Joint Work on Agriculture
LULUCF	Land Use, Land Use Change and Forestry
MEA DaRT	Data Reporting Tool for Multilateral Environmental Agreements
Mha	Million hectar
MPGs	Modalities, procedures and guidelines for the transparency framework for action and support
Mt	Mega tonnes
N	Nitrogen
N_2O	Nitrous oxide
NbS	Nature-based Solutions
NDC	Nationally Determined Contributions under the Paris Agreement
P	Phosphor
pH	Potential of hydrogen

AFOLU	Agriculture, Forestry and Other Land Use
RCP	Representative concentration pathway
REDD+	Reducing Emissions from Deforestation and Forest Degradation
SBI	Subsidiary Body for Implementation
SBSTA	Subsidiary Body for Scientific and Technological Advice
SOC	Soil organic carbon
t	Tonne
UNFCCC	United Nations Framework Convention on Climate Change
yr	year

Summary

The recognition that nature can contribute to addressing and solving societal challenges, including climate crisis, is referred to as "Nature-based Solutions" (NbS). NbS build synergies between biodiversity conservation and societal challenges and deliver environmental and social benefits. Although the 'NbS' term is widely used, there is still no common understanding of NbS in the scientific and political debate. This paper derives a **working definition of NbS** based on an **evaluation of existing definitions**, in particular the IUCN (2016) definition: *Nature-based Solutions are locally appropriate, adaptive actions to protect, sustainably manage or restore natural or modified ecosystems in order to address targeted societal challenge(s) - such as climate change mitigation -, while simultaneously enhancing human well-being and providing biodiversity benefits.* It comprises the key elements of the existing definitions, that we believe to be important to inform the scope of this study. On the basis of this definition, the study critically assesses the global mitigation potential of NbS. Furthermore, recommendations for international climate policy are derived.

It is crucial to critically assess the **mitigation potential** associated with NbS in order not to overestimate their contribution to climate protection. The paper reviews a number of prominent studies on measures associated with NbS towards their mitigation potential, and their methodologies and assumptions in order to develop a better understanding of the potential and limits of NbS measures as a mitigation strategy. The studies were assessed and compared with regard to their scope, the range of mitigation potential provided, approaches towards the quantification of this potential, assumptions regarding safeguards and co-benefits as well as costs, constraints and uncertainties included in the studies.

Potentials provided for **forests** through reforestation, afforestation, forest protection as well as forest management vary greatly depending on assumptions regarding land availability and constraints on co-benefits and trade-offs (afforestation/reforestation), assumed future baselines of drivers (avoided emissions from deforestation) as well as forest growth and assumed harvest intensity (forest management). Differences in assumptions but also definition of activities makes a comparison of different estimates difficult if not impossible. Given the wide concept of NbS adopted by the reviewed studies, there is a risk that potentials are largely overestimated. The risk of overestimation is larger for afforestation/reforestation (up to five times higher) and lower but still significant for forest management (about two times lower). Deviation of estimates for avoided deforestation were found to be between the two.

NbS in **croplands** mainly contribute to climate change mitigation by increasing CO_2 sequestration in mineral soils and on farmland and by reducing CH_4 emissions from rice cultivation. Estimates for global sequestration potentials in croplands range from 0.2 $GtCO_2e/yr$ to 11 $GtCO_2e/yr$ and have high uncertainties. Global estimates derived from global soil models do not reflect the high natural variability of carbon stocks and there is currently a lack of systematic and reliable measurement of soil carbon in mineral soils in countries. However, constant sustainable soil management in croplands (e.g. planting cover crops during fallow periods, increasing the returns of organic input to soils) is needed to maintain the capacity for soil carbon sequestration and to protect soil carbon stocks. Estimates of the CO_2 sequestration potential of agroforestry range from 0.3 $GtCO_2e/yr$ to 5.7 $GtCO_2e/yr$. Estimates often reflect enhancements of SOC, which is also constrained by the issues mentioned above, and increases in biomass, which is currently not systematically assessed in most countries. The mitigation potentials of agroforestry systems are strongly influenced by soil and climate variables, as well as by the system under consideration. Estimates for reducing CH_4 emissions from rice cultivation range from 0.08 to 0.87 $GtCO_2e/yr$. The diversity of rice cultivation systems poses a

strong limit to assessing generalised potentials and trade-offs between the reduction of CH_4 emissions. Increasing N_2O emissions need to be considered, if alternative water management is not accompanied by improved fertiliser management.

Compared to other ecosystems, NbS in **grasslands** show a very wide range of climate mitigation potentials assumingly because of differing assumptions for soil carbon sequestration rates, e.g. for improved grazing (0.15 and 1 tCO_2/ha/yr, Griscom et al. 2017; Conant et al. 2017) and for the potentially suitable area extent of this NbS. Hence, total mitigation potentials from improved grazing range from 0.15 (Griscom et al. 2017) to 1.5 $GtCO_2e$/yr (Smith et al. 2008). The highest mitigation potentials can be expected from the avoidance of grassland conversion to cropland, although the total estimate of avoided emissions varies according to the underlying soil carbon assumptions. Also, the active restoration of abandoned cropland substantially increases the soil carbon sequestration (1.9 tCO_2/ha/yr and 3.3 tCO_2/ha/yr; Yang et al. 2019; Conant et al. 2017). Yet, there are no estimates on the potential restoration area. Although the overall climate mitigation potential of grasslands due to NbS is very uncertain, the co-benefits of NbS protecting grasslands from conversion and restoring them can be very high for biodiversity and ecosystem services like flood control and improved soil structure (Griscom et al. 2017).

Protection and restoration of **terrestrial wetlands** can avoid and reduce further carbon loss primarily from soils. Maximum global mitigation estimates for peatland restoration is estimated at 0.8 GtCO2e/yr (Griscom et al. 2017) and 0.9 GtCO2e/yr (Leifeld and Menichetti 2018). Additionally, the avoidance of further loss of peatlands could mitigate about 0.7 GtCO2e/yr (Griscom et al. 2017). Main uncertainties related to these mitigation potentials result from different estimates for degraded peatland areas as well as different estimates regarding a full implementation of the global restoration potential. Also, there is a lack of emission factors that better reflect the different phases of peat degradation in order to make more accurate assumptions. Another uncertainty are future GHG fluxes of peatlands under climate change that could lead to increased emissions from intact peatlands (Leng et al. 2019). Finally, global mitigation potentials for terrestrial wetlands are predominantly limited to peatlands but do not consider impacts on the emission fluxes from lake and river sediments as well as alluvial (floodplain) forest soils and biomass (Ramsar Convention Secretariat 2018).

The restoration of **coastal wetlands** (mangroves, seagrass meadows and saltmarshes) can mitigate up to 0.8 $GtCO_2e$/yr but this mitigation potential could be lower especially because of potentially lower emission factors for seagrass meadows. However, there are high uncertainties in the number of sequestration rates, area extent as well as the impact of disturbances on the emission fluxes of coastal wetlands (Jia et al. 2019; Pendleton et al. 2012; Howard et al. 2017; IUCN 2021b), which makes mitigation potential estimates very challenging. The effect of climate change on coastal ecosystems and their carbon stocks is still highly debated and probably has a high geographic variation but is not considered in the studies. Sea level rise could be beneficial for coastal ecosystems, while marine heatwaves, storms and altered availability of fresh water could have a negative impact (Macreadie et al. 2019). Currently, impacts of disturbances to seafloor sediments of the open sea mainly due to bottom trawling have not been considered in global assessments so far (Jia et al. 2019; Griscom et al. 2017).

Enhancing urban green infrastructure in **settlements** can contribute to mitigating emissions as well as to cities' adaptation to climate change. At the same time, they involve co-benefits for food security, improve air quality and can have positive impacts on soil and water. Overall, the potential to abate pollution is evaluated as more substantial than the potential to mitigate GHG emissions (Baro et al. 2017). Additionally, the circumstances for urban greening are very different across the globe. Local data remains fragmentary (Nowak et al. 2013).

More research is required, as **it is likely that NbS potentials provided by the scientific literature overestimate the realistic potential of such activities for climate change mitigation**. This is partly due to the **lack of integrated studies** that achieve a consistent and comprehensive assessment of activities competing for land and financial resources, affecting production levels and causing displacement of production to provide the net mitigation potential. Moreover, many studies make **overly optimistic assumptions on land availability** and do not consider negative impacts on ecosystems, human well-being or non-GHG effects (e.g. albedo) of measures. Additional constraints relate to the **quality of available information** on the current state of ecosystems and the influence of measures on their GHG fluxes and other ecosystem components like biodiversity. Furthermore, underlying assumptions towards ecosystem carbon fluxes as well as quantification methodologies bear significant **uncertainties**. **Climate impacts** are not taken into account in any of the studies assessed. Also, the majority of studies focus on the **technical mitigation potential** which can differ significantly from economic potentials and related assumptions are not always clear. A lot of studies do not consider opportunity, transaction or transition costs. Also, land use conflicts and other **social, cultural and political barriers** to the implementation of NbS are barely taken into account. **General ecological constraints** such as existing threats to ecosystems, consumption patterns, as well as biodiversity impacts further limit the mitigation potentials provided in the literature. Also, the **risk of non-permanence** inherent to mitigation activities in the land use sector needs to be accounted for when quantifying mitigation potentials from NbS. A tonne of CO_2 removals achieved through NbS can thus not be considered equivalent to one tonne of CO_2 of fossil fuel avoided that has a much lower risk of non-permanence. Available global mitigation potentials therefore need to be considered as rough estimates with considerable constraints.

Nevertheless, the uncertainties related to the quantification of mitigation effects of NbS should not be used as an argument against their implementation. Advancing NbS is often described as a 'no-regret' option, as they entail benefits to people in a range of scenarios. To realise these benefits, **NbS need to be carefully designed, be based on metrics that take into account their various benefits to human beings and the environment and have robust social and biodiversity safeguards in place**. At the same time, the mitigation benefits implied by NbS will be an important contribution to reaching the goals of the Paris Agreement, but they should always be seen as a **complement to ambitious mitigation action to reduce emissions**. The success of NbS to mitigate climate change and deliver ecological and social co-benefits will also very much depend on a successful implementation of the goals and targets of the Rio Conventions, in particular the CBD and its global biodiversity framework. This will mean to **eliminate direct and indirect pressures on ecosystems related to recent drivers of global change,** including land- and sea-use change, ecosystem and species exploitation and pollution, caused by current patterns of consumption and production.

For the UNFCCC negotiation process, the following recommendations can be derived:

- If Parties also report on the implementation of NbS in their **biennial transparency reports**, this may serve as a basis for technical discussion to improve methodologies and indicators to assess how NbS contribute to achieving NDCs and to direct capacity building resources to support the development of better policies to enhance and promote their implementation.

- Including **NbS in market-based mechanisms involves risks** related to the uncertainty in setting baselines, monitoring carbon stock changes, non-permanence of achieved mitigation and social and environmental safeguards. In implementing cooperative approaches under Article 6 of the Paris Agreement, these risks must be taken into account. Particularly, eligible activities need to be designed in a careful manner in order to manage reversal risks. A prudent policy approach would be to use crediting mechanisms only for those activities for which the likelihood of additionality is high and for which baselines can be estimated with reasonable certainty.

- Under the UNFCCC negotiations, more attention should be paid to those types of NbS that are less prevalent but bear significant benefit to people and the preservation of ecosystems such as coastal and marine habitats. In the development of processes or support schemes to foster NbS under the UNFCCC process, special attention needs to be paid to ensuring that **social and environmental safeguards** are put in place. While the Warsaw framework for REDD+ explicitly requires the conservation of biodiversity and the respect of indigenous peoples' and local communities' rights, guidance on such safeguards for other types of NbS measures is too vague under the UNFCCC. Progress on NbS safeguard frameworks has been made for example under the CBD (ecosystem approach; principles and safeguards for ecosystem-based approaches to climate change adaptation and disaster risk reduction) or the IUCN Global Standard for NbS on which the UNFCCC process can further build on.
- An **integrated view** on NbS is necessary, as they need to be understood as measures to enhance mitigation as well as adaptation and biodiversity conservation. Coherence with other ongoing work under the UNFCCC (e.g. KJWA, Nairobi Work Programme, Standing Committee on Finance) and close collaboration with the work under the other Rio Conventions, in particular the CBD global biodiversity framework, is required to foster synergies. For this purpose it would be beneficial to work on common or at least aligned concepts as well as indicators for reporting and tracking NbS activities under these different processes, e.g. under initiatives such as MEA DaRT[1].

Making use of NbS for long-term carbon storage can only be successful if the **sink potential of forests, wetlands and soils is maintained through sustainable land use and existing carbon stocks are protected**. Synergies between conservation and use objectives can be realised if **climate protection, biodiversity conservation and climate adaptation are thought together**.

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[1] See https://dart.informea.org/.

Zusammenfassung

Die Erkenntnis, dass die Natur zur Bewältigung und Lösung gesellschaftlicher Herausforderungen, einschließlich der Klimakrise, beitragen kann, wird unter dem Begriff "naturbasierte Lösungen" (NbS) subsumiert. NbS schaffen Synergien zwischen dem Schutz der Biodiversität und gesellschaftlichen Herausforderungen und bringen somit ökologische und soziale Vorteile mit sich. Obwohl der Begriff "NbS" weit verbreitet ist, gibt es in der wissenschaftlichen und politischen Debatte noch kein gemeinsames Verständnis von NbS. In diesem Papier wird eine **Arbeitsdefinition von NbS** abgeleitet, die auf einer Bewertung der **bestehenden Definitionen**, insbesondere der Definition der IUCN (2016) **basiert**: *Naturbasierte Lösungen sind lokal angemessene, anpassungsfähige Maßnahmen zum Schutz, zur nachhaltigen Bewirtschaftung oder zur Wiederherstellung natürlicher oder veränderter Ökosysteme, um gezielte gesellschaftliche Herausforderungen - wie die Abschwächung des Klimawandels - anzugehen und gleichzeitig das menschliche Wohlergehen zu verbessern und die biologische Vielfalt zu fördern.* Die Arbeitsdefinition enthält die zentralen Elemente der bestehenden Definitionen, die für den Rahmen dieser Studie wichtig sind. Sie bildet somit die Grundlage, um das globale Minderungspotenzial von NbS kritisch zu bewerten. Außerdem werden Empfehlungen für die internationale Klimapolitik abgeleitet.

Es ist von entscheidender Bedeutung, das mit NbS verbundene **Minderungspotenzial** kritisch zu bewerten, um ihren Beitrag zum Klimaschutz nicht zu überschätzen. In dem Papier wird eine Reihe prominenter Studien über Maßnahmen im Zusammenhang mit NbS im Hinblick auf ihre Minderungspotenziale sowie ihre Methoden und Annahmen untersucht, um ein besseres Verständnis für das Potenzial und die Grenzen von NbS-Maßnahmen als Minderungsstrategie zu entwickeln. Die Studien wurden hinsichtlich ihres Umfangs, des Umfangs des Minderungspotenzials, der Ansätze zur Quantifizierung dieses Potenzials, der Annahmen zu Schutzmaßnahmen und Zusatznutzen sowie der in den Studien enthaltenen Kosten, Einschränkungen und Unsicherheiten bewertet und verglichen.

Die Potenziale, die für **Wälder** durch Wiederaufforstung, Aufforstung, Waldschutz und Waldbewirtschaftung angegeben werden, variieren stark, je nach den Annahmen über die Flächenverfügbarkeit und die Einschränkungen bei den Zusatznutzen und Kompromissen (Aufforstung/Wiederaufforstung), dem angenommenen künftigen Referenzszenario der Einflussfaktoren (vermiedene Emissionen aus Entwaldung) sowie dem Waldwachstum und der angenommenen Nutzungsintensität (Waldbewirtschaftung). Unterschiede in den Annahmen, aber auch in der Definition der Aktivitäten machen einen Vergleich der verschiedenen Schätzungen schwierig, wenn nicht gar unmöglich. Angesichts des weit gefassten Konzepts von NbS, das in den untersuchten Studien verwendet wird, besteht die Gefahr, dass die Potenziale weitgehend überschätzt werden. Das Risiko einer Überschätzung ist bei Aufforstung/Wiederaufforstung größer (bis zum Fünffachen) und bei der Waldbewirtschaftung geringer, aber immer noch signifikant (etwa das Zweifache). Bei der vermiedenen Entwaldung liegen die Abweichungen zwischen den beiden Schätzungen.

NbS in **Anbauflächen** tragen hauptsächlich zur Abschwächung des Klimawandels bei, indem sie die CO_2-Sequestrierung in Mineralböden und auf Ackerland erhöhen und die CH_4-Emissionen aus dem Reisanbau verringern. Die Schätzungen für das globale Sequestrierungspotenzial von Ackerland reichen von 0,2 $GtCO_2e$/Jahr bis 11,0 $GtCO_2e$/Jahr und sind mit großen Unsicherheiten behaftet. Globale Schätzungen, die aus globalen Bodenmodellen abgeleitet werden, spiegeln die hohe natürliche Variabilität der Kohlenstoffvorräte nicht wider, und es fehlt derzeit an einer systematischen und zuverlässigen Messung des Bodenkohlenstoffs in Mineralböden in den einzelnen Ländern. Allerdings ist es notwendig, eine nachhaltige

Bodenbewirtschaftung im Ackerbau (z. B. Anbau von Zwischenfrüchten während der Brachezeiten, Erhöhung des Rückflusses von organischen Stoffen in die Böden) dauerhaft beizubehalten, um die Bindung von Kohlenstoff im Boden sicherzustellen und die Kohlenstoffvorräte im Boden zu zu erhalten. Die Schätzungen des CO_2-Bindungspotenzials der Agroforstwirtschaft reichen von 0,3 $GtCO_2e$/Jahr bis 5,7 $GtCO_2e$/Jahr. Die Schätzungen beziehen sich häufig auf die Erhöhung des Anteil an organischem Bodenkohlenstoff (SOC), die ebenfalls durch die oben genannten Probleme eingeschränkt wird, und auf die Erhöhung der Biomasse, die in den meisten Ländern derzeit nicht systematisch bewertet wird. Das Minderungspotenzial agroforstwirtschaftlicher Systeme hängt stark von den Boden- und Klimavariablen sowie von dem jeweiligen System ab. Die Schätzungen für die Reduzierung der CH_4-Emissionen aus dem Reisanbau reichen von 0,08 bis 0,87 $GtCO_2e$/Jahr. Die Vielfalt der Reisanbausysteme stellt eine starke Einschränkung für die Bewertung der verallgemeinerten Potenziale und der Kompromisse bei der Verringerung der CH_4-Emissionen dar. Ein Anstieg der N_2O-Emissionen muss in Betracht gezogen werden, wenn ein alternatives Wassermanagement nicht mit einem verbesserten Düngemittelmanagement einhergeht.

Im Vergleich zu anderen Ökosystemen weisen NbS im **Grünland** eine sehr große Bandbreite an Klimaschutzpotenzialen auf, vermutlich aufgrund unterschiedlicher Annahmen für die Kohlenstoffbindung im Boden, z. B. bei verbesserter Beweidung (0,15 und 1 tCO_2/ha/Jahr, Griscom et al. 2017; Conant et al. 2017) und für die potenziell geeignete Flächengröße dieser NbS. Die gesamten Minderungspotenziale durch verbesserte Beweidung reichen daher von 0,15 (Griscom et al. 2017) bis 1,5 $GtCO_2e$/Jahr (Smith et al. 2008). Die höchsten Minderungspotenziale können von der Vermeidung der Umwandlung von Grünland in Ackerland erwartet werden, obwohl die Gesamtschätzung der vermiedenen Emissionen je nach den zugrunde liegenden Annahmen zum Bodenkohlenstoff variiert. Auch die aktive Wiederherstellung von aufgegebenem Ackerland erhöht die Kohlenstoffbindung im Boden erheblich (1,9 tCO2/ha/Jahr und 3,3 tCO_2/ha/Jahr; Yang et al. 2019; Conant et al. 2017). Es gibt jedoch keine Schätzungen über die potenzielle Wiederherstellungsfläche. Obwohl das gesamte Klimaschutzpotenzial von Grünland durch NbS sehr ungewiss ist, können die Zusatznutzen von NbS, die Grünland vor der Umwandlung schützen und wiederherstellen, für die biologische Vielfalt und Ökosystemleistungen wie Hochwasserschutz und verbesserte Bodenstruktur sehr hoch sein (Griscom et al. 2017).

Der Schutz und die Wiederherstellung von **terrestrischen Feuchtgebieten** kann weitere Kohlenstoffverluste vor allem aus Böden vermeiden und verringern. Die maximalen globalen Minderungsschätzungen für die Wiederherstellung von Moorgebieten werden auf 0,8 $GtCO_2e$/Jahr (Griscom et al. 2017) und 0,9 $GtCO_2e$/Jahr (Leifeld und Menichetti 2018) geschätzt. Zusätzlich könnte die Vermeidung eines weiteren Verlusts von Torfgebieten etwa 0,7 $GtCO_2e$/Jahr einsparen (Griscom et al. 2017). Die größten Unsicherheiten in Bezug auf diese Minderungspotenziale resultieren aus unterschiedlichen Schätzungen für degradierte Moorflächen sowie aus unterschiedlichen Schätzungen hinsichtlich einer vollständigen Umsetzung des globalen Wiederherstellungspotenzials. Außerdem fehlt es an Emissionsfaktoren, die die verschiedenen Phasen der Torfdegradation besser widerspiegeln, um genauere Annahmen treffen zu können. Eine weitere Ungewissheit sind die zukünftigen THG-Flüsse von Torfgebieten unter dem Klimawandel, die zu erhöhten Emissionen aus intakten Torfgebieten führen könnten (Leng et al. 2019). Schließlich beschränken sich die globalen Minderungspotenziale für terrestrische Feuchtgebiete in erster Linie auf Torfgebiete, berücksichtigen aber nicht die Auswirkungen auf die Emissionsflüsse von See- und Flusssedimenten sowie von Auwaldböden und Biomasse (Ramsar Convention Secretariat 2018).

Die Wiederherstellung von **küstennahen Feuchtgebieten** (Mangroven, Seegraswiesen und Salzwiesen) kann bis zu 0,8 $GtCO_2e$/Jahr eindämmen, aber dieses Minderungspotenzial könnte niedriger sein, insbesondere aufgrund potenziell niedrigerer Emissionsfaktoren für Seegraswiesen. Es bestehen jedoch große Unsicherheiten in Bezug auf die Sequestrationsraten, die Flächenausdehnung sowie die Auswirkungen von Störungen auf die Emissionsflüsse von Küstenfeuchtgebieten (Jia et al. 2019; Pendleton et al. 2012; Howard et al. 2017; IUCN 2021b), was Schätzungen des Minderungspotenzials sehr schwierig macht. Die Auswirkungen des Klimawandels auf Küstenökosysteme und ihre Kohlenstoffvorräte werden immer noch heftig diskutiert und weisen wahrscheinlich eine große geografische Variation auf, werden aber in den Studien nicht berücksichtigt. Der Anstieg des Meeresspiegels könnte sich positiv auf die Küstenökosysteme auswirken, während marine Hitzewellen, Stürme und die veränderte Verfügbarkeit von Süßwasser negative Folgen haben könnten (Macreadie et al. 2019). Die Auswirkungen von Störungen der Meeresbodensedimente auf offener See, die vor allem auf die Grundschleppnetzfischerei zurückzuführen sind, wurden bisher in globalen Bewertungen nicht berücksichtigt (Jia et al. 2019; Griscom et al. 2017).

Die Verbesserung der städtischen grünen Infrastruktur in **Siedlungen** kann sowohl zur Emissionsminderung als auch zur Anpassung der Städte an den Klimawandel beitragen. Gleichzeitig bringen sie einen Zusatznutzen für die Ernährungssicherheit mit sich, verbessern die Luftqualität und können positive Auswirkungen auf Boden und Wasser haben. Insgesamt wird das Potenzial zur Verringerung der Umweltverschmutzung als größer eingeschätzt als das Potenzial zur Minderung von Treibhausgasemissionen (Baro et al. 2017). Hinzu kommt, dass die Bedingungen für die Stadtbegrünung weltweit sehr unterschiedlich sind. Lokale Daten sind nach wie vor lückenhaft (Nowak et al. 2013).

Es besteht weiterer Forschungsbedarf, da **die in der wissenschaftlichen Literatur angegebenen NbS-Potenziale das realistische Potenzial solcher Aktivitäten für den Klimaschutz wahrscheinlich überschätzen**. Dies ist zum Teil auf das **Fehlen integrierter Studien** zurückzuführen, die eine kohärente und umfassende Bewertung von Aktivitäten vornehmen, die um Land und finanzielle Ressourcen konkurrieren, das Produktionsniveau beeinflussen und Produktionsverlagerungen verursachen, um das Nettominderungspotenzial zu ermitteln. Darüber hinaus gehen viele Studien von **zu optimistischen Annahmen hinsichtlich der Flächenverfügbarkeit** aus und berücksichtigen nicht die negativen Auswirkungen der Maßnahmen auf die Ökosysteme, das menschliche Wohlergehen oder die Nicht-THG-Effekte (z. B. Albedo). Weitere Einschränkungen betreffen die **Qualität der verfügbaren Informationen** über den aktuellen Zustand des Ökosystems und den Einfluss der Maßnahmen auf die Treibhausgasflüsse und andere Ökosystemkomponenten wie die biologische Vielfalt. Darüber hinaus sind die zugrundeliegenden Annahmen zu den Kohlenstoffflüssen in Ökosystemen sowie die Quantifizierungsmethoden mit erheblichen **Unsicherheiten** behaftet. **Klimaauswirkungen** werden nicht in allen untersuchten Studien berücksichtigt. Außerdem konzentrieren sich die meisten Studien auf das **technische Minderungspotenzial**, das sich erheblich von den wirtschaftlichen Potenzialen unterscheiden kann, und die damit verbundenen Annahmen sind nicht immer klar. In vielen Studien werden Opportunitäts-, Transaktions- oder Übergangskosten nicht berücksichtigt. Auch Landnutzungskonflikte und andere **soziale, kulturelle und politische Hindernisse** für die Umsetzung von NbS werden kaum berücksichtigt. **Allgemeine ökologische Zwänge** wie bestehende Bedrohungen für Ökosysteme, Konsummuster sowie Auswirkungen auf die biologische Vielfalt schränken die in der Literatur genannten Minderungspotenziale weiter ein. Außerdem muss bei der Quantifizierung des Minderungspotenzials von NbS das **Risiko der Nicht-Permanenz** von Minderungsmaßnahmen im Landnutzungssektor berücksichtigt werden. Eine Tonne CO_2-Entfernung durch NbS kann daher nicht als gleichwertig mit einer Tonne CO_2 aus vermiedenen fossilen Brennstoffen angesehen werden, bei denen das Risiko der Nichtdauerhaftigkeit viel geringer ist. Die verfügbaren globalen Minderungspotenziale müssen daher als grobe Schätzungen mit erheblichen Einschränkungen betrachtet werden.

Dennoch sollten die Unsicherheiten im Zusammenhang mit der Quantifizierung der Minderungseffekte von NbS nicht als Argument gegen ihre Umsetzung dienen. Die Förderung von NbS wird oft als "No-regret"-Option bezeichnet, da sie für die Menschen in einer Reihe von Szenarien Vorteile mit sich bringt. Um diese Vorteile zu realisieren, müssen **NbS sorgfältig konzipiert werden, auf Metriken beruhen, die ihren verschiedenen Vorteilen für Mensch und Umwelt Rechnung tragen, und über solide soziale und biodiversitätsbezogene Schutzmechanismen verfügen.** Gleichzeitig werden die mit den NbS verbundenen Minderungsvorteile einen wichtigen Beitrag zur Erreichung der Ziele des Pariser Abkommens leisten, doch sollten sie stets als **Ergänzung zu ehrgeizigen Minderungsmaßnahmen** zur Reduzierung der Emissionen gesehen werden. Der Erfolg der NbS bei der Abschwächung des Klimawandels und der Erzielung ökologischer und sozialer Zusatznutzen wird auch in hohem Maße von der erfolgreichen Umsetzung der Ziele und Vorgaben der Übereinkommen von Rio abhängen, insbesondere des Übereinkommens über die biologische Vielfalt (CBD) und ihres globalen Rahmens für die biologische Vielfalt. Dies bedeutet, dass die **direkten und indirekten Belastungen der Ökosysteme** im Zusammenhang mit der veränderten Land- und Meeresnutzung, der Ausbeutung von Ökosystemen und Arten sowie der Umweltverschmutzung aufgrund der vorherrschenden Produktions- und Konsummuster **beseitigt werden müssen**.

Für den UNFCCC-Verhandlungsprozess lassen sich die folgenden Empfehlungen ableiten:

- Wenn die Vertragsparteien in ihren **zweijährlichen Transparenzberichten** auch über die Umsetzung von NbS berichten, kann dies als Grundlage für technische Diskussionen zur Verbesserung der Methoden und Indikatoren dienen, um zu bewerten, wie NbS zur Erreichung der NDCs beitragen, und Ressourcen zu mobilisieren, um die Entwicklung besserer Strategien zur Verbesserung und Förderung ihrer Umsetzung zu unterstützen.

- Die **Einbeziehung von NbS in marktbasierten Mechanismen birgt Risiken** im Zusammenhang mit der Unsicherheit bei der Festlegung von Baselines, der Überwachung von Kohlenstoffbestandsveränderungen, der fehlenden Dauerhaftigkeit der erzielten Minderungsmaßnahmen und den sozialen und ökologischen Garantien. Bei der Umsetzung von kooperativen Ansätzen unter Artikel 6 des Übereinkommens von Paris müssen diese Risiken berücksichtigt werden. Insbesondere müssen förderfähige Aktivitäten sorgfältig gestaltet werden, um das Risiko zu verringern, dass erzielte Minderungsergebnisse wieder aufgehoben werden. Ein umsichtiger politischer Ansatz wäre es, den internationalen Handel mit Zertifikaten nur für solche Tätigkeiten zu verwenden, bei denen die Wahrscheinlichkeit der Zusätzlichkeit hoch ist und für die die Referenzszenarien mit angemessener Sicherheit geschätzt werden können.

- Im Rahmen der UNFCCC-Verhandlungen sollte jenen Arten von NbS mehr Aufmerksamkeit geschenkt werden, die zwar weniger verbreitet sind, aber einen erheblichen Nutzen für die Menschen und die Erhaltung von Ökosystemen wie Küsten- und Meereslebensräumen haben. Bei der Entwicklung von Verfahren oder Unterstützungsregelungen zur Förderung von NbS im Rahmen des UNFCCC-Prozesses muss besonders darauf geachtet werden, dass **soziale und ökologische Schutzmaßnahmen** eingeführt werden. Während der Warschauer Rahmen für REDD+ ausdrücklich die Erhaltung der biologischen Vielfalt und die Achtung der Rechte indigener Völker und lokaler Gemeinschaften vorschreibt, sind die Leitlinien für solche Schutzmaßnahmen für andere Arten von NbS-Maßnahmen unter der UNFCCC zu vage. Fortschritte im Bereich der Schutzmaßnahmen für NbS wurden beispielsweise im Rahmen des CBD-Übereinkommens (Ökosystemansatz; Grundsätze und Schutzmaßnahmen für ökosystembasierte Ansätze zur Anpassung an den Klimawandel und zur Verringerung des Katastrophenrisikos) oder des Globalen Standards der IUCN für NbS erzielt, auf denen der UNFCCC-Prozess weiter aufbauen kann.

- Eine **integrierte Sichtweise** auf NbS ist notwendig, da sie als Maßnahmen zur Verbesserung des Klimaschutzes und der Klimaanpassung sowie der Erhaltung der biologischen Vielfalt verstanden werden müssen. Kohärenz mit anderen laufenden Arbeiten im Rahmen des UNFCCC (z. B. KJWA, Nairobi Arbeitsprogramm, Ständiger Finanzausschuss) und eine enge Zusammenarbeit mit den Arbeiten im Rahmen der anderen Rio-Konventionen, insbesondere der CBD, sind erforderlich, um Synergien zu fördern. Zu diesem Zweck wäre es von Vorteil, gemeinsame oder zumindest angeglichene Konzepte und Indikatoren für die Berichterstattung und Verfolgung von NbS-Aktivitäten für diese verschiedenen Prozesse zu erarbeiten, z.B. im Rahmen von Initiativen wie der MEA DaRT[2].

Die Nutzung von NbS für die langfristige Kohlenstoffspeicherung kann nur dann erfolgreich sein, wenn das **Senkenpotenzial** von Wäldern, Feuchtgebieten und Böden durch eine nachhaltige Landnutzung **erhalten bleibt** und bestehende Kohlenstoffvorräte geschützt werden. Synergien zwischen Schutz- und Nutzungszielen können realisiert werden, **wenn Klimaschutz, Biodiversitätserhalt und Klimaanpassung zusammen gedacht werden.**

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[2] Siehe https://dart.informea.org/.

1 Introduction

Improved sustainable management, protection and restoration of the world's diverse ecosystems are increasingly recognised as powerful tools for climate change mitigation (IUCN 2016a). The recognition that nature can contribute to addressing and solving societal challenges, including the climate crisis, is referred to as "Nature-based Solutions" (NbS). NbS imply reliance on natural ecosystems and delivery of environmental and social benefits. Although the term 'NbS' is widely used, there is still no common understanding of NbS in the scientific and political debate. Given the prolific use of the term, a definition with clear standards and criteria is needed in order to avoid potential trade-offs and greenwashing of measures which might not entail NbS in a strict sense.

Moreover, various studies provide estimates of mitigation potentials of NbS or land use measures in a broader sense on a global, regional or ecosystem-specific scale. To evaluate these potentials the underlying assumptions of the studies have to be critically assessed. Also, there are methodological differences in the assessment of mitigation potentials which lead to considerably different estimates in these studies. It is crucial to critically assess the mitigation potential associated with NbS in order not to rely on an overly optimistic assessment of their role as a climate mitigation option. Firstly, the measures covered in given potentials might not adhere to strict criteria for NbS, therefore entailing social or environmental drawbacks. Secondly, methodologies for quantifying the potential of NbS imply significant uncertainties and rely on a number of assumptions, so that conservative estimates might be the more realistic ones. Additionally, relying on the notion that NbS bear large mitigation potentials which could be used to counterbalance GHG emissions might divert attention from putting all possible effort into decarbonising economies (Seddon et al. 2021).

Against this background, this paper critically assesses the global mitigation potential of NbS as provided in existing literature and to derive recommendations for international climate policy. To do so, it first compares and evaluates different understandings of NbS and summarises a definition based on IUCN (2016) to inform the scope of this study (Chapter 2). Chapter 3 compares and critically reviews relevant studies that provide estimates of the mitigation potential of NbS in order to get a sound understanding of a plausible contribution of NbS towards long-term climate targets. Additionally, Chapter 4 analyses the role of NbS in international climate policy, focusing on the UNFCCC context. On the basis of these analyses, Chapter 5 provides conclusions and recommendations for future treatment of NbS in the UNFCCC process.

2 Definition of Nature-based Solutions

'Nature-based Solutions' (NbS) is an umbrella concept encompassing a variety of established approaches stemming from different sectoral and geographic backgrounds across policy, practice and academia and established in their respective sectors, such as e.g. ecosystem-based adaptation and mitigation, green and blue infrastructure or ecological restoration (Seddon et al. 2020; Pauleit et al. 2017; Nesshöver et al. 2017; IUCN 2016a; EEA 2021). The term itself indicates that through a provision of ecosystem services nature can provide solutions to societal challenges such as climate mitigation and adaptation, air quality, public health and well-being, water management or disaster risk reduction. Most established definitions highlight the aspect of multifunctionality, specifying that NbS should address specific social and environmental challenges, while also producing wider co-benefits.

The first publication on NbS from the World Bank (2008) did not define the term but made the case that the sustainable use of natural ecosystems was critical to fulfilling the World Bank's mission of alleviating poverty and supporting sustainable development. The publication also underlined that the sound management of ecosystems provides society with multiple benefits and opportunities (Sobrevila et al. 2008).

Two widely used definitions of NbS stem from the International Union for Conservation of Nature (IUCN 2016a) and the European Commission (EC 2015; 2020) (see Table 1). The EC's publication introducing NbS emphasised their relevance in urban areas and framed NbS in the context of green growth (EC 2015). The IUCN subsequently released a Global Standard for NbS, providing clear parameters for defining NbS and a common framework to help benchmark progress (IUCN 2020). More recently, the Nature-based Solutions Initiative, a consortium of conservation and development organisations and research institutions led by the University of Oxford created a set of NbS guidelines for successful, sustainable nature-based solutions in the context of climate change mitigation that were submitted to the UK COP presidency (Seddon et al. 2021). NbS principles were also proposed by WWF (WWF 2020). Other sources consulted for this study (e.g. Albert et al. 2017; Balian et al. 2014; Chausson et al. 2020; EC 2017; IIED 2018; IPCC 2019b; Maes and Jacobs 2017; Nature-based Solutions Initiative 2021; WWF 2020; UNEP 2021) either directly use one of these definitions or a variant thereof, building on similar terms and elements. Although the other definitions are not listed here, specific elements of relevance are discussed in Sections 2.1.1 and 2.1.2.

Table 1: Definitions of NbS

Source	Definition
IUCN (2016b)	NbS are defined by IUCN as actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g. climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits.
European Commission (2015)	NbS aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions, e.g. mimicking how non-human organisms and communities cope with environmental extremes. NbS use the features and complex system processes of nature, such as its ability to store carbon and regulate water flow, in order to achieve desired outcomes, like reduced disaster risk, improved human well-being and socially inclusive green growth. Maintaining and enhancing natural capital, therefore, is of crucial importance, as it forms the basis for

Source	Definition
	implementing solutions. These NbS ideally are energy- and resource-efficient, and resilient to change, but to be successful they must be adapted to local conditions.
European Commission (2020)	NbS to societal challenges are solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions. NbS must benefit biodiversity and support the delivery of a range of ecosystem services.

Source: International Union for Conservation of Nature (2016b); European Commission (2015; 2020)

Climate change is among the societal challenges that can be addressed with NbS which has increasingly been recognised by major international scientific bodies and governments. NbS have been highlighted in e.g. the Global Commission on Adaptation Report and the three IPCC Special Reports published since 2018. Also in the context of the UNFCCC process, NbS are playing an increasing role (see Chapter 4).

This increased interest in NbS for climate mitigation highlights the importance of clearly defining NbS and ensuring individual interventions fulfil shared basic standards and criteria. For example, the 2019 "Nature-based Solutions for Climate Manifesto" supported by 70 governments, made calls to scale-up NbS for mitigation and mainstream NbS within climate policy-related instruments, and collected nearly 200 initiatives and best practices of NbS (Nature-based Solutions (NBS) Facilitation Team 2019; UNEP 2020; NbS for Climate Coalition 2020) – yet without ever defining what NbS actually are, or providing any qualifying criteria for NbS.

Under carbon market approaches, the term NbS is often used rather specifically, e.g. as a synonym for mitigation activities in the land use sector or to achieve a price premium, when selling certificates for mitigation outcomes. Business-driven initiatives often convey the notion that there exists a solution to climate change and there is no need to decarbonise economies and curtail the use of fossil fuels (see e.g. the Natural Climate Solutions initiative[3] by IETA or Shell's communication on NbS).[4]

While 'NbS for climate change mitigation' are increasingly cited as such, there is a number of related, more narrow terms used in climate discussions. Some of these are defined based on the intended outcome (e.g. ecosystem-based mitigation, natural climate solutions, sustainable climate action), while others highlight the specific actions involved (ecological restoration, green and blue infrastructure). These terms and approaches share a common focus on enhancing the provisioning of ecosystem services as a means to address societal challenges and build on the understanding of the key roles that ecosystems play in supporting human well-being and safety (EEA 2021).

2.1 Core elements of the NbS definition

This section discusses key defining characteristics of NbS as considered in existing definitions in order to arrive at a working definition of NbS. The definition in Section 2.1.1 clearly distinguishes between measures that do and do not constitute NbS, despite their use of nature or

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[3] https://ncs.ieta.org/

[4] https://www.shell.com/energy-and-innovation/new-energies/nature-based-solutions.html#iframe=L3dlYmFwcHMvMjAxOV9uYXR1cmVfYmFzZWRfc29sdXRpb25zL3VwZGF0ZS8

working with natural processes. Section 2.1.2 discusses characteristics of NbS that are included in some of the existing NbS definitions, but were excluded in the working definition created for this study.

2.1.1 Defining characteristics of NbS

The core element of the NbS definition is a specification of the term “nature-based”. This refers to measures which are **aligned with natural ecosystems**. NbS are different from other measures that may use natural processes but which lack alignment with natural ecosystem processes and functions, require an ongoing and significant human intervention using engineered structures, ongoing provision of energy or water, or lead to soil sealing, ecosystem destruction, exploitation or harmful effects to biodiversity. NbS are differentiated from solutions that are *nature-derived,* i.e. which come from the natural world, but which are not directly based on functioning ecosystems (e.g. wind and solar energy) and solutions that are *inspired by nature* or modelled on biological processes (e.g. biomimicry), but which are not based on functioning ecosystems’ ability to provide natural services either (IUCN 2021a).

In the context of climate change mitigation, “nature-based” refers to measures that **use natural ecosystem processes** such as CO_2 uptake by photosynthesis and biomass build-up which can be used in a diverse cascade by different organisms of the specific ecosystem. The focus of NbS is on the protection, restoration, sustainable management or creation of ecosystems to build on their capacity for self-regulation, renewal, nutrient cycling and provision of various services (IUCN 2016b). At the same time, it is important to bear in mind that nearly all NbS measures include some degree of design or alteration of existing ecosystems, such as selecting certain species or prioritising a given ecosystem service over another, depending on the primary societal challenge to be addressed by the intervention (Nesshöver et al. 2017). Moreover, NbS can be used together with other measures to form so-called “hybrid solutions” that combine elements of grey infrastructure with natural elements, e.g. Sustainable Urban Drainage Systems. NbS include working with a variety of ecosystems, including modified or novel ecosystems in urban areas.

Second, an important element distinguishing NbS from other solutions that use nature or natural processes is **the explicit expectation that NbS provide benefits to biodiversity** through enhancement of diverse ecosystem functions, ecosystem resilience and ecosystem health or protection or enhancement of species richness in a given ecosystem, or ecosystem richness in a given area. While not all climate NbS may realise the full potential of biodiversity benefits, positive contributions distinguish NbS from “actions that exploit nature to address societal challenges, but which create trade-offs and can damage biodiversity in doing so”, e.g. BECCS or commercial monoculture plantations that can disrupt natural ecosystem processes, remove or fragment habitats or directly harm habitats and species (Seddon et al. 2021). This stance is in line with both the IUCN (2021a) and the EC (2020) definitions of NbS.

Long-term planning, **preparing for change and maintaining natural adaptability** in the context of NbS are further critical considerations (Nesshöver et al. 2017). This criterion is elaborated in the IUCN’s Global Standard: NbS implementation plans should consider the uncertainty inherent to ecosystem management, given their complex, dynamic and self-organising nature and consequently enable adaptive management “to effectively harness ecosystem resilience” to be able to “respond to unanticipated social, economic or climate events” with a wider range of options. Such adaptive management should result in a greater resilience and adaptive capacity of ecosystems (IUCN 2021a). The synergies of climate adaptation and NbS are also specifically included in the definition of “NbS for climate change” proposed by the WWF. They indicate that NbS for climate change “have human development and biodiversity co-benefits managing anticipated climate risks to nature that can undermine their long-term effectiveness” (WWF 2020). The EC definition indicates that NbS should “help build resilience” (EC 2020).

Another element is the need for NbS to be locally adapted (EC 2020) or **locally appropriate** (UNEP 2021), suggesting e.g. the use of native species and consideration of economic and social local conditions as well as tradition and culture. This is an important consideration in the context of NbS for climate mitigation, given the emphasis on tree planting as a way to increase carbon sinks. Not every afforestation or tree-planting project qualifies as NbS. For example, evidence shows that plantations involving fast-growing non-native species can introduce new pests and diseases or themselves become invasive and monoculture plantations harm biodiversity (Seddon et al. 2020) (see also Section 3.2.1).

Moreover, the NbS concept represents a paradigm shift in ecosystem management, shifting away from single-objective management (e.g. separating conservation from water issues) and focusing on solutions that are **multifunctional** (i.e. providing numerous (co-)benefits in parallel for human beings and the environment) (Nesshöver et al. 2017). Furthermore, this delineates NbS from interventions such as BECCS, which do not generate additional ecosystem services (IUCN; Oxford University 2019). The multifunctionality aspect also differentiates NbS from Natural Climate Solutions. The two terms are sometimes used interchangeably but have a different meaning: Natural Climate Solutions is a narrower concept, focusing on only one objective (climate mitigation), although pointing to the associated co-benefits (Osaka et al. 2021).

Finally, the explicit focus of NbS to **address societal challenges** distinguishes NbS from traditional conservation activities focused on e.g. the protection of individual species, without considering how they address societal challenges. According to the EC (2020) definition, NbS should simultaneously provide environmental, social and economic benefits. IUCN uses a more open framing, indicating that NbS should provide human well-being and biodiversity benefits while addressing societal challenges. We propose to use the IUCN framing of ‘human well-being’ due to the fact that traditional concepts of economic benefits and their measurement in monetary terms do not appropriately take into account natural capital or costs of biodiversity loss. The inclusion of economic benefits as a prerequisite could also put undue emphasis on generating short-term economic benefits at the cost of a long-term delivery of a full range of ecosystem services or an emphasis on functions quantifiable in monetary terms compared to functions for which this is difficult (see also IUCN 2016a). The reference to economic benefits would also require a more standardised methodological framework related to the measurement of economic benefits of ecosystems which is not yet widely implemented. The concept of ‘human well-being’ includes economic aspects, but in a more holistic and qualitative way, avoiding such potential bias arising from quantification methodologies.

Table 2 summarises the arguments presented in this section, comparing key characteristics of NbS versus measures that may use nature or natural processes but do not meet the criteria outlined above and are therefore not qualified as NbS in light of scientific discourse.

Based on the **existing definitions**, in particular the IUCN (2016) definition and following the previous arguments as well as the resulting delineation between NbS and non-NbS, we **derive** the following **working definition of NbS.** It comprises the key elements of the existing definitions, that we believe to be important to inform the scope of this study, as outlined above:

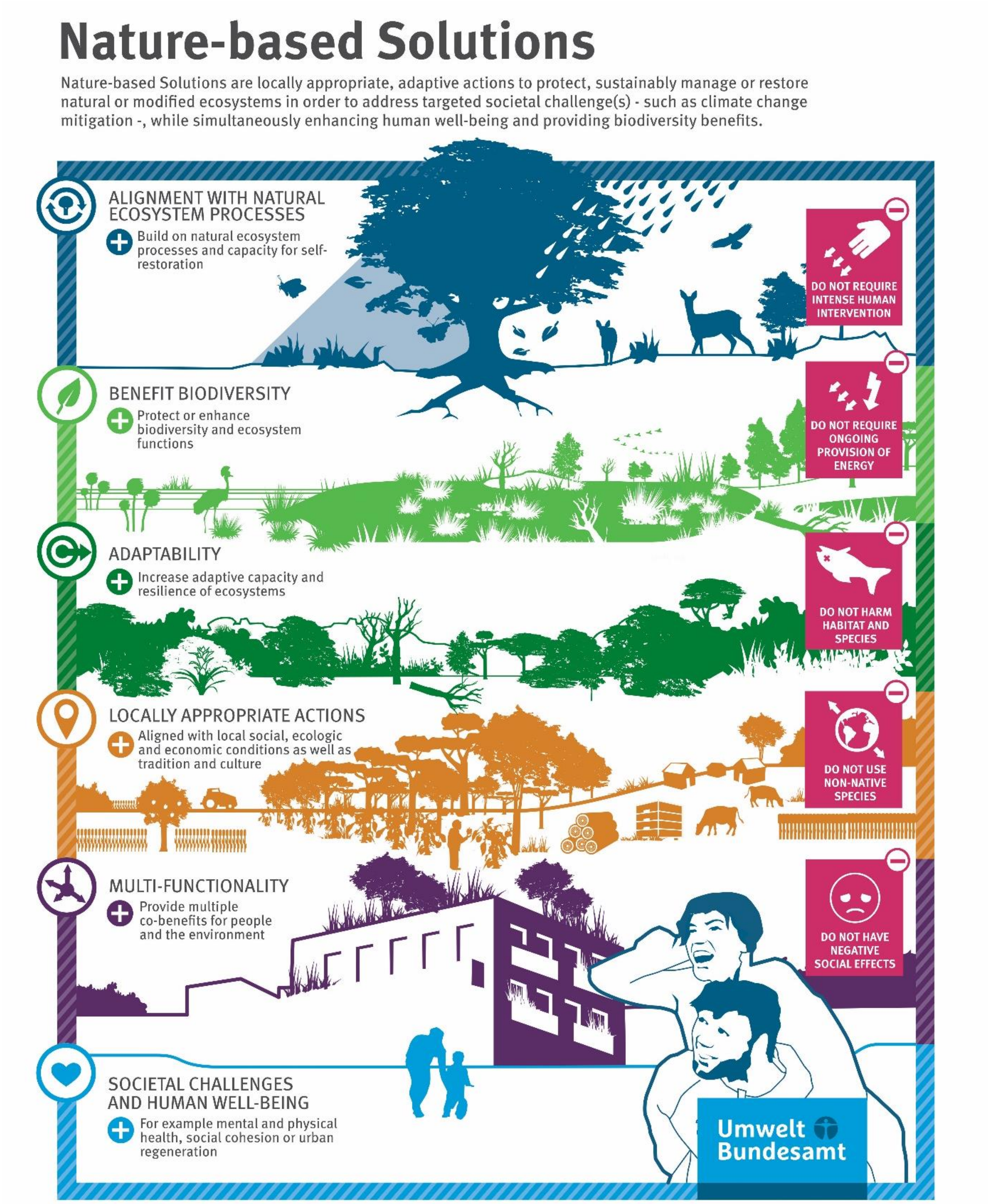
Nature-based Solutions are locally appropriate, adaptive actions to protect, sustainably manage or restore natural or modified ecosystems in order to address targeted societal challenge(s) - such as climate change mitigation -, while simultaneously enhancing human well-being and providing biodiversity benefits.

Table 2: Defining characteristics of NbS

	NbS	Non-NbS
Alignment with natural ecosystem processes	Use natural ecosystem processes (e.g. CO_2 uptake by photosynthesis and biomass build-up which can be used in a diverse cascade by different organisms of the specific ecosystem); build on ecosystem capacity for self-regulation, renewal, nutrient cycling and the provisioning of various services.	Lacks alignment with natural ecosystem processes; require an ongoing and significant human intervention using engineered structures, ongoing provision of energy or water; lead to soil sealing and ecosystem destruction. May come from natural world or be modelled on biological processes but is not directly based on functioning ecosystems.
Benefit biodiversity	Benefits for biodiversity are achieved by protecting and restoring natural ecosystem processes. They support the adaptive capacity and quality of ecosystems and habitats.	Can damage biodiversity by disrupting natural ecosystem processes, removing or fragmenting habitats or directly harming habitats and species.
Adaptability	Is planned in a manner that supports the natural adaptability of ecosystems.	Does not include considerations of adaptability and ecosystem resilience.
Locally appropriate actions	Consider local economic and social conditions and use native species.	Uses non-native species; does not consider the characteristics, importance and ecological resilience of local ecosystems; is not designed with the local social and economic conditions in mind.
Multi-functional	Provides numerous (co-)benefits in parallel for people and the environment.	Focuses specifically on one objective and/or does not generate additional ecosystem services.
Address societal challenges and enhance human well-being	Provides benefits to human well-being and helps to address societal challenges.	Focuses on conservation, biodiversity or other objectives, without considering how they address societal challenges.

Source: Own compilation, Ecologic Institute.

Figure 1: Graphic illustration of the core elements of Nature-based Solutions



Nature-based Solutions

Nature-based Solutions are locally appropriate, adaptive actions to protect, sustainably manage or restore natural or modified ecosystems in order to address targeted societal challenge(s) - such as climate change mitigation -, while simultaneously enhancing human well-being and providing biodiversity benefits.

Design: Erik Tuckow, sichtagitation.de

2.1.2 Common qualities of NbS

This section discusses two elements that are common to many NbS and are included in some of the existing NbS definitions and explains why these elements were excluded from the working definition created for the purpose of this study.

First of all, the EC definition states that NbS are solutions that are **“cost-effective”** (EC 2020). Cost-effectiveness is seen as a by-product of multifunctionality, with significant long-term (co-) benefits being produced alongside the primary targeted impact. The IUCN Global Standard for NbS requires that they are “economically viable”, i.e. that long-term gains are balanced against short-term costs, with short-term actions developed with a long-term perspective in mind. Sufficient consideration should be given to returns on investment, efficiency, and effectiveness and equity in the distribution of benefits and costs (IUCN 2020). However, a number of challenges are related to assessing cost-effectiveness. While literature on Natural Climate Solutions provides quantified evidence of their cost-effectiveness as a mitigation option (Osaka et al. 2021), assessing cost-effectiveness of the multifunctional NbS is more complex as: (1) many co-benefits are often not accounted for; (2) calculations need to factor in trade-offs between different measures or between stakeholder groups who may have different preferences and therefore perceive the benefits and costs differently; (3) it may be difficult to quantify changes in ecosystem service provisioning over time, not least due to uncertainty regarding future conditions; and (4) it may be challenging to attribute a positive change or benefit to a specific activity. Finally, while NbS might be a more effective solution in the long term, the full scale of the benefits might not be evident while the costs are incurred (IUCN; Oxford University 2019). As a consequence, we argue against including this qualification in the NbS definition – while agreeing with the IUCN’s indication that NbS projects should be appraised to the extent possible to ensure economic viability.

Good governance including the wide variety of stakeholders impacted by or able to impact the delivery and maintenance of NbS is key to their effective implementation and long-term viability (Seddon et al. 2021; Nesshöver et al. 2017). The aspect of governance is considered in a definition proposed by the NbS Initiative of the University of Oxford, stating that NbS should be “designed and implemented with the full engagement and consent of local communities and Indigenous Peoples” (Nature-based Solutions Initiative 2021). Considerations of good governance are also included in the IUCN Global Standard for NbS, which requires that NbS are based on an “inclusive, transparent and empowering governance process” (IUCN 2020). However, while inclusive and transparent governance should be a standard for the design and implementation of NbS, it does not need to form part for the definition itself – as good governance is not something that specifically delineates NbS from other solutions.

2.2 Categorisation of NbS

For the purposes of an assessment and discussion of NbS mitigation potentials in this study, we categorise NbS along three criteria: the ecosystem they are applied in, the type of greenhouse gas (GHG) emission mitigation as well as the type of management change, as shown in Table 3. These NbS are described and qualified further in Chapter 3.

Related to the type of mitigation, we refer to a **reduction of emissions** when the activity that generates emissions is already occurring and when the amount of emissions not released into the atmosphere as a result of an NbS is compared against an existing level of emissions. For example, natural forest management involves decreased harvest intensity which leads to a decrease in emissions. We use the term **avoided emissions** when the emission-generating activity has not yet occurred and when the amount of emissions not released into the atmosphere is calculated against a hypothetical level of future emissions that would have occurred without the intervention (e.g. protecting an existing forest from being degraded or deforested). The **removal of emissions** is an active process where CO_2 is removed from the atmosphere by e.g. photosynthesis and carbon is stored in biomass for long periods.

The third criterion for categorisation distinguishes NbS that require a change in management practices of an existing land use (practice shift), including ecosystem protection, from those that include land use changes (e.g. conversion of agricultural land to forest) or those that prevent a land use change (e.g. avoided grassland conversion).

Table 3: Categorisation of NbS

		Type of GHG emission mitigation			**Management change**	
Natural or modified ecosystem	**NbS**	**Reduction**	**Removal**	**Avoided**	**Practice shift**	**Land use change**
Forests	Reforestation & Afforestation		X		X	X
	Natural forest management	X	X		X	
	Avoided forest conversion			X		X
	Forest protection			X	X	
	Improved plantations	X	X		X	
Croplands	Nutrient management	X			X	
	Agroforestry/ Trees in croplands/ Alley cropping		X		X	X
	Improved manure management	X			X	
	Conservation agriculture	X			X	
	Cover crops	X	X		X	
	Improved rice cultivation	X			X	
Grasslands	Grazing optimisation	X	X		X	
	Legumes in pastures	X	X		X	
	Grassland restoration		X		X	X
	Avoided grassland conversion			X		X
Terrestrial wetlands	Peatland restoration	X	(X)[+]	X	X	X
	Peatland protection		(X)[+]	X	X	

		Type of GHG emission mitigation			Management change	
	Avoided degradation/conversion of peatlands			X		X
Coastal wetlands	Coastal wetland restoration	X	X		X	X
	Coastal wetland protection		X	X	X	
	Avoided degradation/conversion of coastal wetlands			X		X
Settlements	Urban greening		X		X	X

Source: Own compilation, Öko-Institut, with selection of NbS pathways based on Griscom et al. (2017) and Roe et al. (2019).
Notes: NbS are categorised according to ecosystems and the type of mitigation effect they have on greenhouse gas emissions as well as the change in management they imply.

[+] Removals by peatlands are very slow and long-term compared to other ecosystems like forests and are therefore not the main benefit of this measure.

Biochar as NbS?

In simple terms, biochar is charcoal that is incorporated into soils. To produce biochar, biomass is heated in the absence of oxygen (pyrolysis) or under controlled low-oxygen conditions (gasification). Sources of the biomass can be wood, organic waste or other natural feedstocks. Biochar is traditionally used in some regions, e.g. in Thai traditional kiln biochar from Eucalyptus (Ding et al. 2016). The key assumption is that biochar persists for hundreds or thousands of years (under right conditions), thus storing carbon that would otherwise decompose.

Various **benefits of biochar** are discussed in the literature: Many studies evaluate nutrient (N, P and K) availability from biochar and related higher crop yields. However, the findings of several studies have not been tested in field experiments (Ding et al. 2016). Jones et al. (2012) demonstrated that biochar had no effect on the growth of maize but increases growth of a subsequent grass crop. Effects on crop yields were related to the biomass source of the biochar, pyrolysis temperature and soil type. Some research indicates that biochar reduced N_2O emissions from different soils to a large extent, however some studies found no such effect or even increase of N_2O emissions after biochar application (Ding et al. 2016). Ding et al. (2016) conclude that the effect on N_2O emissions could be dependent on biochar pyrolysis temperature, soil types, fertiliser doses and types, and soil water contents. Additionally, biochar has been found to increase microbial abundance in soils, change microbial composition and activity. But it can also have negative effects on microbial community due to harmful components (e.g. phenolic and polyphenolic substances, see below) (Ding et al. 2016). Moreover, biochar has been found to improve physical soil qualities and water holding capacities, but it is unclear whether these effects can be maintained over longer periods or whether they only occur immediately after biochar application. Overall, most laboratory and field studies were focused on the short-term effects of biochar on soil properties and few studies have conducted long-term experiments (Ding et al 2016). Large-scale industrial pyrolysis plants have not been built so far (Schmidt and Hagemann 2021) and costs for large-scale production infrastructure are not accounted for in the literature.

The IPCC indicates a global mitigation potential of biochar of 0.03-4.9 $GtCO_2e/yr$ by 2050 and up to 6.6 $GtCO_2e/yr$ if energy substitution is included (Jia et al. 2019). According to Lal et al. (2018), biochar bears sequestration potentials of 1.6-3.5 $GtCO_2e$/yr. Griscom et al. (2017) estimate that biochar could deliver 1.1 $GtCO_2e$/yr of carbon removals by 2030, if approx. 80% of biochar carbon remains stored for more than 100 years and assuming that there is no impact on methane or nitrous oxide emissions. Studies giving higher sequestration potentials of biochar assume that all crop residues globally are used for the production and subsequent burial of biochar (e.g. Lenton 2014).

However, such assumptions on the availability of biomass are not realistic due to a high competition regarding the use of biomass for different purposes. **The availability of excess feedstock biomass is limited** for the production of biochar, leading to a lower “sustainable” global potential of 0.3-2.0 $GtCO_2e$/yr in 2050 (Fuss et al. 2018; a similar order of magnitude is provided in Minx et al. 2018 and Hepburn et al. 2019). If biomass is removed from cropland areas for the production of charcoal/biochar, biomass inputs to soils will be missing for the formation of soil organic carbon which will reduce soil fertility. Biochar will also compete with biomass needs for bio-based products or for biomass as an energy source. Additionally, biochar needs large land areas for the production of biomass to produce charcoal. This adds to the competition for land. A **broader lifecycle assessment is therefore necessary** in order to determine the overall mitigation effect of biochar as an exogenous carbon input. It will depend on where and how the offsite biomass is removed, how it is transported and processed, what their alternative end use would be (burning, adding to landfill or left in place as residues), how it interacts with other soil GHG-producing processes and the condition of the soil to which the inputs are added (Paustian et al. 2016; Minasny et al. 2017; National Academies of Sciences, Engineering, and Medicine 2018).

Additionally, the **precise interactions of biochar with soils are uncertain** (Smith 2016; Tammeorg et al. 2016). For example, in a study conducted by Budai et al. (2016), high temperature-produced biochar with a half-life 60 times higher than the parent material, enhanced the positive priming (increased mineralisation rate) of soil organic carbon (SOC), causing changes in the composition of bacterial and fungal communities due to increase in pH levels (see also Paustian 2016). Also, pollutants can be introduced into the soil by the pyrolysis of waste products (UBA 2016) and biochar application can also release black carbon aerosols which diminish air quality (Ravi et al. 2016). Biochar might change the albedo of soils when applied to large areas, which can lead to an increase in soil temperature and therefore loss of SOC. Hence, according to Bozzi et al. (2015) the biochar mitigation potential might be reduced by up to ~30%. Also, **experience with large-scale production and use of biochar is still missing** and “feasibility, long-term mitigation potentials, side-effects and trade-offs therefore remain largely unknown” (Fuss et al. 2018, p. 26).

The uncertain effects of biochar on biodiversity and ecosystem functions (UBA 2016) raise the question whether it can be considered an NbS according to the definition set in this paper. Especially the differing effects of the amount and duration of biochar application to soil microbial diversity mainly due to changes in altered soil pH (Jiang et al. 2016; Budai et al. 2016; Hardy et al. 2019) raise doubts about positive effects on biodiversity. Additionally, the production of biochar requires the provision of external energy input. For these reasons, and even though it is often listed as an example of NbS (e.g. Griscom et al. 2017; Bossio et al. 2020; Fargione et al. 2018), **biochar should not be considered an NbS in the view of the authors** (see NbS requirements in Table 2).

3 Assessment of the global potential of Nature-based Solutions

Few studies have estimated the global mitigation potentials which could be achieved through NbS measures and measures in the land sector. Two studies stand out in terms of comprehensiveness and visibility. Griscom et al. (2017) have estimated that NbS (or "natural climate solutions") could deliver 37% of the necessary cost-effective CO_2 mitigation potential 2030 (23.8 $GtCO_2$ e/yr) and 20% by 2050. The highest potentials in the study are associated with forest-related measures such as reforestation and avoiding conversion of forest to other land uses. Moreover, establishing agroforestry systems and avoiding conversion of wetlands have a high climate change mitigation effect. Other global studies by Roe et al. (2019, 2021) use mainly results by Griscom et al. (2017, 2020) for measures in agriculture, forestry andwetlands as well as some additional studies on specific measures (e.g. Pendleton et al. 2012; Humpenöder et al. 2020; Paustian et al. 2016). Beside measures in the land sector, Roe et al. (2019) take into account the effects of bioenergy, BECCS and consumption behaviour (e.g. reducing food waste). They conclude that all of these measures could contribute up to 30% (15 $GtCO_2$ e/yr) of global GHG mitigation required until 2050 to reach the 1.5 °C target.

While these studies suggest that there is significant mitigation potential associated with NbS, there is an ongoing debate around how much NbS can realistically contribute to climate change mitigation because the potential estimates very much depend on time frames, considered land availability and other assumptions (Girardin et al. 2021). This means single estimates cannot be easily compared with each other, but rather need to be interpreted in the light of their differing assumptions and methods.

This chapter critically reviews a number of prominent studies on measures associated with NbS in terrestrial (forests, croplands, grasslands, wetlands) and marine (coastal wetlands) ecosystems as well as settlements regarding their estimated mitigation potentials, applied methodologies and assumptions in order to develop a better understanding of the potential and limits of NbS measures as a mitigation strategy.

Potentials provided in the literature comprise measures which do not necessarily meet the definition of NbS developed in Chapter 2 because they do not consider or specify ecological and social constraints. Therefore, important ecological and social requirements were formulated for each ecosystem considered to assess whether the considered measures qualify for NbS.

3.1 Methodological approach

In a first step, the ecosystems were briefly introduced with respect to their role for the climate system, biodiversity protection and other ecological services. Also, the current drivers of destruction and degradation from land or marine resource use were highlighted. Finally, measures were defined which qualify as NbS and specifically address climate mitigation.

In a second step, a summary of global mitigation potentials was compiled for each ecosystem based on a literature review, drawing on studies published after 2010 to include most recent methodological approaches. Another selection criterion was that measures are comparable regarding target and approach, especially in view of the study by Griscom et al. (2017) as the most comprehensive and most frequently cited study on NbS mitigation potential. In some cases, regional studies were included in the assessment of global potentials in order to better evaluate the specific potential (mitigation potential per area unit).

These studies were assessed and compared with regard to the following aspects:

- **Scope:** The scope of the study determines which GHGs have been covered, which carbon pools have been addressed, and which time frame has been set. The potential and conditions for the implementation of measures can differ with **biogeographical regions**, which can be divided into e.g. boreal, temperate, subtropical, tropical regions. The scope also includes the different **type of mitigation measures**, i.e. GHG emission reductions, CO_2 removal and/or avoided GHG emissions (see Section 2.2 above). Moreover, the scope includes the **type of management change** that can be either a practice shift within one land use or a land use change. Finally, the **alignment** of the conceptualisation of mitigation measures in the studies **with the definition of NbS** developed in this paper is assessed.
- Range of **total as well as specific mitigation potential:** The mitigation potential is expressed in absolute terms, e.g. as $MtCO_2e$ per year but can also be related to the area on which it is implemented (specific potential), e.g. as tCO_2e per ha and year.
- **Approaches towards quantification of potential**: Which approach is used to estimate the mitigation potential? The assessment can be top-down, e.g. using global simulation models or bottom-up, e.g. based on empirical data, project information and statistics. Is the input data geographically specific or unspecific? Are ecological processes explicitly modelled (e.g. tree growth) or does the study apply default values and generic assumptions? Quantifying the mitigation potential of NbS also requires **assumptions on the baseline** development. For measures related to afforestation and reforestation, the baseline typically assumes the original land use and can therefore be set easily and transparently, e.g. using historic data. Baseline setting for measures of avoided land conversion is more complex, as it needs to assume an expected future rate of carbon stock depletion. Baseline setting can considerably affect the mitigation potential, especially for the latter type of measures. Baseline setting is also used for assessing whether activities are additional to a country's emissions development path. In this context, baselines determine whether mitigation measures can be considered as ambitious. Additionality also plays a role in the funding of mitigation measures, e.g. through results-based finance.
- **Assumptions regarding safeguards and co-benefits:** The implementation of NbS to achieve mitigation outcomes might imply other negative environmental or social effects, e.g. regarding biodiversity, food security, land tenure. The assessment evaluates to what extent safeguards are taken into account as constraints in the calculation of potentials. A focus will be put on biodiversity implications. At the same time, mitigation measures can also have **co-benefits** for other environmental and social goals. Co-benefits form an essential element of the definition of NbS (see Section 2.1.1).
- **Assumptions on costs**: Do the studies assess technical or economic potentials? Which types of costs of measures are assumed to achieve the given potential? Which assumptions are made with regard to the development of CO_2 prices and opportunity costs?
- **Constraints and uncertainties**: Studies need to make assumptions and simplifications that limit their results, e.g. in terms of generalisability. Moreover, the approach taken, and the underlying data used determine the level of uncertainty associated with estimates. The question is whether and how uncertainties have been estimated and communicated regarding the mitigation potential, including the type of uncertainties that are associated with the estimation of potentials for different measures. Constraints can also include assumptions on how **interactions with the climate system** have been considered. The question is whether the studies take effects of climate change on ecosystems or other

climatic effects of e. g. vegetation changes into account. Such impacts can have positive or negative effects on the mitigation potential.

3.2 Assessment of potentials for different ecosystems

3.2.1 Forests

State of the ecosystem and measures for NbS

Globally, forests cover about 4,000 Mha (Harris et al. 2021) comprising important reservoirs that store carbon in living and dead biomass, forest soil and harvested wood products but also regulating water cycles, filtering the air, providing habitat to a large diversity of species and being an essential source for human well-being. Between 2001 and 2019 global forests removed carbon of about -15.6 $GtCO_2e$/yr from the atmosphere but deforestation and forest disturbances resulted in global gross GHG emissions of about 8 $GtCO_2e$/yr, mainly occurring in rainforests of South America and Southeast Asia due to commodity-driven deforestation (~3 $GtCO_2e$/yr, Harris et al. 2021).

Through different measures, NbS targeting forests can contribute to **avoiding GHG emissions** and **increasing removals of CO_2**. **Reforestation** and **afforestation** activities introduce trees on areas without or only sparse tree cover in order to increase CO_2 removals compared to the previous land use (e.g. agricultural land). Tree planting is a very popular activity which also gains a lot of public attention but also raises a lot of concerns (Seddon et al. 2021), which are further discussed below. **Forest protection** measures instead aim at avoiding potential emissions from forest conversion or forest degradation. **Forest management** for climate mitigation mainly addresses an increase in living and dead biomass as well as soil carbon through better management. Hence, harvesting cycles can be adjusted. Also, selective harvesting and a minimum diameter per tree species could be introduced to ensure forest reproduction. Forest soil protection can be addressed by applying a minimally invasive harvesting strategy (WBGU 2020). Furthermore, to comply with biodiversity needs, the diversity of site native tree species and natural tree age class distribution should be secured. Also, natural successional states of the forests should be represented in managed forests to maintain habitat structures.

Harvested wood products cannot remove CO_2 from the atmosphere but retain carbon from being emitted after biomass harvest. Therefore, the extension of lifetime of harvested wood products is also considered a measure to reduce emissions, although these measures extend to activities required beyond ecosystem boundaries. Hence, prolonging the use of harvested wood products is not considered as an NbS because it has no direct benefits for biodiversity. Also, mitigation options involving harvested wood products are independent from ecosystem processes once they have been extracted from the ecosystem. But they are a very important co-benefit for people managing forests.

Forests deliver significant co-benefits, including ecosystem and biodiversity preservation, reduction of flooding, erosion, eutrophication as well as enhanced water quality and quantity (Nabuurs et al. 2007). Therefore, measures to preserve forests or extend their coverage are typically associated with these positive trade-offs. However, similarly to other land use changes, afforestation and reforestation can significantly affect provision of goods from the land to be afforested, including biodiversity services (e.g. in the case of afforestation of grassland), food and feed supply (e.g. in the case of afforestation of agricultural land) and thus increase competition for land. Previous land use is therefore an important factor for assessing the **risk of leakage** that occurs if the supply of goods is negatively affected and production is displaced to other areas with potential negative effects. NbS involving afforestation can reduce negative impacts by constraining activities to **unused land**, bearing in mind that the definition of such lands can be challenging. Changes in forest management do not constitute a land use change and thus bear lower risks of leakage and negative trade-offs. However, measures leading to a reduction of timber and biomass supply can indirectly affect other areas through trade if not accompanied with demand-side measures, e.g. for improved efficiency and reduced consumption of wood.

NbS related to forests may include **changes of tree species composition**. If such activities lead to the dominance of one species (e.g. monocultures) and reduction of ecosystem structure (e.g. even-aged forests) they could negatively affect biodiversity and would thus not comply with the definition of NbS. This applies to forest restoration and afforestation as well as to forest management activities. For example, evidence shows that plantations involving fast-growing non-native species can introduce new pests and diseases or themselves become invasive. Monoculture plantations harm biodiversity and negatively affect ecosystem resilience (Seddon et al., 2019). Another example is afforestation of fire-adapted savannah and dryland grassland ecosystems in which increased levels of biomass can lead to changes in the fire regime towards hotter fires and associated higher carbon losses (Bennett and Kruger 2015).

Establishing resilient and healthy tree stands that secure the delivery of co-benefits of forests to establish a complex system of interactions among ecosystem elements, requires careful management over decades (Seddon et al. 2021, p. 1529). This holds especially for sensitive ecosystems, such as mangroves that require particular conditions of soil, climate, and tidal conditions (Singh 2006; Thivakaran et al. 2016) but also those established as commercial plantations with a dedicated focus on economic (and thus rather short-term) objectives.

Forests, like other ecosystems, will be affected by future climate change. As regeneration cycles and natural dynamics are rather slow and long-term, rapid changes of environmental conditions will put forest ecosystems under pressure. Expected changes are altered species ranges and changes in forest communities (Grimm et al. 2013; Lindner et al. 2014; Nolan et al. 2018), increased role (severity and frequency) of natural disturbances (Seidl and Rammer 2017; Seidl et al. 2014). NbS in forests need to support the **natural adaptability** of forests and increase resilience by maintaining natural diversity of species and genotypes as well as protect ecosystem processes like succession and nutrient cycling.

Potentials of NbS, constraints and uncertainties

Reducing deforestation and forest degradation have the second largest mitigation potential among forest-related NbS but also the most variable estimates, ranging from 0.4 to 8.6 $GtCO_2e$ annually (IPCC 2019b, p. 49). The large variability of estimates is due to underlying assumptions of future developments of deforestation and degradation and their drivers that form the basis for estimating what could potentially be avoided. This includes assumptions on the alternative land use and its opportunity costs but also on geographical information, e.g. fragmentation of forests. Additionally, the potential for avoiding emissions from deforestation and degradation depends on the type of forest to be protected from conversion or exploitation (i.e. its carbon content). Zarin et al (2016) assessed that halving tropical deforestation emissions from historically (2001-2011) 2.27 $GtCO_2e$ annually to 1.135 $GtCO_2e$ per year within only five years could potentially be achieved under favourable conditions. These include a shift of economic development in forest-rich countries away from a natural resource depletion towards acknowledging and making (non-destructive) use of the goods and services that tropical forests provide (Zarin et al. 2016). Griscom et al. (2017) estimate avoided emissions of 3.6 Gt $GtCO_2e$/year due to avoided forest conversion, mainly in the tropical and sub-tropical climate zone. Due to a lack of information on the future development of drivers of deforestation and degradation, studies base their potential estimates on approximate baselines. These can be historic rates (Zarin et al. 2016) or projections of drivers, costs and associated emissions (Kindermann et al. 2008; Center for Global Development 2015; d'Annunzio et al. 2015), resulting in different baseline scenarios for calculating potentials.

The global potential for increasing carbon storage in forest biomass and soil through **afforestation and reforestation** ranges between 0.5-10 $GtCO_2e$ per year, based on studies estimating potentials per year for 2020-2050 (Jia et al. 2019, p. 138). Estimating afforestation potentials similarly relies on assumptions regarding economic development and scenarios of alternative uses of land. A scientific controversy was caused by estimates presented by Bastin et al. (2019) that found global carbon sequestration potential through natural regeneration of tree cover to be 752 $GtCO_2e$ until forest maturity (expected to be reached after several decades) on 900 Mha tree cover to be established. The estimate was challenged (Veldman et al. 2019; Friedlingstein et al. 2019) and reduced to only 20% of this potential, especially through accounting for existing soil carbon stocks and excluding areas where unintended consequences are expected from afforestation, such as deserts, tundra, shrublands, and various types of grasslands. The criticising authors argued that afforestation can have negative impacts on provisioning of water, fire regimes, biodiversity and albedo effects if implemented on these areas (Veldman et al. 2019). Griscom et al. (2017) estimated a potential for reforestation in 2030 of 15 tCO_2e per hectare per year. This potential only includes areas which are ecologically appropriate for forests and excludes boreal areas, where the albedo effect may lead to net warming as well as naturally unforested habitats such as savannahs. Griscom et al. (2017) also excluded all existing cropland area to prevent danger for food security. However, reforestation in semi-natural grasslands in Europe, which are mostly found in naturally forested sites, could potentially harm biodiversity. These habitats have been an essential part of the European cultural landscape for centuries and are among the most species-rich habitats in Europe (EC 2008).

Permanent grassland covers about 49 Mha in Europe (European Union 2020) and should not be converted to forests (Feurdean et al. 2018; Veldman et al. 2019). Hence, the maximum potential extent of reforestation implementation given in Griscom et al. (2017) would be diminished by about 7%, resulting in a lower mitigation potential in the temperate region by approximately - 20%[5] and - 5% in the total mitigation potential for reforestation (9.7 $GtCO_2e$/yr). Other uncertainties in the mitigation potential estimates result from different potential sequestration rates that vary according to data quality and resolution (Abeliotis and Pakula 2013). Cook-Patton et al. (2020) identified a slightly lower global mitigation potential of 12 tCO_2e/ha/yr (8 $GtCO_2e$/yr) on the same area assumptions as Griscom et al. (2017) due to improved spatial resolution. The controversy around the estimates published by Bastin et al. (2019) shows that the availability of land is the crucial determining factor for options of afforestation and reforestation. This also includes the properties of land, previous land use, land tenure and marketability of products from previous land use, e.g. the type of agricultural commodities (The Royal Society and The Royal Academy of Engineering 2018).

By **improved forest management**, 0.4-2.1 $GtCO_2e$ per year could be mitigated, based on studies estimating the technical potential per year for the period 2020-2050 (Jia et al. 2019, pp. 190–191). Griscom et al. (2017) estimated the sequestration potential of forest management in 2030 at the higher end of the range with 2.11 $GtCO_2e$/yr, including natural and plantation forest

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[5] Griscom et al. (2017) area estimate for reforestation in Europe is 206 Mha which is 157 Mha when 49 Mha permanent grassland are excluded from Europe (Eurostat 2020). The additional sequestration potential for temperate regions was estimated at 2.82 t C/ha/yr, resulting in ~500 Mt CO_2 e/yr reduction of the current mitigation estimate for temperate regions (2,100 Mt CO_2 e/yr) by Griscom et al. 2017.

management (0.77 and 1.7 t CO_2e/ha/yr) and fire management. Options for changes in forest management are especially emerging in areas where intensively managed forests can be found. This includes the EU, for which Nabuurs et al (2017) found that forest management can deliver an additional 0.17 $GtCO_2e$/yr by 2050, i.e. 0.9-2.5 t CO_2e/ha/yr.

However, the underlying assumptions on how such contributions to climate change mitigation can be achieved and implications for forest ecosystems are not always well documented in studies assessing the potential of such measures. For example, assumptions related to forest growth have a strong impact on the identified potentials. Yet, forest growth can be reduced through natural disturbances. Also, the choice of tree species matters regarding how fast biomass is accumulating. Differentiating natural regeneration and planting of trees is also important for assessing co-benefits and trade-offs. Naturwald Akademie (2020) found that carbon sequestration in EU forests could be increased from 0.25 to 0.49 $GtCO_2e$ annually until 2050 if harvest rates were reduced by one third (from 77% to 50% of annual increment) and forests managed complying with a close-to-nature approach that includes natural regeneration of native species and restoration of natural species composition.

Summary

Forests, their conservation, restoration but also their sustainable management offer substantial potential for climate change mitigation. Potentials vary greatly depending on assumptions regarding land availability and constraints related to co-benefits and trade-offs (afforestation/reforestation), assumed future baseline of drivers (avoided emissions from deforestation) as well as forest growth and assumed harvest intensity (forest management).

Potentials derived from the literature can only adequately be interpreted in the light of these assumptions. Differences in assumptions but also in the definition of activities makes a comparison of different estimates difficult if not impossible. Given the wide concept of NbS adopted by the reviewed studies, there is a risk that potentials are largely overestimated. The risk of overestimation is larger for afforestation/reforestation (up to five times higher) and lower but still significant for forest management (about two times lower). Deviation of estimates for avoided deforestation were found to be between the two.

3.2.2 Croplands

State of the ecosystem and measures for NbS

There are a number of activities to sequester CO_2 in mineral and organic soils in croplands and in biomass of perennial plants or reduce emissions from croplands.[6] This section focuses on **croplands on mineral soils** because organic soils are covered in the section on terrestrial wetlands (see Section 3.2.4). This approach is broadly consistent with other reports related to global mitigation potentials on croplands such as the estimates for potentials provided by the IPCC.

All soils have a maximum level of carbon stocks that depends on site-specific conditions (e.g. soil types, water capacity or nutrients). Historically, soil organic carbon (SOC) stocks on mineral soils used for agricultural production have been decreasing and agriculture has been a dominant driver of global land degradation. This is due to simplified crop rotations, removals of crop residues, separation of arable and livestock farming as well as losses from soil erosion. The potential to increase SOC stocks depends on the current level of SOC stocks in relation to the

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[6] Regarding the boundaries of GHG emissions from croplands it needs to be kept in mind that CH_4 and N_2O emissions from manure management from livestock systems are part of agriculture GHG emissions. Emissions from livestock housing systems or manure storage sites are not directly related to croplands. With regard to emissions related to livestock, only emissions from manure application to cropland soils are considered in this section.

maximum level that different soils can achieve (so-called saturation level) (van Groenigen et al. 2017; Mackey et al. 2013). Carbon sequestration occurs when the balance of input of biomass carbon to soils exceeds the loss of soil carbon through mineralisation, erosion and leaching (Lal et al. 2018). There is not one universal practice, but a wide set of site-specific practices depending on soil characteristics and management practices that lead to a positive carbon balance and net carbon sequestration in soils. The key practices that **enhance the SOC content or prevent the loss of carbon in soils** include maintaining a continuous soil cover throughout the year by planting cover crops during fallow periods, covering soils with crop residues or mulch, increasing the returns of organic input to soils (e.g. harvesting residues, compost or manure), reducing soil erosion and leaching, and improving soil structure and processes in the rhizosphere through crop rotations with crops with dense roots and avoiding soil compaction through heavy machinery.[7]

The maintenance of high levels of SOC has been a key objective for healthy soils by farmers across the globe in many agriculture management systems. It is also a key indicator for soil fertility and soil health. Soils with higher organic carbon levels can store nutrients better and release them slowlier through mineralisation. Therefore, they need less nitrogen or fertiliser input. This reduces nutrient leaching and nitrogen emissions. Soils with higher soil organic carbon levels also have higher soil structure stability and higher water capacities. As a result, they are more resilient to climate change impacts such as droughts and heavy rainfalls. Some of the practices to enhance SOC also reduce soil erosion and nutrient leaching. Additionally, practices to enhance SOC do not require additional land areas and the enhancement of soil carbon is generally considered as a negative cost option.

Under **agroforestry**, land is managed by integrating woody perennials (trees or shrubs) and agricultural crops and/or livestock. This can take place in the form of windbreaks/shelterbelts, alley cropping or scattered trees within croplands. Agroforestry increases the carbon stored in woody biomass, soil carbon and dead organic matter.[8]

Agroforestry can deliver significant co-benefits for biodiversity and wildlife, including by functioning as ecological corridors between habitats or providing habitats for pollinators and insects. The number of species on such lands is higher compared to croplands without trees. Additionally, agroforestry supplies input of organic material from trees. If nitrogen-fixing trees are used, e.g. in improved fallows, high amounts of nitrogen are added together with the organic material. In a review of 94 studies from sub-Saharan Africa, Akinnifesi et al. (2010) showed that nitrogen-fixing trees could add more than 60 kg of nitrogen per ha and year and reduce the requirements of inorganic nitrogen fertilisers by 75% while still achieving optimal yields. Agroforestry can also reduce soil erosion, improve soil health, enhance flooding protection and reduce nitrate leaching (Kay et al. 2019). To protect against the impacts of climate change, trees also provide shade to the plants and improve water storage in soils. They use a large soil volume to withdraw water and can thus grow and produce food even during long lasting droughts. An agroforestry system occupies more ecological niches and has the potential to use the available water more efficiently. Compared to annual crop systems, agroforestry also reduces surface runoff and evaporation. Furthermore, agroforestry can relieve the pressure on illegal logging of forests for energy purposes by providing fuel wood.

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[7] Reduced or no tillage is also discussed as a measure to reduce soil disturbance and thus the mineralisation of soil organic carbon. However, this only has effects on the concentration of SOC levels in the top soil layer. Additionally, a single tillage event can reverse the effects on soil carbon, the effects on global climate mitigation are therefore questioned (see e.g. VandenBygaart und Angers (2006)).

[8] Agroforestry can take place on cropland or on forest soils. Due to the fact that agroforestry has not been covered in the section on forests, it is included in this section on croplands, but analysed separately for better comparability with other studies. Many studies refer to agroforestry as ‘trees in croplands’.

However, in dry conditions trees can also increase water consumption and compete with crops. Most countries have not included agroforestry in their agricultural policies, land management strategies or agricultural services and few value chains have been established for the trees in agroforestry. To implement agroforestry, upfront investments are necessary for which capital may be lacking in poor areas. Moreover, research is focused on biophysical parameters, but not on socio-economic parameters of the establishment of agroforestry systems.

Further measures to reduce emissions from croplands include **improved rice cultivation** in order to avoid CH_4 emissions from rice production, for example by alternative wetting and drying of previously permanently irrigated rice soils. The anaerobic conditions in flooded rice paddies lead to CH_4 emissions which are reduced by alternative wetting and drying of the rice fields. Co-benefits are reduced water use and better adaptation to drought. In terms of mitigating CH_4 and N_2O emissions, trade-offs can occur, e.g. improved water management can reduce CH_4 emissions, but partially aerobic conditions can cause nitrification and denitrification processes leading to increased N_2O emissions.

Reduced nitrogen fertilisation is included as '**cropland nutrient management'** in several global assessments of NbS on croplands. Such management refers to activities to avoid N_2O emissions due to reduced over-fertilisation and improved timing and methods for fertiliser application. The activity focuses on addressing the over-application of fertilisers, therefore crop yields are not negatively impacted. Reduced N fertilisation also reduces N leaching and runoff and contamination of groundwater and surface waters that imply high costs for N removals for human consumption. Reducing nitrate pollution in surface and coastal water also reduces negative effects such as eutrophication and excess algae and plant growth in water bodies. Reducing over-fertilisation is cost-effective for farmers as they can save fertiliser costs. However, emission reductions achieved in one year are reversible and fertiliser use can increase if reduction policies are discontinued.

It is questionable whether reduced over-fertilisation is really a 'nature'-based solution. The activity reduces useless and detrimental human inputs in ecosystems that cause high follow-up costs to societies in an area where the polluter-pays-principle for environmental damage has been ignored for decades. The activity thus aims to minimise detrimental human impacts on nature, but is neither based on using natural ecosystem processes as highlighted in the NbS definition in Section 2.1.1 nor is the measure aligned with natural ecosystems.

Potentials of NbS, constraints and uncertainties

There is a considerable number of different practices that have different effects on soil types and soil conditions. Studies include a variety of individual mitigation activities under **soil carbon management** in croplands which makes it difficult to compare the studies and their estimates. Additionally, the terminology used is not always very clearly related to the exact activities covered.

Hepburn et al. (2019) estimate global sequestration potentials through enhancing SOC to range between 0.9 and 1.9 $GtCO_2e$/yr, including grazing land; Lal et al. (2018) give estimates between 0.2 and 2.2 $GtCO_2e$/yr. Higher estimates between 2.0 and 5.0 $GtCO_2e$/yr are provided by Minx et al. (2018) as well as Zomer et al. (2017) (3.3-6.8 $GtCO_2e$/yr) and Minasny et al. (2017) (7.3-11.0 $GtCO_2e$/yr). Griscom et al. (2017) provide a potential average estimate of 0.4 $GtCO_2e$/yr for the expansion of cover crops. The IPCC Special Report on Climate Change and Land Use (Shukla et al. 2019, chapter 2.6.1) summarised the range of global potentials for CO_2 removals by soil carbon management in croplands at 0.25-6.8 $GtCO_2e$/yr in the period 2020-2050.

The ‘4 per mille Soils for Food Security and Climate’ launched at COP21 to increase global soil organic matter stocks by 0.4% per year investigated 20 regions in the world and found significant potentials to enhance soil organic carbon in all countries. Minasny et al (2017) indicated that reported SOC sequestration rates globally show that under best management practices, sequestration rates of 0.4% per year or even more are possible. High C sequestration rates of up to 1% can be achieved for soils with low initial SOC stocks. However, this estimate has been disputed (White et al. 2017).

Soils have a natural maximum carbon storage capacity, therefore the total potential is limited. However, carbon in most agricultural soils is strongly depleted and many authors assume long periods of 25 to more than 50 years of continuous CO_2 sequestration before this maximum would be reached (Lal et al. 2018; Griscom et al. 2017). Bossio et al. (2020) assume that in many cases it is not possible to restore SOC to the original levels on climate-relevant time scales.

Yet, the measurement and monitoring of soil organic carbon to produce reliable estimates at country level is difficult and linked to large uncertainties. Many countries have not yet implemented reliable methodologies for measuring soil carbon in mineral soils. For instance, in Germany soil carbon stocks in mineral soils on cropland soils that remain croplands are currently not estimated at all in the national GHG inventory. The methods involve measurements of permanent soil carbon monitoring sites over large time spans and upscaling to national level. Long-term measurement plots are rather limited in many countries. Upscaling is usually done with soil models (e.g. Denmark, Sweden, Australia). Ground truthing of model results is challenging for carbon stock estimates in soils due to the high natural variability in measured carbon stocks. Estimated potentials are therefore often derived from global soil models which are linked to high uncertainties as well and operate at coarse scales. Considerable efforts are still needed in most countries to increase the reliability of the estimates related to soil carbon stocks. Even for the EU, costs for sampling and modelling are high and considered to be a key barrier for results-based carbon farming systems (COWI, Ecologic Institute, IEEP 2021). Results from specific sites with NbS soil activities can only be integrated in national GHG data sets if the national data sets are geographically referenced in a sufficiently dense grid. However, such a detailed geo-referenced approach for soil carbon is currently not available in many developed countries and even less in developing countries. This makes it difficult to integrate geographically limited NbS activities in the national mitigation policies and national data.

Additionally, changes in land management practices that disturb soils can reverse soil carbon sequestration and release the stored carbon in short time frames. As another caveat, Fuss et al (2018) point out that there is a need for additional N and P inputs to soils to maintain stoichiometry for the formation of soil organic matter (see also White et al. 2017).

With regard to **agroforestry**, there are no reliable statistical sources on the trees located on agricultural land areas. Based on satellite data, Zomer et al. (2017) estimated that in 2000 more than 40% of the agricultural land area had more than 10% tree coverage with a CO_2 storage of 166 $GtCO_2$. Average estimates range from 0.3 $GtCO_2e$/yr in Bossio et al. (2020) (only considering SOC contribution), 1.1 $GtCO_2e$/yr in Griscom et al. (2017) to 3.4 ± 1.7 $GtCO_2e$/yr in Kim et al. (2016). Jia et al. (2019) estimate the potential between 0.1 and 5.7 $GtCO_2e$/yr and Lal et al. (2018) between 1.6 and 3.5 $GtCO_2e$/yr (technical potential). Potentials for the enhancement of CO_2 storage by agroforestry vary widely with the type of system, soil types, climate, tree species and tree densities.

However, similar problems related to measurement and monitoring of soil organic carbon apply to agroforestry systems as described above for the enhancement of soil carbon. The trees on croplands are currently not systematically counted either and the biomass is not estimated in most countries.

For **improved rice cultivation**, Tran et al. (2018) found 26% CH_4 emissions reduction through alternate wetting and drying in Vietnam with stable rice yields and 15% lower water use. Setyanto et al (2018) reported a reduction of 35-38% CH_4 emissions through alternate wetting and drying in Indonesia with no impact on yields. However, in the Philippines with a tropical wet and dry season, the annual GHG emissions were not affected substantially through alternate wetting and drying (Sibayan et al. 2018). Griscom et al. (2017) estimated a maximum global area of 163 Mha and an annual global emission reduction of 0.27 $GtCO_2e$/yr. The IPCC Special Report on Climate Change and Land Use (Shukla et al. 2019) estimated the global emission reduction potential between 0.08 and 0.87 $GtCO_2e$/yr. Factors impacting the mitigation potential of alternate wetting and drying are environmental factors, such as soil type and climate as well as management practices, namely the amount of organic matter in the field and fertiliser application and the rice cultivar. The diversity of rice cultivation systems poses a strong limit to assessing generalised potentials. The amount of available N directly impacts the amount of N_2O emissions that would result when fields change from wet to dry condition and vice versa (Wassmann et al. 2009). Some studies also include improvements of residue management, improvement of fertiliser application and application of organic soil amendments under this activity.

The relationship between nitrogen inputs and direct and indirect N_2O emissions is linked with high uncertainties (direct and indirect N_2O emissions from agricultural soils are usually the source categories with largest uncertainties in countries' national GHG inventories). Even at EU level, there are information gaps despite the monitoring and reporting of nitrogen since the start of the EU Nitrates Directive in 1991[9]. Better data requires country-specific emission factors and a geographic explicit modelling approach reflecting the inputs and conditions with sufficient regional resolution.

For **reducing N_2O emissions by N fertilisation**, Griscom et al. (2017) assume a maximum potential of 0.71 $GtCO_2e$/yr or a 32% reduction of baseline fertiliser use in 2030. The IPCC Special Report on Climate Change and Land (Shukla et al. 2019) assessed a large number of global studies and estimated the global potential between 0.11 and 1.58 $GtCO_2e$ per year. The effects on the production of nitrogen fertiliser and related GHG emissions are not considered in any of these estimates.

Summary

NbS in croplands mainly contribute to climate change mitigation by increasing CO_2 sequestration in mineral soils and on farmland and by reducing CH_4 emissions from rice cultivation. Estimates for global sequestration potentials in croplands range from 0.2 $GtCO_2e$/yr to 11.0 $GtCO_2e$/yr and have high uncertainties. Global estimates derived from global soil models do not reflect the high natural variability of carbon stocks and there is currently a lack of systematic and reliable measurement of soil carbon in mineral soils in countries.

Estimates of the CO_2 sequestration potential of agroforestry range from 1 $GtCO_2e$/yr to 5.7 $GtCO_2e$/yr. Estimates often reflect enhancements of SOC, which is also constrained by the issues mentioned above, and increases in biomass, which is currently not systematically assessed in most countries. The mitigation potentials of agroforestry systems are strongly influenced by soil and climate variables, as well as by the system under consideration.

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[9] Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources, see https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A31991L0676.

Estimates for reducing CH_4 emissions from rice cultivation range from 0.08 to 0.87 $GtCO_2e$/yr. The main potential lays in alternative water management to reduce the anaerobic conditions in flooded fields that favour methanogenesis. The diversity of rice cultivation systems poses a strong limit to assessing generalised potentials and trade-offs between the reduction of CH_4 emissions. Increasing N_2O emissions need to be considered, if alternative water management is not accompanied by improved fertiliser management.

Organic agriculture and NbS

Organic agriculture or organic farming “is a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects” (IFOAM 2008). The objectives of such farming systems go beyond food production to include caring for and protecting the environment (landscapes, climate, habitats, biodiversity, air and water) and the wellbeing of people and animals (IFOAM 2009). Practices in organic agriculture that are beneficial for GHG mitigation are the use of organic fertilisers such as compost and manure, the integration of perennial plants or the optimisation of crop rotations with legumes and cover crops.

Organic agriculture also implements a low nitrogen input system. Organic farming methods focus on establishing closed nutrient cycles, minimising nitrogen losses via runoff and volatilisation and they do not allow the use of synthetic nitrogen fertilisers. In Germany for example, nitrogen losses are 28% lower in organic farming systems (Sanders and Heß 2019). Additionally, organic farming has positive impacts on biodiversity due to the prohibition of most pesticides in organic farming. In a review for Germany, for example, organic farmland showed 95% higher species diversity for plants, 35% higher for birds and generally 49% higher for fauna (Sanders and Heß 2019). Organic agriculture is also likely to increase climate resilience due to better soil structure and higher soil organic carbon contents. It significantly reduces the pollution of water with nitrates and pesticides and increases animal welfare. All the co-benefits listed for enhancing soil organic matter and avoided N_2O emissions from fertilisation also apply to organic farming.

According to a large meta-analysis of 79 studies Gattinger et al. (2012) showed that soil carbon stocks are 3.5 ± 1.08 tCO_2/ha higher than in non-organically managed soils, and sequestration rates were 1.65 tCO_2/ha/yr higher. The Soil Association (2009) estimates the global carbon sequestration of organic farming at 5.5 $GtCO_2e$/yr for the next 20 years. For Germany, soils in organic croplands show 10% higher soil organic carbon stocks and a sequestration rate of 0.94 tCO_2/ha/yr. Skinner et al. (2019) observed a 40% reduction of N_2O emissions per hectare for organic farming systems compared to non-organic systems in Switzerland.

However, even though organic farming implements several practices described in this chapter that lead to net carbon sequestration in soils and a reduction in N_2O emissions, none of the global studies related to NbS potentials investigates organic agriculture as a pathway to implement NbS. This might be because there are various concepts describing such practices, including agro-ecology, permaculture or conservation agriculture, and the measures implied by these concepts are not precisely delineated. Additionally, due to the lower use of pesticides and synthetic fertiliser, organic farming does not reach the same productivity levels per crop as non-organic agriculture. Therefore, it is sometimes claimed that the approach at global scale would not produce sufficient food for the global population (e.g. Muller et al. (2017)). The need for additional cropland area could be compensated by a reduction of animal feed grown on arable land and a corresponding reduction in animal numbers and production as well as the reduction of food waste. Additionally, reduced crop losses and enhanced pest control can bring synergies if properly managed (Röös et al. 2018). Particularly, in industrialised countries with higher rates of food waste, nitrogen surpluses and high meat consumption, strengthening organic farming would therefore be an integrated way to promote NbS on croplands.

3.2.3 Grasslands

State of ecosystem and measures for NbS

Grasslands include rangelands, shrublands, pastureland as well as cropland sown with pasture and fodder crops. In total they cover about 40% (3,200 Mha, FAO 2021) of the land surface. Grasslands are predominantly used as grazing areas and represent 70% of the world agricultural area (Conant 2010). Natural grassland ecosystems are characterised by periodic drought which makes natural succession towards scrubland and forests not possible. Their vegetation is usually dominated by grass species and legumes and they are also habitat to numerous other species of e.g. insects, birds and mammals (Dengler et al. 2014). Typical examples for natural grasslands are the prairie in North America, pampas of South America, tropical dry savannas as well as the Eurasian steppe (Gibson 2009). There are also man-made grasslands which are located on sites whose natural vegetation is forests. These semi-natural grasslands result from centuries of low-intensity land use and mainly occur in Europe as an essential part of the cultural landscape (Ellenberg and Leuschner 2010). Afforestation to enhance carbon sequestration in semi-natural and even natural grasslands is often considered as a climate mitigation measure (see Section 3.2.1). Introducing tree species in grasslands may lead to an increase in above-ground carbon stocks but can cause substantial losses of below-ground carbon and lead to a loss of biodiversity specifically adapted to grasslands (Dass et al. 2018). Hence, afforestation, especially in natural grassland ecosystems is not considered as an NbS and is generally not recommended under any other framework.

Permanent grasslands deliver many ecosystem services like flood control, maintaining water resources, soil erosion control, forage production and carbon sequestration (Zhao et al. 2020). Grasslands contain about 20% of the world's SOC stocks (340 Gt C, Conant 2012) and their natural soil fertility makes them especially attractive for intensive management (FAO and ITPS 2015). Around 20% of the global natural grassland area has been converted to cropland (Ramankutty et al. 2008). Also, the global livestock industry predominantly depends on managed grasslands and about 30% of the world's milk and 20% of beef production are based on grassland. Hence, for about 1 billion people, grasslands are an essential contribution to their livelihoods (FAO 2017). However, many of the world's grasslands are in a poor condition and show signs of degradation, mostly caused by overgrazing resulting in soil erosion and loss of SOC. Approximately 73% of the global grazing area suffers from degrading soils and vegetation, this is mainly due to an increase in the consumption of animal products (IPBES 2018). Additionally, managed pastures were found to contribute 86% of the net global N_2O emissions from grasslands, mainly because of direct deposition of livestock excreta on soils (Dangal et al. 2019).

Hence, to secure the ecosystem services of grasslands, NbS should focus on **protecting** natural and semi-natural grassland ecosystems by **avoiding** their **conversion** to other land uses such as cropland, pasture and settlements. Additionally, natural grasslands should be distinguished from degraded forest area to avoid their conversion to forests. Also, the intensity of **livestock grazing** should be **controlled** to sustainable levels which ensures carbon sequestration and other natural processes. **Integrating legume species** can increase carbon sequestration **in planted pastures** despite increasing N_2O emissions (Henderson et al. 2015). In contrast, N_2O emissions from nitrogen (N) fertilisation exceeded soil carbon sequestration (Henderson et al. 2015). Additionally, N fertilisation can have negative impacts on grassland plant biodiversity (Humbert et al. 2016; Bai et al. 2010) and should therefore not be considered as NbS. The **conversion and restoration of abandoned cropland** to permanent grassland can also increase soil carbon stocks and provide grassland related ecosystem services (Conant et al. 2017; Yang et al. 2019). Griscom et al. (2017) introduce two measures linked to grazing, “improved feed”, which describes the avoided CH_4 emissions resulting from more energy dense feed for cattle (0.68 $GtCO_2e$/yr), and “animal management” which includes avoided CH_4 emissions from improved livestock breeds and animal health (0.2 $GtCO_2e$/yr). These measures are not considered as NbS according to our definition (Chapter 2) because they do not directly protect, restore or sustainably manage grasslands and do not have direct positive implications for their biodiversity. However, these measures address important drivers of CH_4 emissions in the agricultural sector and therefore contribute to the overall mitigation of climate change.

Potentials of NbS, constraints and uncertainties

Stopping grassland conversion to cropland (1.7 Mha/yr) can save SOC and avoidable emissions were estimated at 0.12 $GtCO_2e$/yr in the top 30 cm of the soil for temperate, tropical and subtropical grasslands (Griscom et al. 2017). This estimate is substantially increased to 0.23 $GtCO_2e$/yr if the loss of SOC down to 1 m is taken into account due to a soil carbon pool that is twice as high (Bossio et al. 2020). Hence, the mitigation potential estimates substantially depend on the soil depth considered relevant for SOC sequestration and storage.

Improved grazing intensity on pastures and rangeland (712 Mha) can mitigate 0.15 $GtCO_2e$/yr due to enhanced SOC sequestration of about 0.22 tCO_2/ha/yr (Henderson et al. 2015). These estimates are only about half as high compared to estimates (0.4 $GtCO_2e$/yr) by Herrero et al. (2016). Also, Conant et al. (2017) reviewed a much higher sequestration rate of 1 tCO_2/ha/yr for improved grazing compared to Griscom et al. (2017). Smith et al. (2008) showed a substantially higher estimate for the global mitigation potential until 2030 for improved grazing management of 1.5 $GtCO_2e$/yr but do not provide information on the underlying sequestration rates and area. Hence, it is not clear where this substantial difference to other mitigation potentials originates from.

The **active restoration of abandoned croplands to grasslands** with high diversity of late-successional plant species could triple the annual rate of soil carbon storage in 0-20 cm soil depth (from 0.6 tCO_2/ha/yr up to 1.9 tCO_2/ha/yr; Yang et al. 2019). The main reason is that more species of C4 grasses and legumes have more above- and below-ground biomass that contributes to higher soil carbon storage (Yang et al. 2019). Also, Conant et al. (2017) found an increase in soil carbon stock of almost 3.3 tCO_2/ha/yr on average after the conversion of annual cropland to permanent vegetation. Restoring abandoned croplands to grasslands is an NbS that seems to be in direct competition with afforestation. However, where the natural vegetation is grasslands, restoration should also focus on grasslands to ensure biodiversity benefits. Henderson et al. (2015) estimated a net mitigation potential of **legume sowing on planted pasture** (72 Mha globally) of 0.2 $GtCO_2e$/yr, which was offset by 28% due to N_2O emissions, resulting in 0.15 $GtCO_2e$/yr (2 tCO_2/ha/yr) (Griscom et al. 2017). This estimate is in the same range as findings by Conant et al. (2017) for sowing legumes (2.4 tCO_2/ha/yr).

Mitigation potentials in grassland measures are subject to uncertainties due to the limited understanding of management impacts on the carbon sequestration process as well as N_2O and CH_4 emissions (Paustian et al. 2019). Also, the global mitigation potentials presented here do not account for changing climate conditions and their impacts on the carbon sequestration of grasslands. Especially during drought stress, carbon sequestration can be decreased due to reduced plant photosynthetic activity like in the extreme drought in 2003 (Ciais et al. 2005; Reichstein et al. 2007).

Summary

Compared to other ecosystems, NbS in grasslands show a very wide range of climate mitigation potentials assumingly because of differing assumptions for soil carbon sequestration rates, e.g. for improved grazing (0.15 and 1 tCO_2/ha/yr, Griscom et al. 2017; Conant et al. 2017) and potentially suitable area extent of this NbS. Hence, total mitigation potentials from improved grazing range from 0.15 (Griscom et al. 2017) to 1.5 $GtCO_2e$/yr (Smith et al. 2008). Legume sowing shows a comparatively high specific sequestration potential in the soil (~2 tCO_2/ha/yr) due to increased plant diversity but the NbS is restricted to about 72 Mha of planted pastures (Griscom et al. 2017). The highest mitigation potentials can be expected from the avoidance of grassland conversion to cropland (~0.23 $GtCO_2e$/yr), although the total estimate of avoided emissions varies according to the underlying soil carbon assumptions. Also, the active restoration of abandoned cropland substantially increases the soil carbon sequestration (1.9 tCO_2/ha/yr and 3.3 tCO_2/ha/yr; Yang et al. 2019; Conant et al. 2017). Yet, there are no estimates on the potential restoration area. Although the overall climate mitigation potential of grasslands due to NbS is very uncertain, the co-benefits of NbS protecting natural and semi-natural grasslands from conversion and restoring them can be very high for biodiversity and ecosystem services like flood control and improved soil structure (Griscom et al. 2017).

3.2.4 Terrestrial wetlands

State of ecosystem and measures for NbS

According to the Ramsar Convention on Wetlands of International Importance[10] wetlands are "areas of marsh, fen, peatland or water whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine waters the depth of which at low tide does not exceed 6 metres." Saltwater wetlands or coastal wetlands are discussed in Section 3.2.5. Terrestrial wetlands occur in all climatic zones and are dominated by peatlands, marshes and swamps as well as natural lakes. They cover about 1,100 Mha globally (Ramsar Convention Secretariat 2018) and are habitat to numerous species specifically adapted to wet conditions and therefore highly relevant for biodiversity protection. Also, they improve water quality by filtration and are freshwater reservoirs. Terrestrial wetlands are of great importance for terrestrial long-term carbon storage because of low biomass decomposition in water-saturated anaerobic wetland soils. Soils which contain at least 12% of organic carbon in the upper 20 cm are defined as organic soils (IPCC 2006). These carbon rich soils are mainly found in peatlands, marshes and swamps, which make up more than half of the total global terrestrial wetland area (Ramsar Convention Secretariat 2018). Peatlands are mainly distributed in the boreal and temperate climate zones and hold the biggest terrestrial carbon storage which is about twice the global carbon stored in forest biomass today (600 Gt C, Leifeld and Menichetti 2018, WRI 2021a).

Terrestrial wetlands suffer from land conversion and degradation through drainage for forestry and agriculture, peat extraction and fires (Ramsar Convention Secretariat 2018). About 51 Mha of peatlands are already degraded causing emissions from peat decomposition of about 2 $GtCO_2e$/yr (Leifeld and Menichetti 2018). Also climate change-induced elevated temperatures already affect peatlands in the Arctic region and lead to substantial peat decomposition in the permafrost and release approximately 5.8 $GtCO_2e$/yr (Natali et al. 2019).

NbS to mitigate climate change should focus on **protecting intact terrestrial wetlands** and also **stop further conversion and degradation** of managed wetlands to protect their high carbon stocks and prevent further emissions mainly from peat decomposition. Additionally, **degraded**

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[10] Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat (1971)

wetlands can be restored by elevating soil water tables and restoring the landscape water regime (Schumann and Joosten 2008). These measures carry multiple environmental co-benefits such as biodiversity conservation, flood protection, improved soil and water quality as well as cultural ecosystem services (The Royal Society and The Royal Academy of Engineering 2018).

Peatlands show the highest carbon density per area unit compared to other terrestrial ecosystems, which makes the protection of their carbon stocks particularly important for climate change mitigation (Günther et al. 2020). However, their potential to increase carbon storage is low compared to other ecosystems like forests (Roe et al. 2019).

Potentials of NbS, constraints and uncertainties

According to a study by Humpenöder et al. (2020) missing peatland protection and restoration policies will lead to emissions of up to 1.6 $GtCO_2e$/yr until 2100 globally. The implementation of **protection and restoration** could lead to much lower emissions of 0.6 $GtCO_2e$/yr and hence mitigate emissions of about 1 $GtCO_2e$/yr globally. The **avoidance of degradation** of above- and below-ground biomass and soil carbon in peatlands can lead to an avoidance of about 0.75 GtCO2e/yr until 2030 according to Griscom et al. (2017). The **restoration** potential of the total area of degraded **peatlands** (50.1 Mha) is estimated to avoid 0.08 to 0.9 $GtCO_2e$/yr, accounting for all GHG (CO_2, N_2O, CH_4) concerned (Leifeld and Menichetti 2018). The avoided emissions from peatland restoration (46 Mha) given by Griscom et al. (2017) are lower (0.8 $GtCO_2e$/yr) compared to the maximum potential given by Leifeld and Menichetti (2018) because their area estimate of degraded tropical peatlands is 40% higher. This has a significant effect because of high emissions factors of tropical peatlands compared to e.g. temperate peatlands.

Additionally, Griscom et al. (2017) do not include the removal of emissions by carbon sequestration of rewetted peatlands because they would be offset by CH_4 emissions. In total, CH_4 emissions of rewetted peatlands entail lower radiative forcing compared to CO_2 emissions from drained peatlands because the latter have a longer lifetime in the atmosphere. Moreover, CH_4 emissions can also be found on drained peatlands, mainly in drainage ditches (Günther et al. 2020). Overall, estimating mitigation potentials for peatland restoration is very challenging because of complex GHG emission fluxes of drained and rewetted peatlands and different assumptions about the potential area for restoration. All cited studies assume restoration of the total area of degraded peatlands, which could be unrealistic because most of these peatlands are used for crops or as pastures and are privately owned. Hence, land will probably have to be made available for exchange to farmers. The Ramsar Convention on Wetlands (2021) estimates that at least two-thirds of the degraded peatlands have to be rewetted (30 Mha) to prevent farming in these areas turning into a source of carbon. This is about 35% and 40% less peatland restoration area compared to Griscom et al. (2017) and Leifeld and Menichetti (2018) and corresponding lower mitigation potentials of about 0.53 $GtCO_2e$/yr and 0.06-0.6 $GtCO_2e$/yr. Additionally, the choice of emission factors and the estimated peat oxidation duration influences the overall mitigation estimates. The IPCC guidelines for wetlands (IPCC 2013) do not provide emission factors for different periods of peat degradation either. Hence, emissions from long-term degraded peatlands could be overestimated if peat layers may be close to depletion. This can slow down their emission rates by about 60% after five years already (Hooijer et al. 2012). But highly degraded peatlands are a significant source of N_2O which is about 265 times more potent than CO_2 and should also be considered (Liu et al. 2020)

Neither Leifeld and Menichetti (2018) nor Griscom et al. (2017) account for future changes in temperature and precipitation patterns due to climate change, which can reduce the carbon storage potential of peatlands (Leng et al. 2019). Especially under future climate conditions SOC accumulation rates may slow down to almost half compared to current capacities. This could cause the carbon-dense Amazonian peatland to switch from carbon sink to source in the 21st century (Wang et al. 2018). Also, in the Arctic regions model predictions show an increase of winter CO_2 emissions from permafrost of up to 41% under the business-as-usual scenario (RCP 8.5). Hence, carbon losses in winter may exceed the carbon uptake during the growing season in the northern terrestrial regions (Natali 2019).

All presented mitigation potentials for peatland restoration consider the whole degraded peatland area globally. But rewetting measures can cause societal and economic challenges if the area is used for commercial agriculture, forestry and peat extraction. About 25 Mha[11] of peatlands are currently used for agriculture, which is about half of the degraded peatland area (Leifeld and Menichetti 2018). If rewetting only occurs on non-productive land, the mitigation potential could substantially be lowered.

Summary

Protection and restoration of wetlands can avoid and reduce further carbon loss primarily from soils. Maximum global mitigation potentials for peatland restoration are estimated at 0.8 $GtCO_2e/yr$ (Griscom et al. 2017) and 0.9 $GtCO_2e/yr$ (Leifeld and Menichetti 2018). Additionally, the avoidance of further loss of peatlands could mitigate about 0.7 $GtCO_2e/yr$ (Griscom et al. 2017). Main uncertainties related to these mitigation potentials result from different estimates for degraded peatland areas as well as different estimates regarding the full implementation of the global restoration potential. Also, there is a lack of emission factors that better reflect the different phases of peat degradation in order to make more accurate assumptions. Another uncertainty are future GHG fluxes of peatlands under climate change that could lead to increased emissions from intact peatlands (Leng et al. 2019). Finally, global mitigation potentials for terrestrial wetlands are predominantly limited to peatlands (Griscom et al. 2017; Leifeld and Menichetti 2018; Humpenöder et al. 2020; Jia et al. 2019) but do not consider impacts on the emission fluxes from lake and river sediments as well as alluvial (floodplain) forest soils and biomass which cover about 600 Mha globally (Ramsar Convention Secretariat 2018).

3.2.5 Coastal wetlands

State of ecosystem and measures for NbS

Globally, marine coastal wetlands like mangroves, salt marshes and seagrass meadows cover about 2% of the ocean area. Mangrove forests only occur in the tropics and sub-tropics, while seagrass meadows can be found in all regions as well as salt marshes, which, however, are mainly distributed in the temperate region. Together these ecosystems account for approximately 50% of the carbon that is sequestered in ocean sediments (IUCN 2017). Carbon stocks in biomass and the top metre of the sediment have been estimated at 400 t C per ha for mangroves, 250 t C per ha for salt marshes and 140 t C per ha for seagrass meadows (Pendleton et al. 2012). Hence, they are often referred to as “coastal blue carbon ecosystems” (IPCC 2019a).

Besides carbon sequestration and storage, coastal wetlands provide key habitats for many terrestrial and marine species. They are of particular importance for most marine fish, shrimps, molluscs, crab and turtle species, e.g. as nursery grounds and food habitat. Therefore, about 90% of marine fisheries depend on coastal wetlands (Hinrichsen 1998). Also, coastal wetlands are an important protection against impacts of floods caused by tsunamis and storms (Li et al. 2018). They enhance the water quality by filtering nutrients and sediments and recycle and accumulate organic and inorganic material (IUCN 2021c).

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[11] FAO statistic 2019 available at https://www.fao.org/faostat/en/#data/GV

However, due to land use change, especially drainage and spread of agriculture and settlements, coastal wetlands suffer from rapid loss. Another problem is the conversion of coastal ecosystems through tidal flow restriction and modification of coastal waterways, which disturb the flow of nutrients and can lead to loss of carbon in sediments (Macreadie et al. 2017). Also, unsustainable wood harvest in mangroves, nutrient input from agriculture which deteriorate water quality as well as direct impacts such as trawling lead to degradation and loss of coastal ecosystems (Pendleton et al. 2012). Estimates by Li et al. (2018) show that up to 50% of the natural extent of global coastal wetlands have been lost since the 19th century. Still, about 800,000 ha of coastal wetlands are lost each year and under current conversion rates approximately 30-40% of salt marshes and seagrass meadows and almost 100% of mangroves could be lost in the next 100 years (Pendleton et al. 2012). Hence, area loss and degradation are the main disturbances, resulting in loss of coastal carbon stocks especially because only about 2% of the marine sediment carbon stocks are located in protected areas that can prevent seafloor disturbances (Atwood et al. 2020).

Coastal ecosystems can best contribute to climate change mitigation through measures that **protect existing coastal ecosystems** and **prevent further degradation and destruction** of coastal ecosystems under management. Also, emission reductions and potential removal of CO_2 from the atmosphere could be achieved by **restoring these ecosystems**. Coastal ecosystems play a significant role for the food security of people depending on sea food. Therefore, sustainable use of these ecosystems is of crucial importance when NbS for coastal ecosystems are implemented, e.g. in the form of sustainable harvest practices in mangrove forests that still maintain habitat and coastal protection functions. Also, fishing methods that protect sediments from destruction and keep biodiversity of sea organisms would be an example of a well-designed NbS targeting coastal wetlands. Finally, the success of restoration measures also depends on whether the underlying threats to the ecosystem are removed. Hence, eutrophication from discharge of nutrients into the sea as well as pollution from plastics and other harmful substances have to be stopped. Additionally, the spread of infrastructure at the expense of coastal ecosystems has to be halted and natural hydrology restored. Also, the protection of salt marshes could involve management changes such as lowering mowing intensity and excluding cattle grazing on salt marshes.

Potentials of NbS, constraints and uncertainties

Griscom et al. (2017) estimate the mitigation potential for the **restoration of mangroves, seagrass meadows and saltmarshes** of up to 0.84 $GtCO_2e$/yr until 2030 on 29 Mha. The estimate includes avoided emissions from the oxidation of existing soil carbon and the sequestration rates of soils as well as mangrove biomass. Mangroves show the highest total (0.6 $GtCO_2e$/yr) and specific (54 tCO_2e/ha/yr) mitigation potential. However, the restoration of seagrass meadowscan also enhance CH_4 emissions, which were found to reduce the total GHG benefit by about 6% and enhanced N_2O emissions by about 5% (Oreska et al. 2020). Taking into account this effect, carbon sequestration rates were estimated at about 1.5 tCO_2e/ha/yr in a regional study from the USA (Oreska et al. 2020), which is much lower compared to the sequestration estimates by Griscom et al. (2017) for seagrass meadows, 5 t CO_2/ha/yr. The IPCC (2013) provides emission factors after rewetting soils in coastal ecosystems, with 1.6 tCO_2/ha/yr for seagrass meadows which match the results of the local study by Oreska et al. (2020). Applying the lower estimates of seagrass carbon sequestration by Oreska et al. (2020), the total mitigation potential by Griscom et al. (2017) would be 0.78 $GtCO_2e$/yr. Additionally, as already discussed under the terrestrial wetland section 3.2.4, the total area suitable for restoration could be overestimated because about half of the world's coastal wetlands was converted to agricultural lands (Pendleton et al. 2012). Their restoration may cause threats to food security in some regions or lead to leakage. The **avoidance of impacts on coastal wetlands** due to drainage and degradation is estimated at 0.3 $GtCO_2e$/yr (Griscom et al. 2017), which is close to the lower estimates for global emissions released due to coastal wetland degradation (0.2-2.3 $GtCO_2e$/yr) by Howard et al. (2017). The wide range of emission estimates for coastal wetland degradation by Howard et al. (2017) is caused by a wide range of global carbon stock estimates for coastal ecosystems compared to those in Griscom et al. (2017).

Summary

The restoration of mangroves, seagrass meadows and saltmarshes can mitigate up to 0.8 $GtCO_2e$ but this mitigation potential could be lower especially because of potentially lower emission factors for seagrass meadows. However, there are high uncertainties in the number of sequestration rates, area extent as well as the impact of disturbances on the emission fluxes of coastal wetlands (Jia et al. 2019; Pendleton et al. 2012; Howard et al. 2017; IUCN 2021b), which makes mitigation potential estimates very challenging. Additionally, future impacts from climate change are not accounted for in any of the current mitigation potentials. The effect of climate change on coastal ecosystems and their carbon stocks is still highly debated and probably has a high geographic variation. Sea level rise could be beneficial for coastal ecosystems, while marine heatwaves, storms and altered availability of fresh water could have a negative impact (Macreadie et al. 2019).

Currently, impacts of disturbances to seafloor sediments of the open sea mainly due to bottom trawling have not been considered in global assessments (Jia et al. 2019; Griscom et al. 2017). Estimates by Sala et al. (2021) show that between 2016 and 2019 about 4.9 million km^2 (1.3% of the global ocean surface) is trawled each year resulting in 1.47 Gt of aqueous CO_2 emissions through disturbances to the seafloor. These substantial emissions should be addressed by NbS protecting these sediments and by introducing non-disruptive fishing methods.

3.2.6 Settlements

State of ecosystem and measures for NbS

About half of the world's human population live in urban areas which cover about 0.4-0.9% of the global land surface (Esch et al. 2017; Zhou et al. 2015). Urbanisation is a major driver of land degradation by contributing to forest degradation as well as conversion of productive lands (Jia et al. 2019). Due to the increasing population and immigration from rural areas, urban areas are expected to spread by about 1.8-2.4% on agricultural land by 2030 and therefore increase threats to food security (Pradhan et al. 2014). Additionally, densely built-up areas lead to an increasing mean annual surface air temperature in cities and their surroundings between 0.4 and 2 °C (Doan et al. 2016; Torres-Valcárcel, A., R. et al. 2015) and the air quality is diminished in urban areas which negatively affects human health (Sharma et al. 2013).

Hence, establishing urban **green infrastructure** by **planting trees** and increasing inner city park and forest areas can contribute to carbon sequestration in above- and below-ground biomass as well as soil (Baro et al. 2017; Davies et al. 2011; Nowak et al. 2013). However, the overall mitigation effect of such measures is assessed as rather small against the overall emissions from cities (Jia et al. 2019). Nevertheless, greening urban areas is an essential element of cities' adaptation to climate change (Demuzere et al. 2014; Sussams et al. 2015; Elmqvist et al. 2016; Gill et al. 2007; Field et al. 2014; Revi et al. 2014). Firstly, it can have a significant cooling effect in cities and their surroundings (Aram et al. 2019; Di Leo et al. 2016; Cavan et al. 2014; Feyisa et al. 2014; Zölch et al. 2016). This in turn contributes to human health and well-being (Klemm et al. 2015; Brown and Nicholls 2015). Secondly, greening roofs and walls diminishes the energy consumption of buildings (see e.g. Coma et al. 2017). Thirdly, measures for greening urban areas will reduce surface water runoff and exposure to floods (Zeleňáková et al. 2017). Additionally, such measures imply preserving and managing non-sealed surfaces, which in turn can help to counteract land degradation (Scalenghe and Marsan 2009; Murata and Kawai 2018). **Urban agriculture** as one specific type of measure can contribute to meeting the food needs of cities more sustainably while at the same time reducing drivers of land degradation in rural areas (Wilhelm and Smith 2018).

Potentials of NbS, constraints and uncertainties

The majority of estimates of mitigation potentials of NbS in urban areas that are available in the literature relate to assessments for specific cities or geographical regions. For example, Nowak and Crane (2002) estimate the current net annual carbon sequestration of Barcelona at 2 t CO_2/ha/yr. This is similar to sequestration rates in Baltimore (1.9 tCO_2/ha/yr) or Syracuse (2 t CO_2/ha/yr). For the area of Barcelona, this results in removals of 19,036 tCO_2e/yr. Compared to the city's total annual GHG emissions, this direct net carbon sequestration has only limited mitigation effects (0.47%) (Baro et al. 2017). The same has been found for other cities as well (Pataki et al. 2009; Liu and Li 2012). For the entire US urban areas, total tree carbon storage is estimated at 0.64 GtC (2.3 $GtCO_2$) or 0.03 Mt C/yr (0.11 $MtCO_2$). Yet specific carbon density rates vary significantly between different areas and cities due to diverging local forest structures as well as differences in data availability (Nowak et al. 2013).

For the EU, studies have found that greening about 35% of the EU's urban surface (>2.6 Mha) could lead to avoiding up to 0.06 $GtCO_2e$/yr (Quaranta et al. 2021). While space might be available to increase the number of trees and carbon stored in urban areas, human factors (e.g. mowing) as well as natural conditions (e.g. lack of precipitation) limit the potential to increase the sink of urban trees unless current conditions are changed (Nowak et al. 2013).

Lal et al. (2018) provide a global technical mitigation potential estimate for 390 Mha of urban area of 1.7-3.6 $GtCO_2$/yr. The majority of this mitigation potential comes from biomass (~80%), with an estimated carbon sequestration rate of 3.7-7.3 tCO_2/ha/yr. This is substantially higher compared to the carbon sequestration estimates of other cities as mentioned above. Hence, taking into account large local variations and data uncertainties, the mitigation potential provided by Lal et al. (2018) is more likely to represent the upper range of the global mitigation potential of urban greening.

Summary

Enhancing urban green infrastructure can contribute to mitigating emissions as well as to cities' adaptation to climate change. At the same time, they involve co-benefits for food security, improve air quality and can have positive impacts on soil and water. Overall, the potential to abate pollution is evaluated as more substantial than the potential to mitigate GHG emissions (Baro et al. 2017). Additionally, the circumstances for urban greening are very different across the globe. Local data remains fragmentary (Nowak et al. 2013).

3.3 Discussion

Constraints and uncertainties

As shown in Sections 3.2.1 to 3.2.6, the mitigation potentials published by Griscom et al. (2017) and studies based on their results, like Roe et al. (2019), Jia et al. (2019), Bossio et al. (2020) and Lal et al. (2018), need to be considered as rather **rough estimates with considerable constraints.** Their limitations result from the quality of available information on the **current state of ecosystems**, underlying **drivers of ecosystem and environmental change** and the expected **impact of measures on these ecosystems, especially GHG fluxes** and other ecosystem services, including biodiversity. Currently, Griscom et al. (2017) provides the most comprehensive global NbS study that accounts for land demand arising from different NbS and incorporates biodiversity and food security safeguards, and the resulting maximum mitigation potential is 23.8 $GtCO_2$ e/yr until 2030. However, our review indicates that a conservative estimation of the NbS potential, i.e. a potential that considers the most relevant constraints and thus limits the risk of overestimation, lies below this estimate due to the following major constraints:

- Biochar, grazing-improved feed and grazing-animal management cannot be considered as NbS applying a strict definition (see Sections 2.1.1 and 3.2.3), their potential is estimated at 1.98 $GtCO_2$ e/yr.
- European semi-natural grasslands should be excluded from the potential reforestation area due to biodiversity protection (see Section 3.2.1), which results in a lower afforestation mitigation potential by ~0.4 $GtCO_2$ e/yr.
- Restoration of the global total degraded area of terrestrial and coastal wetlands can be considered rather optimistic, especially due to socio-economic concerns often ignored in studies (see Sections 3.2.4 and 3.2.5).
- The reliability of the mitigation potentials provided for croplands is questionable due to high uncertainties of capacities to rebuild SOC stocks (see Section 3.2.2).
- The mitigation potentials provided for grasslands are also very uncertain as documented by high ranges of potential soil carbon sequestration found in the literature (see Section 3.2.3).

The first two constraints limit the mitigation potential by Griscom et al. (2017) already by at least 10%. Other aspects, e.g. concerning wetland restoration area, are very hard to quantify but most likely also lower the estimated mitigation potential. At the same time, some NbS that can provide mitigation potentials are currently missing in global assessments. These include e.g. mitigation potentials of marine seafloor sediments, which are not covered by studies on coastal ecosystems. They could offer huge potentials to reduce and avoid emissions, e.g. from bottom trawling (1.47 Gt of aqueous CO_2 emissions, Sala et al. 2021). Addressing these emissions in global mitigation assessment studies also raises the awareness towards marine ecosystem restoration potentials beyond coastal ecosystems. Other potential NbS not yet quantified globally in Griscom et al. (2017), Roe et al. (2019) and Jia et al. (2019) are urban greening and organic farming.

Beyond such identified constraints to the scope considered by recent mitigation potential studies, there are uncertainties related to the methodological approaches of assessing mitigation potentials. When data from local or regional studies focusing on specific ecosystems is used for scaling up to global level potentials (e.g. Griscom et al. 2017, 2020; Roe et al. 2019), statistical uncertainties are scaled up as well. But also top-down approaches carry uncertainties when looking at the regional level. This becomes obvious when assumptions are compared with e.g. national data provided by countries (see below “Comparison of national data for Costa Rica with global potentials”).

Comparison of national data for Costa Rica with global potentials

Estimates for global potentials for NbS often use coarse data sources which have higher uncertainties compared to national data from countries. Griscom et al (2020) estimate a high potential of 0.06 $MtCO_2e$ per year for avoided deforestation for Costa Rica. This is 160% of the current emissions of 0.04 $MtCO_2e$ from deforestation in Costa Rica and also much higher than the emissions calculated based on historic data for the forest reference level of Costa Rica for the period 2010-2025 which is 0.04 $MtCO_2e$ per year. Thus, for Costa Rica the potential for avoided deforestation indicated by Griscom et al. (2020) seems too high. Griscom et al. (2020) estimate a potential for natural forest management for Costa Rica at 0.05 $MtCO_2e$ per year which is only about half of the actual CO_2 sequestration in secondary forests (-0.089 Mt CO_2e) in Costa Rica. This could however be a conservative estimate taking into account that this potential extends over a long period. Related to reforestation, the potential estimated by Griscom et al. (2020) is about five times the current CO_2 sequestration from reforestation. Given the high share of land area already protected and reforested in Costa Rica, the high potential for reforestation provided by Griscom et al. (2020) seems overestimated. This example indicates that disaggregation of global mitigation estimates can substantially deviate from data reported by countries. It would therefore be useful to analyse these differences for a larger number of countries to reconcile discrepancies and exclude the risk of systematic differences between global and country-specific data derived potentials.

Another major problem for reliably assessing NbS mitigation potentials are the underlying assumptions regarding expected **ecosystem carbon fluxes.** Particularly **carbon sequestration rates** and applied emission factors for specific ecosystems and their conversion and management often **show huge differences between studies** (see Section 3.2). These differences may originate from different methodological approaches but also reflect the diversity of ecosystem process responses to specific site conditions (e.g. local climate, soil condition) and human interference. Emission factors provide a simplification of assumptions regarding carbon fluxes in the ecosystem that are necessary to assess GHG implications of mitigation measures in a cost-efficient way. However, such simplifications can also lead to systematic errors, e.g. due to a lack of incorporating seasonal changes, site-specific conditions and, very importantly, adaptation processes as responses to changing climate and environmental conditions. As shown in Section 3.2, no **NbS mitigation potentials assessed for this study consider climate-induced changes in ecosystem conditions** such as acidification of the ocean and more frequent drought events, which can lead to lowered ecosystem functioning and thereby also threaten carbon sequestration and storage. For example, for the period at the end of the 21st century, earth system models project a significant weakening of the land and ocean sink under the RCP2.6 concentration pathway, which could result into net GHG emissions from ocean and land ecosystems by that time (Jones et al. 2016). Therefore, limiting atmospheric GHG concentration is crucial to sustain ecosystems as carbon sinks as well as habitats and basis for food production.

Besides climate impacts, there are also large uncertainties concerning the impact of further disturbances on ecosystems, e.g. from fragmentation or eutrophication from the discharge of nutrients. The success of NbS to mitigate climate change and deliver ecological and social co-benefits will also very much depend on a successful implementation of the goals and targets of the Rio Conventions. This applies in particular to the CBD and its global biodiversity framework, which aim to **eliminate direct and indirect pressures on ecosystems related to recent drivers of global change,** including land- and sea-use change, ecosystem and species exploitation and pollution, caused by current consumption patterns. An ecosystem-friendly production of goods and the recycling of resources are necessary to stop environmental pollution and reduce waste. Policy measures are needed to ensure more sustainable production, land use and land management by e.g. incentivising NbS. Additionally, they should support the sustainable consumption and use of products, which can also include incentives to consume less meat and dairy products as changes in diet can free land occupied for feed production, currently forming the largest share of agricultural land use. If such pressures on ecosystems continue, there is a high **risk of increased emissions from land use, reduced carbon removals** that can be achieved by NbS but also of reversing historically achieved carbon storage (e.g. Mackey et al. 2013).

Further risks to the mitigation potentials of NbS are related to the valuable resource of productive land. The implementation of NbS can trigger **land use conflicts** as discussed for e.g. reforestation (Section 3.2.1) and rewetting of peatland area (Section 3.2.4). Besides conflicting land use interests also land tenure and weak governance can have a strong influence on the realisation and maintenance of the NbS potential (Nolan et al. 2021). In general, social, cultural and political barriers are barely considered in the reviewed studies. Zeng et al. (2020) conducted a study on the realistic mitigation potential from reforestation in Southeast Asia until 2030, which was decreased by 80% compared to the biophysical mitigation potential. Their estimates consider implementation costs, food security needs of small communities and assume that reforestation takes place only in areas not prone to deforestation. These results underline the huge potential effect of social constraints on implementation and success of NbS. More research is required to **assess the socio-economic parameters that influence the uptake of NbS by stakeholders** and may pose significant constraints on NbS potentials exclusively focused on biophysical parameters.

Last but not least, there is still **little knowledge about the actual potential of NbS to deliver positive outcomes for biodiversity** (Seddon et al. 2020). Biodiversity impacts are even more difficult to assess compared to GHG impacts because of their high spatial variability and complexity (Pereira et al. 2013). For example, a local increase in biodiversity after ecosystem restoration does not necessarily imply regional or global biodiversity benefits if it is due to an increase of non-threatened generalist species (Lennox et al. 2018). Therefore, it is important to develop robust and standardised assessment methods for quantification and comparison of biodiversity impacts associated with NbS (Pettorelli et al. 2021).

Assumptions regarding costs

The majority of analysed studies focus on the **technical potential** (i.e. the biophysical possibilities of mitigation, often calibrated by rules to better reflect reality). This can differ significantly from the **economic potential** (i.e. the amount of mitigation expected to be implemented by economically rational agents in response to a defined carbon price). When considering economic potential, the assumed costs of mitigating climate change and the assumed effective carbon price play a decisive role in estimates of potential. This holds for global simulation models, which calculate the optimal mix of mitigation options to achieve a set GHG concentration pathway (at an equilibrium carbon price). It is also true in bottom-up models, where cost assumptions again determine how much mitigation is considered feasible at different carbon prices. Accordingly, the resulting estimated potential significantly depends on the assumed costs of each mitigation option and how these costs are defined, calculated and used within the simulation models.

It is important to note that the costs discussed here (and used in the models) focus on private costs. While in some cases they include co-benefits enjoyed by the landowner implementing NbS (e.g. increased economic efficiency through land retirement), by definition they exclude **external, societal benefits** that arise from implementing NbS (such as the value of social benefits of climate mitigation, or the many external co-benefits of NbS, such as recreation value, supporting human well-being, etc.). While the general societal benefits of climate mitigation are represented in models (through the assumed carbon price), models generally fail to recognise the value of NbS co-benefits and therefore underestimate the potential of NbS contributing to e.g. human well-being (see also Section 2.1.2).

Including costs in assessment models is challenging and requires considerable simplification and reduction of complexity. Costs of the implementation and ongoing management of NbS vary widely across different contexts. Data is often lacking, especially to capture this locally specific variability (Griscom et al. 2017). In addition to direct implementation and management costs, to realistically reflect cost barriers to NbS implementation (i.e. to reflect economic potential rather than technical potential), costs should also include opportunity costs, transaction costs and transition costs. A particular challenge forms the estimation of opportunity costs, i.e. the value the land would generate if it was not being used for mitigation (e.g. the income agriculture could generate from the same piece of land if it was not kept in trees). The determination requires assumptions on the development of markets and prices and thus incorporates considerable uncertainties. Transaction costs and adjustment costs can also be difficult to include in models and are thus often ignored. Yet, in reality any policy instrument that was put in place to incentivise mitigation would have significant administrative costs for administrators and farmers. An argument against including transaction costs in models refers to the fact that they very much depend on the type of policy instrument used. Nevertheless, omitting these costs can result in overstating the realistic mitigation potential.

Despite the importance of cost assumptions to NbS potential estimations, **it is not always clear what cost data or definitions underpin NbS potential studies**. Cost assumptions were assessed in detail in Griscom et al. (2017), Roe et al (2019) and Fuss et al. (2018). Fuss et al. (2018) collected different existing individual NbS potential and cost studies and it is not fully clear on what data or assumptions these studies are based. Griscom et al. (2017) calculated both the technical and economic potential (at 10 and 100 USD/tCO_2e). However, the cost data behind the economic potential does not consider opportunity[12], transaction or transition costs. In addition, due to a lack of reliable global marginal cost data for most of the different NbS, much of their economic potential results depend on expert judgement and assumptions.[13] Roe et al. (2019) calculated a technical potential based on results of top-down integrated assessment model runs. The technical potential they present for NbS to meet the 1.5 °C objective implies 2050 carbon prices of USD 480, i.e. a significant proportion of these are likely to be ignoring economic constraints. Roe et al. (2019) also updated the Griscom et al. (2017) bottom-up analysis of technical potential, with similar issues regarding costs. This lack of clarity and comparability in terms of costs of NbS makes it difficult to compare or validate the NbS potential estimations.

Conclusions

Against the background of the wide range of assumptions underlying the models and the high uncertainties related to results outlined in this chapter, **estimates of NbS potentials provided in the available literature need to be regarded as rough approximations**. There is evidence for both systematic overestimation and underestimation of the realistic potential due to a number of different influencing factors, including definitions, data sources, methods and models applied, and system boundaries and mitigation options considered.

Nevertheless, the uncertainties related to the quantification of mitigation effects of NbS should not be used as an argument against the implementation of NbS. Advancing NbS is often described as a 'no-regret' option, as they entail benefits to people in a range of scenarios (IUCN; Oxford University 2019). To realise these benefits, **NbS need to be carefully designed, be based on metrics that take into account their various benefits to people and the**

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[12] With the exception of the conservation agriculture pathway.

[13] In many cases, they asked a set of experts what % of technical potential could be realised at the two price points, based on their own judgement and a small number of studies.

environment and have robust social and biodiversity safeguards in place to address risks related to their implementation. Mitigation benefits implied by NbS form an important contribution to reaching the goals of the Paris Agreement, but need to be considered as a complement to ambitious mitigation action to reduce overall GHG emissions and not mainly as a solution to compensate for remaining emissions (see Chapter 4).

Policy makers should be aware of the inherent uncertainty in the assessment and quantification of ecosystem processes underlying NbS potentials due to their complexity and diversity. While uncertainties in quantification should not be used as a justification for delaying action and investment in the protection and restoration of ecosystems, they are important considerations when designing potential incentive schemes for the local implementation of NbS.

NbS are a framework to promote the implementation of measures to protect existing intact ecosystems, restore degraded ecosystems and sustainably use natural resources. Only if measures are designed following the key characteristics of NbS that include the alignment with natural ecosystem processes, biodiversity benefit, adaptability, multi-functionality, locally appropriate actions and addressing societal challenges and enhance human well-being (see Section 2.1.1), can they deliver the desired multiple benefits like preventing further emissions, maintaining carbon stocks and increasing sequestration while safeguarding biodiversity and other ecosystem services.

4 Nature-based solutions in international climate policy

Nature-based solutions have become a major focus in international climate policy. All NbS concepts have in common that they are in close relation to activities managing land. Activities related to land management are often referred to as the land use sector or more explicitly Land Use, Land Use Change and Forestry (LULUCF) or Agriculture, Forestry and Other Land Use (AFOLU) under the UNFCCC process. Agriculture, forestry and spread of settlement and infrastructure are the most important drivers of land use and ecosystem dynamics globally. In the following we will refer to the "land use sector", denoting the area in which activities managing land and terrestrial ecosystems take place that affect the potential and implementation of NbS. This also includes the large spectrum of agricultural and forestry activities aiming at the cultivation of crops and livestock for food, feed, fiber and fuel as well as urbanisation activities. It is therefore wider than the formal definition of LULUCF and potentially narrower than the more comprehensive concept of AFOLU. As the term NbS is barely used in the UNFCCC context, the following sections evaluate the role of and discussions on activities in the land use sector as an approximation of activities with relevance for NbS. At the same time, it needs to be kept in mind that not all activities in the land use sector qualify as NbS (see Chapter 2 and Section 3.2 for further elaboration on the criteria which need to be fulfilled for NbS).

The link of activities in the agricultural sector to the concept of NbS deserves special attention. When implementing activities to mitigate emissions from agriculture, social impact and the local appropriateness of activities are crucial in order to maintain the livelihoods of local communities. On the other hand, various technical measures to mitigate emissions that are discussed for the agricultural sector do not fulfil the requirements of an NbS (e.g. use of CH_4 inhibitors to reduce CH_4 from enteric fermentation). In this context there is a need to differentiate NbS aimed at the protection, sustainable management and restoration of ecosystems from actions that aim to address drivers of biodiversity loss and climate change but are not ecosystem-based and do not directly enhance human well-being and biodiversity. Many necessary measures in the agricultural sector are more likely to fall under the last-mentioned category, like the reduction of the total number of livestock. Even though there is potential for implementing NbS in the agricultural sector (see Section 3.2.3), it primarily needs to be addressed as a *driver* of biodiversity loss and emissions from the land use sector. The implied need for dietary changes and potential impacts on the meat industry as well as food security remains a very controversial topic though.

Activities in the land use sector have always been part of climate debates, but until recently they did not feature prominently therein. With the adoption of a temperature goal under the Paris Agreement, however, it became clear that the land use sector has a major role to play in order to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (Article 4.1 of the Paris Agreement): Firstly, it is necessary to implement high emission reductions in the sector in order to bring it on a path that is compatible with the goals of the Paris Agreement.[14] Secondly, carbon sinks need to be protected and expanded, particularly through reforestation, restoration and increasing soil carbon, in order to compensate for remaining emissions that are difficult or impossible to abate and in order to achieve net negative emissions within the next decades. Thirdly, the sector needs to contribute to substituting fossil fuels by providing bioenergy at a sustainable scale and,

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[14] According to Svensson et al. (2021a) the AFOLU sector makes up about 24% of today's global GHG emissions.

fourthly, it must contribute material input to low GHG products (Svensson et al. 2021b; Svensson et al. 2021a).

While the term NbS is frequently used in international climate policy, it does not feature prominently in official decisions adopted in the international climate regime.[15] The following sections provide an overview of the main developments related to the land use sector and examine to what extent they reflect the concept of NbS. A focus is put on the UNFCCC negotiation process as the most important forum for international climate policy.[16]

4.1 Role of NbS under UNFCCC and the Kyoto Protocol

The text of the Convention contains several links to sustainable development, enshrining the understanding that responses to climate change should go hand in hand with benefits for people and social and economic development (e.g. in the preamble or in Article 3(4)). Additionally, it highlights that measures to mitigate climate change means “addressing anthropogenic emissions by sources and removals by sinks” (Art. 4(1)(b)) as well as to promote sustainable management and the conservation and enhancement of “sinks and reservoirs of all greenhouse gases, “including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems” (Art. 4(1)(d)).

The **Kyoto Protocol** adopted in 1997 introduced GHG emissions targets and a cap-and-trade system for developed countries (Annex I countries to the Convention) for the first time. The role of the land use sector regarding emissions and removals was taken into account by the Kyoto Protocol by setting rules for mandatory and voluntary reporting and accounting of relevant land use activities in its Articles 3.3 and 3.4. Initially, only afforestation, reforestation and deforestation needed to be accounted for and forest management, cropland and grassland activities were accounted for on a voluntary basis. During the second commitment period from 2013-2020, accounting became obligatory for forest management as well. In addition, countries could voluntarily account for activities related to wetland drainage and rewetting thenceforth.

Under the **Clean Development Mechanism** (CDM) as one of the flexible mechanisms of the Kyoto Protocol, developed countries could use emission reductions or removals generated from afforestation and reforestation projects (among other project types) in developing countries to achieve their mitigation targets. Under **Joint Implementation** (JI), another flexible mechanism of the Kyoto Protocol between developed countries, all types of land use activities were eligible.

A set of general principles for accounting for the land use sector towards achieving national targets were laid down in the **Marrakesh Accords** adopted in 2002 in order to address risks related to mitigation involving land use activities. These principles were intended to ensure that accounted activities represent additional mitigation outcomes, to limit the risk of non-permanence, to address safeguards and co-benefits and to ensure the use of consistent methodologies over time for the estimation and reporting of emissions and removals.

Emission reductions from avoided deforestation were not accepted under the CDM of the Kyoto Protocol due to concerns regarding the permanence of emission reductions, challenges in terms of monitoring and accounting and general reservations regarding the crediting of sinks (Boyd et al. 2008; Streck and Scholz 2006). Yet, the topic was put back on the UNFCCC agenda in 2005

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[15] NbS are only mentioned as a voluntary aspect in the context of reporting on adaptation in decision 18/CMA.1, Annex, paragraph 109(g) as well as in decisions 5/CMA.2 paragraph 7 and 11/CP.25 welcoming the decision that the Standing Committee on Finance will organise a forum on NbS.

[16] Other international processes and initiatives related to NbS measures include the Convention on Biological Diversity, the UN Sustainable Development Goals (SDGs) as well as work of UNEP, FAO or OECD.

(Wolff 2011). In the following years, a **REDD+** framework ("Reducing Emissions from Deforestation and Forest Degradation, and the Role of Conservation of Forest Carbon Stocks, Sustainable Management of Forests and Enhancement of Forest Carbon Stocks in developing countries") was developed. The **'Warsaw Framework' for REDD+** adopted at COP19 in 2013 comprises seven main decisions on REDD+[17], while another nine decisions were taken at other conferences between 2007 and 2015.[18]

The Warsaw framework provides an international framework for results-based payments for emission reductions or removals that are measurable and verifiable. These emission reductions or removals can be achieved through reducing forest conversion to other land uses, reducing forest degradation and improving forest management. Over the past years, substantial capacity building was provided to parties that wish to implement REDD+ actions and fulfil the requirements for results-based payments (COWI, Oeko-Institut, CIFOR 2018). More recently, REDD+ activities have increasingly focused on promoting sustainable development to address drivers of deforestation and forest degradation (Bastos Lima et al. 2017).[19]

Furthermore, agricultural activities represent an important driver of land use and are therefore relevant in the context of NbS. **Agriculture** is mentioned in Article 4 of the Convention for which Parties shall "control, reduce or prevent" anthropogenic emissions of greenhouse gases and "cooperate in preparing for adaptation to the impacts of climate change" that includes planning for agriculture. Additionally, **food security** is included in the objective of the Convention. Agriculture is also mentioned in Article 2 of the Kyoto Protocol, with the obligation for Annex I Parties to implement and/or elaborate policies on the "promotion of sustainable forms of agriculture in light of climate change considerations" and Article 10, which requires all Parties to formulate programmes containing mitigation and adaptation measures.

However, these general provisions were basically dormant until 2011. Agriculture was included in the last minute in decision 2/CP.17 and was the starting point for technical discussion between Parties. Six years later, the **Koronivia Joint Work on Agriculture** (KJWA) was initiated through decision 4/CP.23 in 2017. It gives a mandate to the SBI and SBSTA to "jointly address issues related to agriculture, including through workshops and expert meetings, working with constituted bodies under the Convention and taking into consideration the vulnerabilities of agriculture to climate change and approaches to addressing food security" (paragraph 1, decision 4/CP.23). The KJWA does not include clearly stated objectives but is expected to improve the implementation of climate action in the agricultural sector through promoting and exchanging views on technological solutions and/or mobilising or enhancing financial support.

Discussions on agriculture in the context of the KJWA have underlined several challenges related to the role of the sector under the UNFCCC process. Firstly, agriculture is a politically sensitive issue that is intrinsically related to food security. This topic has been dealt with in the UN system long before the UNFCCC process so that there is a potential for duplicating work as well as conflicting competences. Secondly, the economic relevance of the sector and its role in the greenhouse gas emissions profile is very different among countries. Agriculture generally plays a

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[17] Decision 9/CP.19 to Decision 15/CP.19.

[18] All REDD+ related UNFCCC COP decisions: 2/CP.13, 4/CP.15, 1/CP.16, 2/CP.17, 12/CP.17, 1/CP.18, 9/CP.19, 10/CP.19, 11/CP.19, 12/CP.19, 13/CP.19, 14/CP.19, 15/CP.19, 16/CP,21, 17/CP.21, 18/CP.21

[19] This section builds upon the final report of the UBA project "Land use as a sector for market mechanisms under Article 6 of the Paris Agreement" (FKZ 3718 42 005 0) carried out by Oeko-Institut.

larger role in the economies and emission profiles of developing countries, where adaptation needs are key.[20]

4.2 Role of NbS under the Paris Agreement

As noted in Chapter 4, the wording of the long-term neutrality goal of the Paris Agreement enshrined in its Article 4(1) puts a new emphasis on the role of the land use sector in reaching this target. It entails that anthropogenic GHG emissions have to be reduced to the extent possible while any remaining emissions need to be balanced out through GHG removals by sinks (Levin et al. 2015). Article 4 also mentions that mitigation co-benefits resulting from Parties' adaptation actions and/or economic diversification plans can contribute to mitigation outcomes under this Article (Article 4(7)).

In its preamble, the Paris Agreement explicitly recognises "the importance of the conservation and enhancement, as appropriate, of sinks and reservoirs of the greenhouse gases referred to in the Convention" and notes "the importance of ensuring the integrity of all ecosystems including oceans, and the protection of biodiversity, recognized by some cultures as Mother Earth".

Additionally, Article 5 of the Paris Agreement states that all countries should take measures related to the conservation and enhancement of carbon sinks, including forests. In paragraph 2 of the Article, the Paris Agreement explicitly encourages Parties to use the REDD+ framework to that extent. Furthermore, Article 5(2) also mentions approaches that contribute to mitigation and adaptation simultaneously. Article 7 on adaptation highlights benefits of climate action for people, livelihoods and ecosystems, thus implicitly acknowledging the multi-functionality of NbS (see also IUCN; Oxford University 2019).

In the Agreement, there is no explicit reference to the agricultural sector or its contribution to the mitigation of GHG emissions. However, there are indirect links to the sector as the Paris Agreement highlights the need to ensure food security and end hunger and points to the vulnerabilities of food production systems to the adverse impacts of climate change in its Preamble (Climate Focus 2015).

4.2.1 Reporting and accounting rules for the land use sector in the Paris Agreement

Reporting and accounting for the land use sector implies several challenges. This is due to the fact that the land use sector bears several features which distinguish it from other sectors. Firstly, it is not only a source but also a sink of emissions so that accounting needs to take into account emissions as well as removals and to measure fluxes. Secondly, data on emissions and removals involves large uncertainties, in particular for soil carbon. Thirdly, carbon stocks and changes of carbon stocks in the land use sector are variable. They are subject to anthropogenic interventions, but also impacted by processes beyond human control such as droughts, floods, storms, or wildfires ('natural disturbances') which are more likely to occur in the future as a result of global warming. Furthermore, the capacity to store carbon by natural sinks may reach a saturation level at some point, thus limiting the mitigation potential of a specific area. These characteristics further exacerbate the quantification of emissions and removals from the land use sector. They also imply that natural sinks may not necessarily remove carbon permanently from the atmosphere. Addressing the risk of non-permanence is thus one important aspect in accounting for emission reductions or removals (Oeko-Institut 2018; Iversen et al. 2014).

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[20] This section builds upon the study of Oeko-Institut (2020) which provides further analysis of the KJWA and options for future work on agriculture under the UNFCCC.

Article 13 of the Paris Agreement establishes an ‘enhanced transparency framework’ to report GHG emissions and removals and to track progress towards implementing and achieving NDCs. To operationalise this framework, ‘Modalities, procedures and guidelines for the transparency framework for action and support’ (MPGs) were adopted at COP24 in Katowice (decision 18/CMA.1). The MPGs lay down basic principles for accounting, including for the land use sector. Additionally, Article 4 of the Paris Agreement establishes the obligation for Parties to account for the anthropogenic emissions and removals corresponding to their NDCs and “to promote environmental integrity, transparency, accuracy, completeness, comparability and consistency, and ensure the avoidance of double counting” in doing so (Article 4(13)). Further accounting guidance was adopted by the CMA in 2018 with decision 4/CMA.1 (including Annex II) which lists information that countries should include in their NDCs and provides guidance for accounting progress towards reaching the NDCs.

According to this guidance Parties must account in accordance with IPCC methodologies and common metrics, ensure methodological consistency, strive to include all categories of anthropogenic emissions and removals and provide an explanation for the exclusion of categories. Accounting in accordance with IPCC methodologies also implies that Parties which decide to address emissions and removals from natural disturbances on managed lands must provide information on the approach used and how it is consistent with relevant IPCC guidance, as appropriate, or indicate the relevant section of the national GHG inventory report containing that information (decision 1/CP.21, paragraph 31(e)). Additionally, Parties need to provide information on the scope of their NDC as well as underlying methodologies and information that is necessary to track progress made in implementing its NDC according to chapter III of the MPGs.[21] Actual accounting, summing up emissions and removals to allow a comparison with the progress made in implementing and achieving the NDC, will take place upon the submission of Parties’ biennial transparency reports from 2024 onwards.[22]

However, under the Paris Agreement and in contrast to the Kyoto Protocol, there are no longer any binding *common* accounting rules for the land use sector but countries must adhere to the more general accounting guidance included in decision 4/CMA.1. This lack of common accounting rules will affect the consistency of available information on activities in the land use sector and their effects. Even though MRV capacities have improved significantly in recent years, lacking monitoring capacities, particularly with regard to forest degradation, remains an additional challenge to obtaining robust information on the effect of mitigation activities (Svensson et al. 2021a).

All of the general challenges related to accounting for emissions and removals in the land use sector are relevant for the accounting of NbS as well. Most importantly for NbS, however, is the fact that reporting and accounting under the Paris Agreement is done in terms of CO_2e, only focusing on the measurable impact on emissions. All other benefits of NbS are not reflected systematically in reporting and accounting. To address this, a more comprehensive approach towards carbon accounting would be needed that considers the whole carbon cycle, covers

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[21] An analysis by Oeko-Institut (2018) highlights the diversity of approaches for including the land use sector in 190 first NDCs submitted by Parties under the Paris Agreement: 102 countries included the land use sector in their first NDCs albeit in different ways: 76 countries integrated the sector into an economy-wide mitigation target, of these 37 countries formulated an absolute reduction target for the sector, and 39 countries formulated targets that are compared to a business-as-usual scenario. A separate target for the land use sector was chosen by 21 countries. While the majority (92 countries) refers to the land use sector as LULUCF; 18 countries refer to AFOLU and others to forestry or REDD+ activities only. Due to the bottom-up character of the NDCs, they differ in terms of the extent of land uses or land areas included, in terms of the way baselines are being defined or in terms of the accounting rules that the states choose (e.g. for natural disturbances or harvested wood products). Many NDCs are not transparent with regard to which specific source and sink categories or activities are covered by their NDC though (Oeko-Institut 2018).

[22] Common reporting tables for reporting in Parties’ biennial transparency reports have been adopted at COP26.

stocks as well as flows of carbon and takes effects of changes induced by human activity on the biosphere and atmosphere into account (Keith et al. 2021).

4.2.2 The role of NbS in NDCs

The decision adopting the Paris Agreement calls upon all Parties to “strive to include all categories of anthropogenic emissions or removals in their nationally determined contributions and, once a source, sink or activity is included, continue to include it” (decision 1/CP.21, paragraph 31(c)). With this encouragement, the decision asks Parties to include the land use sector in their NDCs if they have not yet done so.

Various studies have examined the role of NbS or the land use sector in NDCs, starting from different questions and assumptions. Of the Nationally Determined Contributions submitted to the UNFCCC, 66% include commitments to implement some form of NbS (Seddon et al. 2021). On the basis of a study by IUCN and Oxford University (2019) key findings in the literature include:[23]

- 86% of the developing countries, 88% of the countries in transition and 98% of developed countries include agriculture and/or LULUCF in their NDCs under the Paris Agreement. Countries **rarely include quantified sector-specific targets** for agriculture and/or LULUCF (FAO 2016).
- 97% of countries include LULUCF in their **mitigation** plan (FAO 2016), 62% of NDCs include NbS as **adaptation** actions (Nature-based Solutions Initiative 2018).
- 74% of NDCs include **forest-related targets**, 20% of which are quantifiable and 55% of NDCs include forests as part of economy-wide targets (IUCN; Climate Focus 2017). 52 developing countries embark on policies and measures for reducing deforestation (FAO 2016).
- 19% of Parties with **coastal ecosystems** include these habitats in the mitigation component of their NDCs, 39% in their adaptation component (IUCN; The Nature Conservancy 2016),
- 28% of NDCs position **NbS prominently**, more common in Africa and Central and South America than in Asia (excluding China and Europe) (IDDRI 2016), while 63% of NDCs state that they intend to protect ecosystems and/or biodiversity through their mitigation actions (Nature-based Solutions Initiative 2018).
- As of November 1, 2021, 61% of current NDCs include commitments related to SOC, particularly with regard to wetland management (43%), agroforestry (34%) and grassland management (22%). However, SOC is only prioritised by 50-60% of the countries with the highest mitigation potentials (CGIAR 2021).

The different analyses of NDCs agree on the fact that NbS can help countries to meet mitigation and/or adaptation goals. Also, action is urgently needed to address the effects of climate change on ecosystems. Enabling conditions are highlighted as a crucial precondition for NbS implementation (IUCN; Oxford University 2019). Additionally, the study by IUCN and Oxford University highlights the following challenges related to the inclusion of NbS in NDCs:

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[23] Many NDCs have been updated after the studies considered here had been published. Most of the existing literature is therefore not based on the most recent information on Parties’ NDCs and not all studies cover all NDCs submitted so far.

- Measures in the forest sector are the most prominent type of NbS while NbS in non-forest ecosystems are underrepresented.
- Overall, countries in the Global South seem to emphasise NbS to a greater extent than countries in the Global North.
- NDCs address the adaptation co-benefits of mitigation activities and vice versa only to a limited extent, particularly for coastal and marine habitats.
- Vulnerabilities identified in NDCs mostly do not translate into corresponding adaptation actions or targets.
- In relation to NbS, proclaimed targets are mostly not measurable as they lack precise definition and the provision of related indicators
- The majority of NbS actions is planned and made conditional upon receiving financial support from developed countries (IUCN; Oxford University 2019).

4.2.3 The role of NbS in the negotiations for Article 6

Under the Paris Agreement, Article 6.2 establishes a framework for Parties to engage in "cooperative approaches" that involve the use of "internationally transferred mitigation outcomes" (ITMOs) to achieve NDCs. Additionally, Article 6.4 establishes a new market-based mechanism to help mitigate GHG emissions and support sustainable development. At COP26, rules on Article 6 have been adopted. Neither Article 6 itself nor the decisions taken at COP26 include an explicit reference to the LULUCF sector. However, the COP26 decisions[24] include many aspects that are central to activities in the land use sector, e.g. the additionality of activities, baseline setting, mitigating the risk of leakage, ensuring permanence, and environmental and social safeguards (see box below). This suggests that activities with non-permanence risks are principally eligible under Article 6 but that these risks need to be adequately addressed. Negotiations on whether the 'avoidance' of emissions should be eligible under Article 6 will continue at the next session of the SBSTA in 2022. Depending on the interpretation of what avoidance means, this could imply that certain land use activities might be excluded, e.g. from countries where the LULUCF sector is currently not (yet) a source of emissions.

NbS are not specifically addressed in the negotiations on Article 6, but as they involve mitigation activities in the LULUCF sector, the concerns outlined below are relevant for potential NbS under Article 6 as well. Another specific challenge is that the benefits of NbS beyond mitigating emissions have not been monetised under carbon crediting approaches so far. Integrating such values would entail that resulting credits are not fungible with other carbon credits in accounting systems or compliance markets. However, some carbon crediting programmes have started to develop standards for taking benefits into account that cannot be measured in CO_2e (WRI 2021b).

Environmental integrity risks of using carbon crediting approaches in the land use sector

To what extent land use activities should be covered by carbon crediting mechanisms has provoked controversial discussions for a long time. This is because some mitigation activities in the

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[24] See https://unfccc.int/process-and-meetings/conferences/glasgow-climate-change-conference-october-november-2021/outcomes-of-the-glasgow-climate-change-conference.

land use sector can involve greater risks to environmental integrity than activities in other sectors. Key issues include:

- **Baseline setting:** For some land use activities, such as avoiding deforestation, setting baselines is associated with considerable uncertainty. Baselines represent counterfactual scenarios based on assumptions how carbon stocks would have developed in the absence of the mitigation activity (infras 2014). In the context of the Paris Agreement, baselines should additionally represent a level of emissions or removals that is aligned with the implementation of the host country's NDC. They should also be set in a conservative manner, i.e. rather underestimate than overestimate emissions in the baseline scenario.
- **Addressing non-permanence:** Mitigation in the land use sector implies the risk of reversals, i.e. that achieved emission reductions or removals are revoked at a later point in time (e.g. Mackey et al. 2013). If carbon credits are issued on the basis of net mitigation achieved in a specific period but the mitigation is subsequently reversed, then the market mechanism will have over-issued credits. This can imply a net increase in global emissions and thus be a threat to environmental integrity (Schneider and La Hoz Theuer 2019).
- **Leakage:** Some land use activities, such as avoiding deforestation, can involve different forms of leakage (i.e. emission increases occurring as a result of the activity but outside its geographical boundaries). If a forest area is protected in one place, and the underlying drivers for deforestation are not fully addressed, deforestation could increase in other places. Global leakage is particularly difficult to address and can play an important role where demand for global agricultural commodities, such as soybean or palm oil, is the main driver for deforestation.
- **Environmental and social impacts:** Further, NbS can involve various co-benefits for people and the environment (see Chapter 2) but also pose particular challenges to ensuring environmental and social safeguards, in particular if the land has competing uses and if indigenous people are affected (UBA 2020; Michaelowa et al. 2019). In practice, the implementation of safeguards varies greatly.

Beyond these risks that are particularly relevant for the land use sector in the context of carbon crediting mechanisms, such mechanisms involve further challenges common to all types of mitigation activities. These include ensuring the additionality of mitigation outcomes, avoiding double-counting and setting a robust governance framework for the mechanism. To ensure environmental integrity and the effectiveness of carbon market mechanisms, it is therefore crucial to take a cautious approach when implementing cooperative approaches under Article 6.

Recently, the debate about using carbon crediting approaches in the land use sector has gained momentum (see also UNEP and IUCN (2021) on the need to set the right framework to address the risks mentioned above in the context of NbS). With more companies adopting net-zero emission targets, the demand for voluntary offsetting as well as awareness of the need to enhance removals is increasing. At the same time, the integrity of carbon crediting approaches in general has been increasingly discussed.[25]

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[25] See the final report of the UBA project "Land use as a sector for market mechanisms under Article 6 of the Paris Agreement" (FKZ 3718 42 005 0) carried out by Oeko-Institut for further elaboration on these challenges in the context of the land use sector. For further information on the quality and integrity of carbon crediting approaches see https://carboncreditquality.org/ and https://www.iif.com/tsvcm.

5 Conclusions and strategic implications for international climate policy

Debates around NbS have intensified in the context of the goals set by the Paris Agreement. The Glasgow Climate Pact adopted at COP26 underlines the importance of protecting, conserving and restoring nature and ecosystems in delivering benefits for climate adaptation and mitigation, as well as the need to ensuring social and environmental safeguards. It also establishes an annual dialogue to strengthen ocean-based action.[26] Additionally, more than 130 leaders have signed the Glasgow Leaders' Declaration on Forest and Land use, committing to work together to halt and reverse forest loss and land degradation by 2030.[27]

However, it needs to be evaluated critically, whether measures currently discussed as NbS live up to the requirements derived from the NbS concept as defined in this paper, i.e. whether they carry benefits for biodiversity and are in line with local conditions and social needs beyond delivering mitigation outcomes. These requirements are key for the success of NbS and for realising their potential for climate change mitigation and adaptation.

While NbS have a crucial role to play in addressing the climate crisis, they should not be considered as a 'silver-bullet' solution to climate change. The climate crisis cannot be mitigated unless fossil fuels are phased out rapidly; not least because ecosystems will be severely damaged and unable to provide additional sinks if global warming is not limited to 1.5 °C (cf. Anderson et al. 2019; Seddon et al. 2021). Additionally, NbS as well as technological options for carbon dioxide removal imply a higher risk of being reversed through human activities or natural disturbances compared to avoiding emissions from fossil fuels (Anderegg et al. 2020; Mackey et al. 2013; McLaren et al. 2019). As a consequence, a tonne of CO_2 removals achieved through NbS cannot be considered equivalent to one tonne of CO_2 of fossil fuel avoided that has a much lower risk of non-permanence. Increasing mitigation ambition targeting fossil fuel emissions by all countries throughout various sectors is urgently needed under the UNFCCC process and should remain a key priority in the negotiations. **The contribution of NbS to reaching the goals of the Paris Agreement must therefore always be framed as an addition/a complement to ambitious mitigation action to reduce fossil fuel emissions.**

So far, there have been no mandates for work on NbS under the UNFCCC. Future work on NbS could benefit from an agreed definition and a related mandate for future work but achieving this will likely require lengthy negotiations among Parties to find consensus. Nevertheless, NbS can still be addressed under ongoing work under the UNFCCC, even without being explicitly mentioned in negotiated text:

- **NbS and NDCs[28]:** Some Parties already have described targets related to NbS in their NDCs and others are considering NbS when implementing adaptation and mitigation actions. If Parties also report on the implementation of NbS in their biennial transparency reports, this may serve as a basis for technical discussion to improve methodologies and indicators to

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[26] See https://unfccc.int/process-and-meetings/conferences/glasgow-climate-change-conference-october-november-2021/outcomes-of-the-glasgow-climate-change-conference.

[27] See https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/.

[28] This consideration also applies to countries' national adaptation plans.

assess how NbS contribute to achieving NDCs and to direct capacity building resources to support the development of better policies to enhance and promote their implementation.

- **NbS and support for implementation:** The financial entities under the UNFCCC respond to needs expressed by Parties. By referring to NbS in their NDCs or providing information on related financial or capacity building needs in their biennial transparency report, Parties can work towards directing resources towards the implementation of NbS.
- **NbS and Article 6**: Due to the importance of the land use sector for achieving the long-term goals of the Paris Agreement, there is an increased interest to incentivise mitigation action in the sector through market-based approaches. However, including NbS in market-based mechanisms involves risks related to the uncertainty in setting baselines, monitoring carbon stock changes, non-permanence of achieved mitigation and social and environmental safeguards. While the rules for Article 6 have been set at COP26, these risks must be taken into account in implementing cooperative approaches under Article 6. Particularly**, activities need to be developed carefully in order to manage reversal risks**. Additionally, a prudent policy approach would be to use crediting mechanisms only for those activities for which the likelihood of additionality is high and for which baselines can be estimated with reasonable certainty.
- **NbS and the KJWA**: The KJWA focus is not on NbS but some of the discussed themes are closely related. Depending on the future of the KJWA, namely whether it continues with the established themes or establishes new ones, exchange on NbS related to the agricultural sector could be discussed under the KJWA.
- The Global Climate Action Agenda of the UNFCCC also offers an opportunity to further address NbS. This would be possible without lengthy negotiations and could allow for a more flexible approach, especially focused on working with a wide range of stakeholders and reaching out to related processes across the UN System.

If there is sufficient momentum to initiate **dedicated work[29] on NbS under the UNFCCC**, the question arises how the UNFCCC could best support the implementation of robust and ambitious NbS. The following aspects should be considered:

- **More focus should be placed on the role of ecosystems other than forests in reaching mitigation goals as well as adaptation targets** and other social or environmental aims; not least to prevent inappropriate tree planting with negative side effects (see Section 3.2.1). Under the UNFCCC negotiations, more attention should be paid to those types of NbS that are less prevalent but bear significant benefit to people and the preservation of ecosystems such as marine and terrestrial wetland habitats.
- **An integrated view on NbS** is necessary, as they need to be understood as measures to enhance mitigation as well as adaptation and biodiversity conservation. Coherence with other ongoing work under the UNFCCC (e.g. KJWA, Nairobi Work Programme, Standing Committee on Finance) is required to foster synergies. Realising the potential of NbS will also require work beyond the UNFCCC process. For example, NbS implementation is closely linked to processes like the SDGs, the other two Rio Conventions on Biodiversity and Desertification and initiatives for ecosystem restoration, e.g. the Bonn Challenge. To facilitate collaboration and synergies it would be beneficial to work on common or at least aligned

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[29] This requires a COP or CMA decision with a specific mandate.

frameworks as well as indicators for reporting and tracking NbS activities under these different processes (IUCN; Oxford University 2019; Pettorelli et al. 2021), e.g. under initiatives such as MEA DaRT[30].

- **In the development of processes or support schemes to foster NbS under the UNFCCC process, special attention needs to be paid to ensuring that social and environmental safeguards are put in place.** If policies offering financial incentives to scale up NbS mainly aim to achieve GHG mitigation, they risk trade-offs with biodiversity targets, issues of land tenure and food security and other land use conflicts, undermining the fundamental idea of NbS. While the Warsaw Framework for REDD+ explicitly requires the conservation of biodiversity and the respect of indigenous peoples' and local communities' rights, guidance on such safeguards for other types of NbS measures is too vague under the UNFCCC (Seddon et al. 2020). Progress on NbS safeguard frameworks has been made for example under the CBD (ecosystem approach; principles and safeguards for ecosystem-based approaches to climate change adaptation and disaster risk reduction) or the IUCN Global Standard for NbS on which the UNFCCC process can further build on.
- **Focus discussion on providing governance frameworks to enhance NbS uptake,** since robust governance structures and well-established planning structures and processes are necessary to successfully implement NbS and realise their benefits. Lacking policy incentives, obstructive land use rights or specific policies in other sectors can hinder the implementation of NbS at a national scale (Seddon et al. 2020).
- **Improve exchange between the scientific community and countries** to improve methodologies to assess the potential of NbS and their contribution to achieving NDCs. This could be accompanied by **financial and technical support to enhance monitoring capacities as well as to support the design and implementation of NbS.**

Work under the UNFCCC on NbS will likely help to raise political awareness and understanding around the benefits of NbS and guide the mobilisation and allocation of financial resources. Considering limited available resources, it will be especially important to strengthen understanding that despite the fact that their mitigation potential is limited at a certain level, NbS have key advantages over technical carbon dioxide removal options: Technical options such as direct air capture or bioenergy with carbon capture and storage (BECCS) are more expensive, more energy-intensive, not yet deployable at scale, their potentially negative impacts are not fully known yet and they do not entail additional ecosystem services and social benefits that can be achieved by well-managed NbS (The Royal Society and The Royal Academy of Engineering 2018; Smith et al. 2019). NbS, on the other hand, promise benefits to people in a range of scenarios. **NbS should therefore be prioritised over technical options in the UNFCCC negotiations when developing guidance to Parties for implementing climate action and in taking decisions on the allocation of financial resources to support climate action.** It is also important to ensure that a lack of agreement under the UNFCCC on NbS does not translate into delaying action on NbS on the ground.

Climate change forms a fundamental risk for the contribution of NbS to climate change mitigation. Natural disturbances are expected to increase in frequency and intensity. The requirement that NbS need to result in adaptive and resilient ecosystems is therefore of utmost importance. Making use of NbS for long-term carbon storage can only be successful if the sink

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[30] See https://dart.informea.org/.

potential of forests, wetlands and soils is maintained through restoration, sustainable land use and if existing carbon stocks are protected. **There is an urgent need to eliminate direct and indirect pressures to ecosystems related to patterns of consumption and production. Synergies between the conservation and better use of land can only be realised if climate protection, biodiversity conservation and climate adaptation are thought together.** Integrated strategies may not represent the optimal benefit for individual objectives. But they allow for a balance that is important for the preservation of all ecosystem functions, including enabling them to make their contribution to global GHG neutrality in the long term.

More research is required, as it is likely that NbS potentials provided by the scientific literature overestimate the realistic potential of such activities for climate change mitigation. This is partly due to the lack of integrated studies that achieve a consistent and comprehensive assessment of activities competing for land and financial resources, affecting production levels and causing displacement of production to provide the net mitigation potential. Moreover, many studies make overly optimistic assumptions on land availability and do not consider negative impacts on ecosystems, human well-being or non-GHG effects (e.g. albedo) of measures.

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